

Cycling in the Age of Automation

Enhancing Cyclist Interaction with Automated Vehicles through Human-Machine Interfaces

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siri hegna berge



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Delft University of Technology

Cycling in the Age of Automation: Enhancing Cyclist Interaction with Automated Vehicles through Human-Machine Interfaces

Dissertation

For the purpose of obtaining the degree of doctor
at Delft University of Technology
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chair of the Board for Doctorates,
to be defended publicly on
Tuesday 10 September 2024 at 15:00 o'clock

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Preface

I went into this PhD endeavour with the sobering expectation of a bumpy but exciting ride. As an early-stage researcher in an international training network of 15 PhDs across Europe, my position at TU Delft came with a substantial travel budget for in-person meetings, workshops, conferences, and work secondments. Little did I know that the entire world would be turned upside down in a global pandemic two weeks before I was scheduled to move and start working in a foreign country. To make things more interesting, the start date of my PhD coincided with April 1st. When you possibly suffer from main character *and* imposter syndrome¹, you do begin questioning if your entire PhD is one extremely elaborate April Fools' joke.

Starting a doctorate from the isolation of my home office was not ideal. Each generation has its quirks, but if there is a mantra my millennial generation lives by, it is to *avoid phone calls* - at all costs. Working from home, I suddenly found myself in the daily agony of virtual calls with strangers with varying English accents, having to interpret complex academic language on a sometimes very choppy internet connection. I expected the PhD to be hard – but not to involve daily exposure therapy!

Fortunately, I had people in my life who remedied most of the effects of the pandemic. Throughout the past four years, the support from my supervisors, **Marjan** and **Joost**, has been invaluable. Thank you, **Marjan**, for believing in me, listening, and offering advice and reassurance when I could not see the light at the end of the tunnel. Your ability to provide simple solutions to what I assume are complex and intricate problems is astonishing. Your mentoring has meant the world to me, and I would not be here without you.

¹ As popularised on TikTok, *main character syndrome* is a term to describe the tendency among people to view themselves as the lead character in their own life story, usually causing them to think everything that happens revolves around them. On the other hand, *imposter syndrome*, is the feeling that you are not as competent as others perceive you to be, resulting in self-doubt and the fear of being exposed as a *fraud*. A very charming combination, if I can say so myself.

To **Joost**: Your openness and ability to ask the right questions, give detailed feedback, and spark ideas is extraordinary. Blending research perspectives from different disciplines can be challenging, but you do it effortlessly. Watching you and Dimitra work and write in perfect symbiosis in real time on Google Docs was a privilege and, frankly, a mind-blowing experience. I have heard that supervisors can make or break a PhD; in my case, it was surely a success factor. I am forever grateful to have you and Marjan as my supervisory team.

Starting amid a pandemic, I spent two years working from home before I could begin working full-time from the university offices. It was another year before I could find permanent accommodation in Delft. In the meantime, I developed friendships with colleagues online. Thank you, **Paul**, for being my PhD guru and unspoken mentor during the first years. Your support during the pandemic, with the ever-growing collection of hysterical memes and peculiar hobbies, surely made life worthwhile. Thank you, **Nikol**, for our countless chats on Slack, fantastic meeting minutes from meetings I conveniently missed, nihilism, vast knowledge, support, and honesty. If we did not get what we expected out of this PhD, we did get a trip to Australia.

Upon finally arriving in Delft, the online friendships extended to real life. Thank you, **Wilbert**, for being my cultural connoisseur and inspirational role model. I have enjoyed all our travels, dinners, chats, museum, and cinema visits, and yes, even the karaoke. Your worth is more than everyone in the House of Nassau combined. To **Vishal**: Our many late-night WhatsApp talks, relationship therapy sessions, the never-ending supply of cat memes, dinners, and clubbing like we were 18 again all brought me life. Thank you for being a good friend during these years and in the years to come.

To **Linda**, whom I first met as an intern at SWOV: Thank you for all the dinners in Delft and the Hague, for introducing me to Dutch culture, King's Night, and for always being optimistic and a spreader of joy. To my fellow cat lady **Sina**, thank you for bringing me onto interesting projects and for all of our open discussions and late-night conversations about life, academia, and everything else. I am looking forward to visiting you wherever you end up in the world.

Working in an academic, international environment, I have been privileged to meet so many fantastic people worldwide. A huge part of academia is meeting people you like and then waving them off somewhere else weeks or – if lucky – months later. Thanks to social facilitator and badminton idol **Nagarjun** and my other office mates, **Yongqi, Samkie, Sina, Vincent, Paul, Solmaz, Ivan, Omid, Chen, Willem-Jan**, and **Laxman**, for making daily life at the university a pleasant experience. The Transport & Planning department and Traffic and Transportation Safety Lab are no exceptions; in particular, **Mahsa, Eilif, Konstantinos, Johan, Narayana, Yiyun, Xiaolin, Riccardo, Mariana, Weiming, Bing, Irene, Saman, Saeed, Monique, Nirvana, Kayhan, Nejc, Lucia, Edwin** and all the others I may have forgotten to name. Thank you, **Yan**, for your work developing the cycling simulator and for being my liaison with the XR Zone at the TU Delft library, where I am also grateful for the help of **Arno, Luuk**, and **Yoshua**. Also, at TU Delft, **Serge** and **Riender** served as my go-or-no-go committee and gave me feedback and motivation to continue my journey from doctoral student to PhD candidate.

A special thanks to **Haneen** for stepping in as my temporary supervisor between years one and two and for bringing me onto the GAZETOAV project. I have valued our many conversations, insights, and help throughout these four years. Your empathy and wisdom are aspirational. I have also enjoyed working with **Dimitra** on the GAZETOAV project, whose intellect, warmth,

and humour are a source of inspiration. While our collaboration was brief, your influence will stay with me, and I am grateful for your help.

To the SHAPE-IT consortium: Thank you, **Jonas** and **Jacqueline**, for outstandingly facilitating, planning, and organising this European project. Thank you to all of the SHAPE-IT professors and our pet supervisors, **John Lee** and **Linda Boyle**. To my fellow early-stage researchers: **Wilbert, Chen, Nikol, Xiaolin, Yuancheng, Xiaomi, Naomi, Chi, Ali, Yue, Amir, Amna**, and meme champion **Sarang**. Although our meetings during the first years were virtual, I had a blast with you once we finally met in person. From October Fest and Swedish Midsummer to that wonky hotel in Delft and hiking in Malham, we have experienced so many things together. I am excited to see where our future careers will take us.

This PhD would not have been possible without the support from the Institute of Transport Economics: Norwegian Centre of Transport Research (TØI). In particular, thank you, **Trine, Bjerne**, and **Anne-Lise**, for making this adventure financially feasible and for your support during these years. To my department and research groups at TØI: Thank you for welcoming me back and keeping me in the loop during the many summer and seasonal festivities. A special thanks to the researchers who contributed to my interviews: Ironically, I cannot name you for research ethics purposes, but you know who you are.

I did not anticipate this preface to become a small novel, but there are still a few people to offer my gratitude for facilitating this dissertation. At the Institute for Road Safety Research (SWOV): Thank you to **Diane, Linda, Anne, Mousa, Matin**, and **Marjolein**. I am also grateful for the assistance of **Sarah, Ragnhild, Kirsten, Rins**, and **Willem**.

At the dusk of my PhD journey, I had the opportunity to spend a revitalising month at the Centre for Accident Research and Road Safety (CARRS-Q) of the Queensland University of Technology. Thank you so much, **Narelle** and **Andrea**, for making this happen on such short notice. I would also like to extend my gratitude to everyone I met at CARRS-Q, particularly **Nathalie, Eugenia, Laura, Delvis, Sina**, and **Amy**, for welcoming me with open arms.

Like with any good thank you speech, I am saving the best for last. To my friends and family back in Norway: Thank you for keeping me strong and relatively sane during these years. A heartfelt thank you goes to my partner and snowflake, **Adrian**, who has been a rock throughout this process. Your unwavering support, love, and encouragement have made all the difference. In the case of another global lockdown, I will gladly spend it with you, Ruski, Evi, and Kiara a hundred times over. Thank you for your patience, blame sponge-ness, and for keeping me grounded. I could not have done this without you.

Lastly, my deepest gratitude goes to my parents, **Jorun** and **Odd Martin**, whose belief in me, unconditional love, and support have been the foundation of everything I have accomplished in life. I dedicate this thesis to you.

Sin

March, 2024

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Summary

The rise of cycling in urban areas offers a sustainable alternative to personal car use, addressing both environmental concerns and public health benefits. However, the safety of cyclists faces new challenges with the advent of automated vehicles. The emerging use of automated driving technologies brings potential benefits, such as reduced road accidents and congestion, but also introduces new dynamics into urban traffic with unknown consequences for the safety of vulnerable road users like cyclists. The transition towards automated traffic systems raises concerns about changes in road user interaction, which has traditionally relied on a mix of explicit (eye contact and hand gestures) and implicit (movement patterns and speed) communication. The potential absence of human drivers in automated vehicles necessitates re-evaluating how cyclists communicate when interpreting and predicting vehicle behaviour. Moreover, introducing automated vehicles into the transport system will likely produce novel behaviours and effects on cyclists, all warrant a thorough investigation.

This dissertation focuses on understanding and improving cyclist interaction with automated vehicles by developing and integrating human-machine interfaces (HMIs) – devices or systems that facilitate communication between road users in traffic. Several HMIs exist in traffic today: We have traffic lights regulating traffic flow, buttons to click indicating an intention to cross the street, and vehicles have turn indicators and brake lights. In the context of automated vehicles, an HMI bridges the social gap created by the absence of a human driver. An HMI could indicate the automated vehicle's planned actions and capabilities, whether the vehicle stops or goes, or confirm to vulnerable road users that the automated driving system has detected them.

Much of the existing research on automated vehicles and vulnerable road users focuses on pedestrians, overlooking the characteristics and requirements of cyclists. This dissertation explores automated vehicle interaction and the use of HMIs from a cyclist's perspective, aiming to fill an important research gap in the literature. The overarching objective of enhancing the interaction between cyclists and automated vehicles is explored by combining qualitative and

quantitative methodologies, including semi-structured interviews, literature reviews, triangulation of data, field tests with eye-tracking, and a cycling simulator. Together, the studies of this dissertation shed light on cyclists' communication strategies in traffic, identify common scenarios of cyclist-automated vehicle interactions, propose HMI designs tailored to cyclists' needs, and highlight the importance of consistent, predictable vehicle behaviour. By taking the cyclists' perspective, this body of work contributes to a broader discussion on creating inclusive and equitable urban mobility solutions in the age of automation.

Structured in eight chapters, this dissertation progresses from setting the context of cycling in urban environments and the advent of automated vehicles to exploring specific interaction scenarios, the role of communication, and the design and evaluation of HMI solutions for cyclists. It concludes with a synthesis of findings sectioned into four main topics covering the research questions (*RQs*), offering insights and recommendations for future research, practical implications, and policy development to ensure the safety and inclusion of cyclists in future traffic systems.

Cyclist-automated vehicle interactions

The topic of cyclist-automated vehicle interactions explores how current interactions between cyclists and drivers inform future expectations of automated vehicles and potential changes in the role of implicit and explicit communication (see Figure S.1).

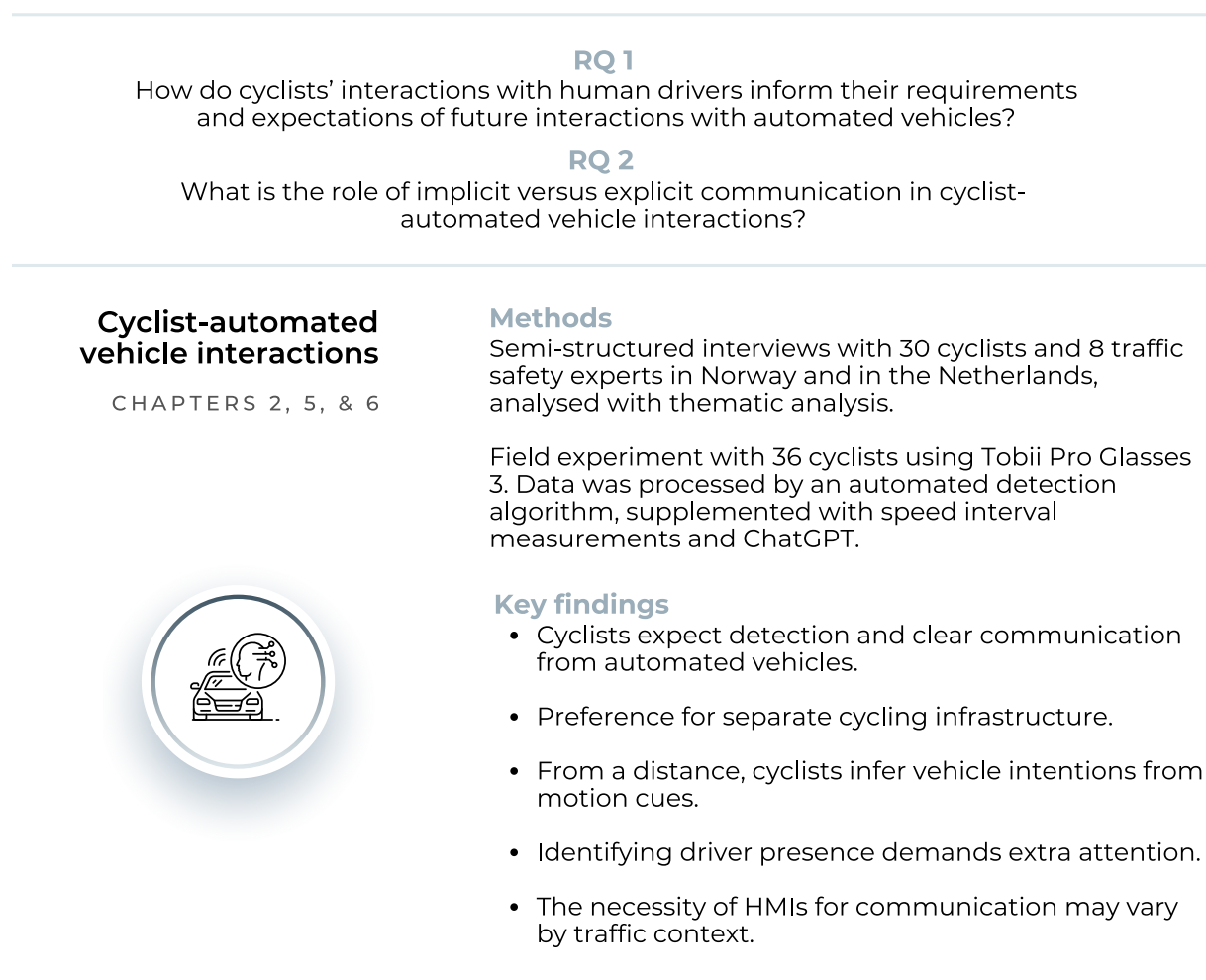


Figure S.1. Overview of the methods and key findings for *RQ1* and *RQ2*.

The overall findings for *RQ1* imply that cyclists expect improved detection and clear communication from automated systems, emphasising the need for sensors and algorithms that identify and accommodate cyclists' behaviour and proactive safety strategies. The interview data from Norway and the Netherlands also highlighted cyclists' preference for separated infrastructure.

Regarding the role of implicit versus explicit communication (*RQ2*), the eye-tracking data from the field experiment we performed combined with interview data indicate that cyclists rely more on implicit cues, such as placement on the road and speed, to interpret vehicle trajectory at a distance. In our study, about 30% of the cyclists noticed the absence of a driver in the experimental vehicle. When prompted to identify whether a human driver was behind the wheel, the cyclist participants could do so with 93% accuracy. However, identifying a driver's absence or presence requires extra attention, as indicated by lower cycling speeds during these trials.

Scenarios and behavioural challenges

The topic of scenarios and behavioural challenges focuses on delineating scenarios and automated vehicle behaviours that influence cyclists' safety and communication in traffic with automated vehicles. Figure S.2 outlines the methods and key findings for *RQ3*.

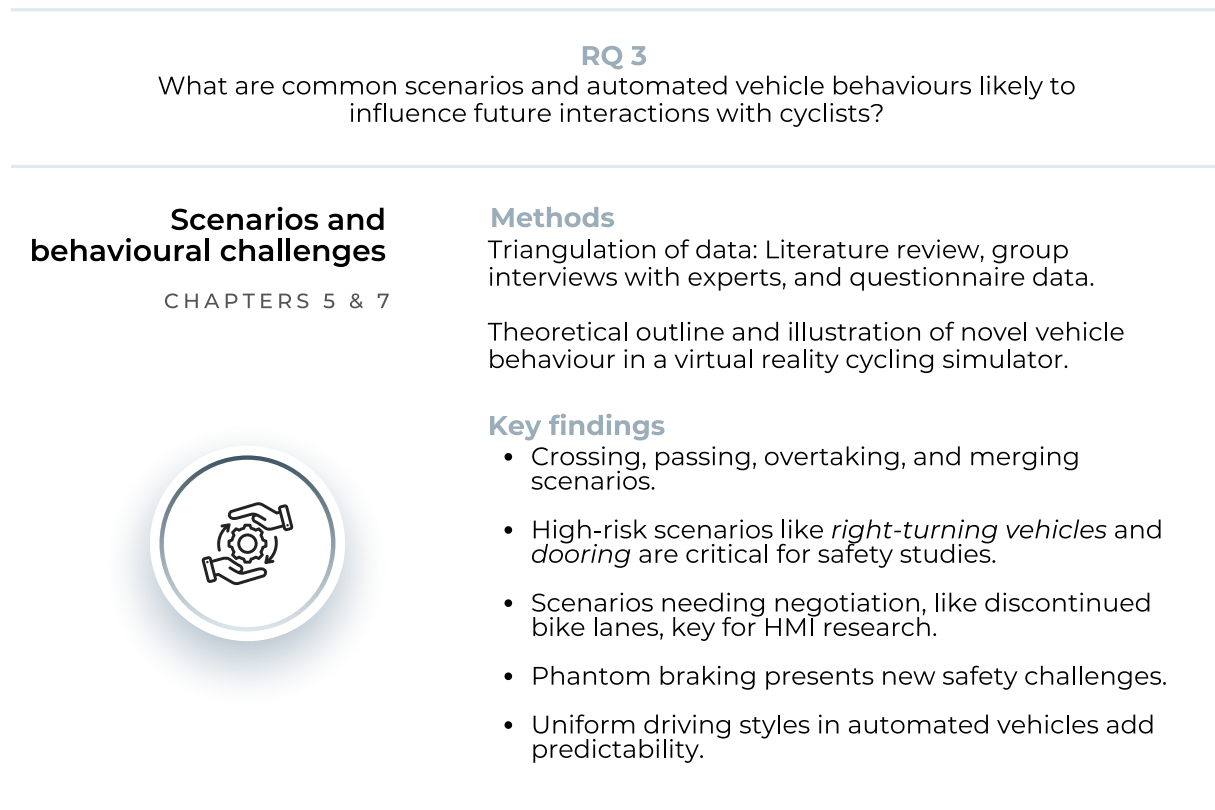


Figure S.2. Overview of the methods and key findings for *RQ3*.

Twenty prototypical scenarios of cyclist-automated vehicle interactions were identified and grouped into crossing, passing, overtaking, and merging scenarios. High-risk scenarios, such as *the right-turning vehicle* and *dooring*, were deemed useful for studies on safety, while scenarios

rich in negotiation and ambiguity, such as the *discontinued bike lane* and passing scenarios, are suitable for HMI research.

Our studies also identified two automated vehicle behaviours relevant to cyclists' safety in future traffic: Phantom braking and driving styles. Phantom braking, defined as unexpected deceleration or stopping in automated vehicles, is anticipated to increase in occurrence with the introduction of automated vehicles. Using *signal detection theory* and *the parallel human and automation alerting system model* to theoretically outline phantom braking, we demonstrated the phenomenon and its potential safety and complacency effects on cyclists in a virtual reality cycling simulator. Phantom braking can be explained as a by-product of an imperfect vehicle sensor system, where the vehicle avoids accidents at the cost of potentially causing rear-end accidents. The occurrence of phantom braking adds a layer of unpredictability to traffic. Similarly, we identified that differences in vehicles' implicit communication cues, mainly related to driving style, will shape cyclists' interactions with automated vehicles in the future. It is recommended that the driving style is uniform across vehicle manufacturers to ensure predictability in traffic, reducing cognitive load and the potential miscommunication in scenarios involving negotiation and ambiguity.

Ethical considerations

The section on ethical considerations addresses the ethical aspects of integrating cyclists into automated traffic environments. *RQ4* explores the moral obligations and practical demands shaping the development of solutions promoting cycling safety. The methods used to address *RQ4* are outlined in S.3.

RQ 4

What ethical and practical considerations should inform design and policy to accommodate cyclists in future automated traffic?

Ethical considerations

CHAPTERS 2, 3, & 8



Methods

Semi-structured interviews with 30 cyclists in Norway and in the Netherlands, analysed with thematic analysis.

A systematic literature review and assessment.

Synthesis of findings.

Key findings

- Prioritise ethical HMI design and policies for active, equitable transport without imposing the burden of safety on cyclists.
- Avoid designing automated systems that rely on personal devices for cyclist detection.
- Support research and policy development for solutions promoting mobility justice.

Figure S.3. Overview of the methods and key findings for *RQ4*.

When developing solutions for improving cyclist-automated vehicle interaction, design and policy must prioritise safety without imposing the burden of safety on vulnerable road users. Considering the ongoing technological advancements and the proliferation of the Internet of Things, connectivity will likely become a standard feature for new devices, including bicycles and cyclist wearables. The efficacy of intelligent transport systems involving connected road users, such as bike-to-everything communication, is contingent on widespread adoption, which may not be realistically achievable in the short term. Our research advocates that automated vehicles must detect cyclists explicitly and communicate detection. However, this communication should be delivered through on-vehicle interfaces, as opposed to requiring devices on the bicycle or wearables for cyclists.

HMI solutions

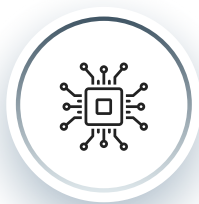
Exploring the interplay of cyclist safety and technology, the section on HMI solutions concerns the design and potential of HMIs to enhance cyclist-automated vehicle interactions. A vital part is developing HMI design strategies tailored to cyclists, accommodating their communication needs and behavioural patterns. Figure S.4 provides an overview of the methods and key findings for *RQ5*.

RQ 5

What key features do cyclists want in HMIs, and how should these HMIs be designed to accommodate the characteristics of cyclists?

HMI solutions

CHAPTERS 2, 3, 4, 5, & 6



Methods

Thematic re-analysis of interview data with 30 cyclists in Norway and in the Netherlands.

Synthesis of the results from semi-structured interviews, literature reviews, and field tests.

Key findings

- The recommended HMI solution is an omnidirectional eHMI visible from all vehicle angles.
- This eHMI should provide cues of detection as well as indicate the vehicle's automated driving mode.
- Messages from an eHMI must be tailored for visibility at varying distances.

S.4. Overview of the methods and key findings for *RQ5*.

Our interview data analysis revealed that cyclists' main concern in interactions with automated vehicles is being adequately detected by these vehicles. Furthermore, the interviewed cyclists preferred automated vehicles to signal their awareness of the cyclist's presence clearly. Other desired HMI features were providing information about the presence and location of other road users, features that facilitate connectivity between road users, and information about automated driving modes.

Combining the findings from ethical considerations with cyclists' movement patterns and gaze behaviour, the results indicate that cyclists would benefit from an HMI that is visible from all around the vehicle. Messages would be delivered on the lower parts of the vehicle at a distance but at the height of the hood and windows at closer proximities.

Future research and policy implications

This dissertation emphasises the need for continued research and policy development focused on cycling safety and communication in the context of increasing vehicle automation. Recommendations for future studies involve exploring realistic and representative cyclist-automated vehicle interaction scenarios and the changes in interaction as automation technology progresses. It is also recommended to design and refine HMIs that are both cyclist-centric and ethically grounded, suggesting that further empirical testing is vital for their development.

In practical terms, our findings advocate for a regulatory framework that ensures automated vehicles reliably detect cyclists, communicate intentions clearly, and mitigate the potential effects of phantom braking. Uniform driving styles across vehicle manufacturers are also recommended. From a cyclist's perspective, it is important that policies prioritise active transport by redesigning infrastructure and encouraging ethical HMI design that accommodates cyclists' needs and prevents the imposition of additional equipment on cyclists for safety.

By aligning research efforts with policy development, we can ensure that automated vehicle technology enhances the safety and rights of cyclists and other vulnerable road users, leading to safer, more inclusive urban traffic environments.

Conclusion

The main contributions of this dissertation include a thorough investigation of cyclists' expectations for future interactions with automated vehicles. It emphasises the need for reliable detection by automated vehicles and the importance of placing the responsibility of safety on vehicle developers rather than on the cyclists themselves. The dissertation provides objective data and self-reported insights into cyclist-automated vehicle interactions, as well as an experimental evaluation of whether cyclists can visually detect the presence or absence of a driver. Moreover, it introduces a collection of 20 scenarios of cyclist-automated vehicle interaction, serving as a resource for safety assessments and HMI research. A comprehensive literature review of existing HMIs for cyclists was conducted, identifying 92 concepts with placements on the vehicle, bicycle, cyclists, and infrastructure. Lastly, the dissertation provides design recommendations for cyclist-centric HMIs, proposing an omnidirectional on-vehicle eHMI communicating detection and automated driving mode.

Samenvatting

Fietsen wordt steeds populairder als vervoermiddel in stedelijke gebieden. Het biedt een duurzaam alternatief voor de privéauto en draagt bij aan zowel het milieu als de volksgezondheid. Fietsers staan echter voor nieuwe veiligheidsuitdagingen met de komst van geautomatiseerde voertuigen. Het opkomende gebruik van technologieën voor automatisch rijden brengt potentiële voordelen met zich mee, zoals minder verkeersongevallen en congestie. De gevolgen van de introductie van deze nieuwe technologieën in een toch al complex en soms chaotisch verkeersbeeld, en wat dit betekent voor fietsers, zijn nog zo goed als onbekend.

De transitie naar geautomatiseerde verkeerssystemen geeft aanleiding tot bezorgdheid over de veranderingen in de interactie tussen weggebruikers die dit met zich meebrengt. Traditionele communicatie tussen verkeersdeelnemers bestaat uit een combinatie van expliciete communicatie (oogcontact en handgebaren) en impliciete communicatie (via bewegingspatronen en snelheid). De potentiële afwezigheid van menselijke bestuurders in geautomatiseerde voertuigen vraagt een herbeoordeling van hoe fietsers communiceren bij het interpreteren en voorspellen van voertuiggedrag. Bovendien zal de introductie van geautomatiseerde technologie in het verkeer waarschijnlijk leiden tot nieuwe gedragingen, die grondig moeten worden onderzocht.

Dit proefschrift richt zich op het begrijpen en verbeteren van de interactie tussen fietsers en geautomatiseerde voertuigen door het ontwikkelen en integreren van mens-machine interfaces (HMIs, gebruikersinterfaces) - apparaten of systemen die de communicatie tussen weggebruikers in het verkeer vergemakkelijken. Vandaag de dag bestaan er verschillende HMIs in het verkeer: We hebben verkeerslichten die de verkeersstroom regelen, knoppen waarop je kunt klikken om aan te geven dat je de straat wilt oversteken en voertuigen hebben richtingaanwijzers en remlichten.

In de context van geautomatiseerde voertuigen vult een HMI de sociale leemte op die ontstaat door de afwezigheid van een menselijke bestuurder. Een HMI kan aangeven wat het

geautomatiseerde voertuig van plan is te doen en of het voertuig stopt of doorrijdt, of kwetsbare verkeersdeelnemers een bevestiging geven dat het automatische rijstelsysteem hen heeft gedetecteerd.

Veel bestaand onderzoek naar geautomatiseerde voertuigen en kwetsbare verkeersdeelnemers richt zich op voetgangers en ziet de unieke kenmerken en behoeften van fietsers in verkeersinteracties over het hoofd. Dit proefschrift verkent de interactie met geautomatiseerde voertuigen en het gebruik van HMIs vanuit het perspectief van de fietser, met als doel een belangrijke leemte in de onderzoeksliteratuur op te vullen. Het algemene doel is de interactie tussen fietsers en geautomatiseerde voertuigen te verbeteren en dit wordt onderzocht door een combinatie van kwalitatieve en kwantitatieve methoden, waaronder semi-gestructureerde interviews, literatuurstudies, data-triangulatie, een veldexperiment met eye-tracking, en met behulp van een fietssimulator.

Samen werpen de studies in dit proefschrift licht op de communicatiestrategieën van fietsers in het verkeer, identificeren ze veelvoorkomende scenario's van interacties tussen fietsers en geautomatiseerde voertuigen, stellen ze HMI-ontwerpen voor die zijn afgestemd op de behoeften van fietsers en benadrukken ze het belang van consistent, voorspelbaar voertuiggedrag. Door het perspectief van de fietser te nemen, draagt dit werk bij aan een bredere discussie over het creëren van inclusieve en rechtvaardige stedelijke mobiliteitsoplossingen in het tijdperk van automatisering.

Het proefschrift bestaat uit acht hoofdstukken die in totaal vijf onderzoeksvragen (*RQs*) beantwoorden. We beginnen met het schetsen van de context van fietsen in stedelijke omgevingen en de opkomst van geautomatiseerde voertuigen. Vervolgens worden studies gepresenteerd die kijken naar de behoeften en specifieke kenmerken van fietsers, evenals de rol van communicatie bij het ontwerpen van gebruiksvriendelijke en verkeersveilige interfaces om de interactie tussen fietsers en geautomatiseerde voertuigen te verbeteren. Ook wordt een aantal specifieke scenario's tussen fietsers en geautomatiseerde voertuigen gepresenteerd, en komt de evaluatie van HMI-oplossingen voor fietsers aan de orde. Het proefschrift sluit af met een discussiehoofdstuk, waarin de bevindingen van de studies in een bredere context worden geplaatst. De resultaten worden gepresenteerd in vier hoofdthema's die inzicht en aanbevelingen bieden voor toekomstig onderzoek, evenals praktische implicaties voor beleidsontwikkeling en regelgeving om de verkeersveiligheid en inclusie van fietsers in toekomstige verkeerssystemen te waarborgen.

Interactie tussen fietsers en geautomatiseerde voertuigen

Het thema “interactie tussen fietsers en geautomatiseerde voertuigen” richt zich op de huidige interactie tussen fietsers en automobilisten en hoe dit de verwachtingen van fietsers ten aanzien van geautomatiseerde voertuigen beïnvloedt, evenals potentiële veranderingen in impliciete en expliciete communicatie bij de introductie van geautomatiseerde voertuigen in het verkeer. Figuur S.1D geeft een overzicht van de methoden en belangrijkste bevindingen voor *RQ1* en *RQ2*.

De algemene bevindingen voor *RQ1* geven aan dat fietsers verbeterde detectie en duidelijke communicatie door geautomatiseerde systemen verwachten, waarbij het belang wordt benadrukt van sensoren en algoritmes die het gedrag en de proactieve veiligheidsstrategieën van fietsers identificeren en daaraan tegemoetkomen. Verder laten interviewgegevens uit

Noorwegen en Nederland een duidelijke voorkeur van fietsers voor gescheiden infrastructuur zien.

RQ 1

Hoe gaan fietsers om met menselijke bestuurders en wat zijn hun verwachtingen van toekomstige interacties met geautomatiseerde voertuigen?

RQ 2

Wat is de rol van impliciete versus expliciete communicatie in interacties tussen fietsers en geautomatiseerde voertuigen?

Interacties tussen fietsers en geautomatiseerde voertuigen

HOOFDSTUKKEN 2, 5, & 6



Methoden

Semigestructureerde interviews met 30 fietsers en 8 verkeersdeskundigen in Nederland, geanalyseerd met thematische analyse.

Veldtests met 36 fietsers met behulp van Tobii Pro Glasses 3, data verwerkt door een geautomatiseerd detectie algoritme, aangevuld met snelheidsmetingen en gebruik van ChatGPT.

Belangrijke bevindingen

- Fietsers verwachten dat ze gedetecteerd worden en duidelijke communicatie van geautomatiseerde voertuigen.
- Voorkeur voor aparte fietsinfrastructuur.
- Van een afstand kunnen fietsers de intenties van voertuigen waarnemen aan de hand van signalen afgeleid uit bewegingspatronen van de voertuigen
- Het identificeren van de aanwezigheid van de bestuurder vraagt extra aandacht.
- De noodzaak van het gebruik van HMIs voor communicatie kan variëren afhankelijk van de verkeerscontext.

Figuur S.1D. Overzicht van methoden en belangrijkste bevindingen voor *RQ1* en *RQ2*.

In onze studie merkte ongeveer 30% van de fietsers het ontbreken van een bestuurder in het experimentele voertuig op. Toen hen werd gevraagd om te identificeren of er een menselijke bestuurder achter het stuur zat, konden de deelnemende fietsers dit met een nauwkeurigheid van 93% doen. Het identificeren van de afwezigheid of aanwezigheid van een bestuurder vereist echter extra aandacht, zoals blijkt uit de lagere fietssnelheden tijdens deze proeven.

Wat de rol van impliciete versus expliciete communicatie betreft (*RQ2*), wijzen de bevindingen van het veldexperiment erop dat fietsers vooral vertrouwen op impliciete communicatie, zoals de plaats van het voertuig op de weg en de gereden snelheid, om de toekomstige koers van het voertuig te voorspellen wanneer het voertuig zich op enige afstand bevindt. In het onderzoek merkte ongeveer 30% van de fietsers het ontbreken van een bestuurder in het experimentele voertuig op. Wanneer hen echter gevraagd werd te identificeren of een menselijke bestuurder achter het stuur zat, kon 93% van de deelnemers dit nauwkeurig doen. Echter, de fietsers hadden een lage snelheid tijdens dit veldexperiment, wat wijst op de extra aandacht die nodig is om de afwezigheid of aanwezigheid van een bestuurder te identificeren.

Scenario's en gedragssuitdagingen

Het thema “scenario's en gedragssuitdagingen” richt zich op het identificeren van scenario's en gedrag van geautomatiseerde voertuigen die de veiligheid en het vermogen tot communicatie van fietsers in geautomatiseerd verkeer kunnen beïnvloeden. Figuur S.2D vat het thema scenario's en gedragssuitdagingen samen door een overzicht te geven van de methoden en belangrijkste bevindingen voor *RQ3*.

Er zijn 20 prototypische scenario's geïdentificeerd die de interactie tussen fietsers en geautomatiseerde voertuigen beschrijven, gegroepeerd in vier categorieën: interacties met kruisend verkeer, inhalen, passeren, en samenvoegen met ander verkeer. Scenario's met een hoog ongevalsrisico op ongevallen, zoals met voertuigen die rechts afslaan en 'dooring' (fietsers botsen tegen openslaand portier), werden door experts als nuttig beschouwd voor verkeersveiligheidsstudies, terwijl scenario's die veel onderhandeling vereisen en ambigu zijn, zoals onderbroken fietsstroken en passeringsscenario's, vooral geschikt zijn voor onderzoek naar gebruikersinterfaces.

RQ 3

Welke gangbare scenario's en welk geautomatiseerd voertuiggedrag zullen toekomstige interacties met fietsers waarschijnlijk beïnvloeden?

Scenario's en gedragssuitdagingen

HOOFDSTUKKEN 5 & 7



Methoden

Triangulatie van gegevens: Literatuurstudie, groepsinterviews met experts, en vragenlijstgegevens.

Theoretisch overzicht en illustratie van nieuw voertuiggedrag in een 'virtual reality' fietssimulator.

Belangrijke bevindingen

- Scenario's met kruisend verkeer, passeren, inhalen en wanneer fietsers en voertuigen moeten samenvoegen.
- Risicovolle scenario's zoals rechts afslaan van voertuigen en 'dooring' zijn cruciaal voor verkeersveiligheidsstudies.
- Scenario's die onderhandeling vereisen, zoals onderbroken fietspaden, zijn essentieel in HMI-onderzoek.
- 'Phantom braking' zorgt voor nieuwe verkeersveiligheidsuitdagingen.
- Eenvormige rijstijlen in geautomatiseerde voertuigen zorgen voor voorspelbaarheid.

Figuur S.2D. Overzicht van methoden en belangrijkste bevindingen voor *RQ3*.

In de studies werden ook twee gedragingen van geautomatiseerde voertuigen geïdentificeerd die bijzonder relevant zijn voor de veiligheid van fietsers in het verkeer van de toekomst: 'fantomremmen' (phantom braking) en rijstijl. Fantoomremmen, gedefinieerd als het onverwacht en abrupt vertragen of stoppen van voertuigen uitgerust met nieuwe rijtechnologie, zal naar verwachting vaker voorkomen met de introductie van geautomatiseerde voertuigen. Door gebruik te maken van *signaaldetectietheorie* en het '*parallel human and automation alerting system model*' om fantoomremmen theoretisch te onderbouwen, hebben we in een

fietssimulator dit fenomeen, de gedragseffecten ervan op fietsers en de mogelijke implicaties voor de verkeersveiligheid gedemonstreerd. Fantoomremmen kan begrepen worden als een bijproduct van een onvolmaakt sensorsysteem van het voertuig, waarbij het voertuig ongevallen vermijdt ten koste van het mogelijk veroorzaken van kop-staartbotsingen. Fantoomremmen voegt een extra laag onvoorspelbaarheid toe aan het verkeer. Ook hebben we vastgesteld dat verschillen in impliciete communicatiesignalen van voertuigen, voornamelijk gerelateerd aan rijstijl (zoals snelheids- en remgedrag van het voertuig), invloed zullen hebben op de interacties van fietsers met geautomatiseerde voertuigen.

Een uniforme rijstijl van voertuigen van verschillende merken wordt aanbevolen om een grotere voorspelbaarheid in het verkeer te bewerkstelligen, de mentale belasting bij menselijke verkeersdeelnemers te verminderen, en om mogelijke misverstanden te minimaliseren. Dit laatste gaat dan om scenario's met ambigue situaties en situaties die onderhandeling vragen.

Ethiek overwegingen

Het thema 'ethische overwegingen' behandelt de ethische aspecten van het integreren van geautomatiseerde voertuigen in verkeersomgevingen met fietsers. *RQ4* streeft naar het bevorderen van discussie en reflectie over morele verplichtingen en praktische implicaties voor beleid dat de ontwikkeling van mobiliteitsoplossingen voor het bevorderen van fietsveiligheid vormt. De methoden die gebruikt worden om *RQ4* te beantwoorden zijn geschetst in S.3D.

Bij het ontwikkelen van oplossingen om de interactie tussen fietsers en geautomatiseerde voertuigen te verbeteren, zouden ontwerprichtlijnen en beleid de prioriteit moeten geven aan verkeersveiligheid zonder de verantwoordelijkheid voor verkeersveiligheid bij kwetsbare verkeersdeelnemers te leggen. Gezien de voortdurende technologische ontwikkeling en de groei van het Internet of Things, zal connectiviteit waarschijnlijk een standaardfunctie worden voor nieuwe apparatuur, waaronder ook fietsen en fietstoebehoren (zoals 'wearables'). Het succes van slimme transportsystemen, waarbij verkeersdeelnemers onderling verbonden zijn en fietsen bijvoorbeeld locatiegegevens kunnen delen met andere apparaten, hangt af van hoe wijdverspreid deze technologieën worden gebruikt; dit is wellicht niet erg realistisch op de korte termijn. Het onderzoek wijst eerder op oplossingsrichtingen waarbij sensoren van geautomatiseerde voertuigen zelfstandig fietsers moeten kunnen detecteren en dit duidelijk moeten communiceren. Deze communicatie moet dan worden geleverd via interfaces in voertuigen, in plaats van te vereisen dat fietsen en fietsers worden uitgerust met extra technologie en apparatuur.

RQ 4

Welke ethische en praktische overwegingen zijn van belang voor beleid en wegontwerp vanuit het oogpunt van fietsers in toekomstig geautomatiseerd verkeer?

Ethische overwegingen

HOOFDSTUKKEN 2, 3, & 8



Methoden

Semi-gestructureerde interviews met 30 fietsers in Noorwegen en in Nederland, geanalyseerd met thematische analyse.

Een systematische literatuurstudie en beoordeling.

Synthese van bevindingen.

Belangrijkste bevindingen

- Geef prioriteit aan ethisch HMI-ontwerp en rechtvaardig mobiliteitsbeleid voor actieve vervoerswijzen zonder de verantwoordelijkheid voor verkeersveiligheid bij fietsers te leggen.
- Vermijd het ontwerpen van geautomatiseerde systemen voor het detecteren van fietsers die vereisen dat fietsen en fietsers worden uitgerust met extra technologie en apparatuur.
- Ondersteun onderzoek en beleidsontwikkeling voor oplossingen die rechtvaardige mobiliteit bevorderen.

Figuur S.3D. Overzicht van methoden en belangrijkste bevindingen voor RQ4.

Gebruikersinterfaces voor fietsers

Binnen dit thema wordt het raakvlak tussen fietsers en technologie onderzocht en dit onderzoek richt zich op het ontwerp en potentieel van mens-machine-interfaces om de interactie tussen fietsers en geautomatiseerde voertuigen te verbeteren. Een belangrijk onderdeel van dit thema is het ontwikkelen van ontwerpstrategieën voor gebruikersinterfaces speciaal voor fietsers, en die voldoen aan hun communicatiebehoeften en gedragspatronen (RQ5).

De analyse van interviewgegevens liet zien dat de belangrijkste zorg van fietsers bij interactie met geautomatiseerde voertuigen is of ze voldoende gedetecteerd zullen worden door deze voertuigen. Uit de interviews bleek ook de wens dat geautomatiseerde voertuigen duidelijk kenbaar maken dat ze de aanwezigheid van de fietser hebben opgemerkt. Andere gewenste functies voor gebruikersinterfaces voor fietsers zijn het ontvangen van informatie over de aanwezigheid en locatie van andere weggebruikers, informatie over of de geautomatiseerde rijmodus dan aan staat, en functies die de connectiviteit tussen verkeersdeelnemers mogelijk maken.

Wanneer ethische overwegingen worden gecombineerd met hetgeen we hebben gevonden over bewegingspatronen en kijkgedrag van fietsers, wijzen de resultaten erop dat fietsers baat zouden hebben bij een gebruikersinterface op het voertuig die van alle kanten zichtbaar is. De plaatsing van zo'n externe interface (eHMI) varieert afhankelijk van of die op afstand of van dichtbij met de fietser moet communiceren. Op afstand zou de interface aan de onderkant van het voertuig

moeten worden geplaatst, terwijl berichten die van dichtbij worden overgebracht ter hoogte van de motorkap en onder de ruiten zouden moeten worden geplaatst.

Figuur S.4D vat de belangrijkste bevindingen en methoden samen die gebruikt zijn om *RQ5* te beantwoorden.



Figuur S.4D. Overzicht van methoden en belangrijkste bevindingen voor *RQ5*.

Toekomstig onderzoek en beleidsimplicaties

Dit proefschrift onderstreept het belang van aandacht voor fietsveiligheid in toekomstig onderzoek naar en beleidsontwikkeling voor geautomatiseerde voertuigen. Er wordt aanbevolen dat toekomstige studies realistische en representatieve scenario's van interacties tussen fietsers en geautomatiseerde voertuigen verkennen en onderzoeken, alsmede de veranderingen die zullen optreden naarmate de technologie zich verder ontwikkelt. Andere aanbevelingen zijn het verder ontwikkelen en verfijnen van HMI-ontwerpen en het testen van ethisch verantwoorde HMIs die voldoen aan de behoeften en gedragspatronen van fietsers.

In meer praktische termen pleiten onze bevindingen voor de ontwikkeling van een regelgevingskader dat ervoor zorgt dat geautomatiseerde voertuigen fietsers betrouwbaar detecteren, duidelijk hun gedragsintenties communiceren en de kans op fantoomremmen beperkt. Verder wordt een uniforme rijstijl van verschillende automerken aanbevolen met de bedoeling dat het voertuiggedrag beter voorspelbaar wordt. Vanuit het perspectief van de fietser is het belangrijk dat beleid prioriteit geeft aan actieve vervoerswijzen door onder meer herontwerp van de infrastructuur, en aan te moedigen dat HMI-designs tegemoetkomen aan de behoeften van fietsers en voorkomen dat fietsers omwille van de verkeersveiligheid extra uitrusting moeten hebben.

Door onderzoeksinspanningen en beleidsontwikkeling op elkaar af te stemmen, kunnen we ervoor zorgen dat geautomatiseerde voertuigtechnologie de verkeersveiligheid van fietsers en andere kwetsbare verkeersdeelnemers verbetert. Dit zal leiden tot veiligere en meer inclusieve verkeersomgevingen.

Conclusie

Dit proefschrift beschrijft onderzoek naar de verwachtingen van fietsers over toekomstige interacties met geautomatiseerde voertuigen. Het benadrukt de noodzaak van betrouwbare detectie van fietsers door geautomatiseerde voertuigen en het belang van het leggen van de verantwoordelijkheid voor veiligheid bij de voertuigontwerpers in plaats van bij de fietsers zelf. Er is gebruik gemaakt van zowel meer objectieve, gemeten, gedragingen als ook zelf-gerapporteerde gegevens, die tezamen inzicht geven in de interactie tussen fietsers en geautomatiseerde voertuigen. Ook beschrijft het proefschrift de resultaten van een experiment naar het vermogen van fietsers om de aan- of afwezigheid van een bestuurder visueel waar te nemen. Daarnaast wordt een verzameling van 20 scenario's gepresenteerd met interacties tussen fietsers en geautomatiseerde voertuigen. Deze scenario's kunnen dienen als uitgangspunt voor verder onderzoek naar verkeersveiligheid en HMIs voor fietsers. Verder is een uitgebreide literatuurstudie uitgevoerd naar bestaande gebruikersinterfaces voor fietsers, waarbij 92 concepten werden geïdentificeerd die op het geautomatiseerde voertuig, de fiets, de fietsers dan wel de infrastructuur worden aangebracht. Het proefschrift geeft voorbeelden van ontwerprichtlijnen en aanbevelingen voor gebruikersinterfaces voor fietsers, en er wordt voorgesteld dat een dergelijke interface op het geautomatiseerde voertuig wordt geplaatst en vanuit alle hoeken zichtbaar is. Tenslotte wordt aanbevolen dat de interface aangeeft dat de fietser is gedetecteerd door het voertuig en wanneer het voertuig in de geautomatiseerde modus rijdt.

Sammendrag

Sykkelen blir stadig et mer populært fremkomstmiddel i bynære strøk. Sykling tilbyr et bærekraftig alternativ til privatbilen, og kan bidra til å redusere klimautslipp og være positivt for folkehelsa. Imidlertid står syklistene overfor nye trafikksikkerhetsutfordringer ettersom bruken av automatisert kjøretøyteknologi vil kunne endre samspillet i trafikken. Med inntoget av automatiserte kjøretøy kommer lovnader om en rekke fordeler. Blant annet skal teknologien føre til færre ulykker og mindre trafikkork. Det vi derimot vet lite om, er konsekvensene av å introdusere ny, automatisert teknologi i et ellers komplekst og tidvis kaotisk trafikkbilde, og hvilke konsekvenser dette vil ha for syklistene.

Overgangen til automatiserte trafikksystemer kan føre til endringer i måten vi samhandler på i trafikken. Hovedsakelig består samhandling mellom trafikanter av to typer kommunikasjon: eksplisitt, ved bruk øyekontakt og av tegn, og implisitt, gjennom bevegelsesmønstre og fart. Fraværet av en fører i automatiserte kjøretøy vil medføre en endring i hvordan myke trafikanter kommuniserer, tolker og predikerer atferden til disse bilene. I tillegg vil økt bruk av automatisert teknologi i trafikken bidra til at det oppstår ny og uventet atferd, som igjen har ukjente konsekvenser for trafikksikkerheten for andre trafikanter.

Fokuset i denne avhandlingen er å øke forståelsen av og foreslå løsninger som forbedrer samhandlingen mellom syklistene og automatiserte kjøretøy gjennom menneske-maskin-grensesnitt – systemer og teknologi som bidrar til at veibrukere kan kommunisere bedre i trafikken.

Det finnes utallige typer grensesnitt i bruk i trafikken allerede: Vi har trafikklys som regulerer trafikkflyt, knapper å trykke på for å indikere at vi vil krysse veien, og kjøretøy har blinklys og bremselys som kommuniserer hvorvidt bilen har tenkt å svinge eller å redusere farten. Alle disse brukergrensesnittene bidrar til at mennesker kan kommunisere med teknologi og automatiserte systemer. I sammenheng med automatiserte kjøretøy er tanken at et grensesnitt skal fylle det sosiale tomrommet som oppstår ved fraværet av en menneskelig sjåfør. Et

grensesnitt kan fungere som en indikator av automatiserte kjøretøys fremtidige atferd eller egenskaper, slik som om bilen har tenkt å fortsette å kjøre, alternativt gi tilbakemelding om at bilen har sett syklisten og har tenkt å stoppe.

Tidligere forskning på temaet automatiserte kjøretøy og myke trafikanter handler stort sett om fotgjengere, og har en tendens til å utelate det faktum at syklist har andre egenskaper og behov enn fotgjengere når det gjelder samhandling i trafikken. Arbeidet i denne avhandlingen tar for seg syklisters syn på samhandling med automatiserte kjøretøy og bruk av grensesnitt, og bidrar dermed til å tette kunnskapshull i litteraturen. Det overordnede målet er å skape gode løsninger som letter samhandlingen mellom syklist og automatiserte kjøretøy, og øke trafikksikkerheten for syklist i en fremtid med stadig mer bruk av teknologi.

Studiene i denne avhandlingen benytter seg av både kvalitative og kvantitative metoder gjennom semistrukturerte intervjuer, litteraturgjennomganger, triangulering av data, felteksperiment, og bruk av sykkelsimulator. Målet er å få innsikt i kommunikasjonsstrategiene syklist bruker i trafikken, identifisere scenariobeskrivelser av samhandlingen mellom syklist og automatiserte kjøretøy, foreslå design av brukergrensesnitt skreddersydd for syklisters behov, og gi bedre forståelse av viktigheten av konsekvent og forutsigbar kjøretøyatferd for økt trafikksikkerhet. Ved å sette søkelys på samhandling fra syklisters perspektiv bidrar arbeidet i denne avhandlingen til å starte en bredere diskusjon om inkluderende og rettferdige mobilitetsløsninger i fremtidens trafikkbilde.

Avhandlingen er strukturert i åtte kapitler som besvarer til sammen fem forskningsspørsmål (*RQs*). Vi starter med å sette sykling på agendaen, før vi går over til betydningen av fremveksten av automatiserte kjøretøy. Deretter følger studier som tar for seg syklisters behov og spesifikke karakteristika samt rollen av kommunikasjon når vi skal designe brukervennlige og trafikksikre grensesnitt for å forbedre samhandlingen mellom syklist og automatiserte kjøretøy. Spesifikke scenarioer mellom syklist og automatiserte kjøretøy blir også presentert, i tillegg til endringer i kjøreatferd ved økende grad av automatisering. Avhandlingen avsluttes med et diskusjonskapittel, hvor funnene fra studiene blir satt i en større sammenheng. Funnene blir presentert i fire hovedtemaer som evner å gi innsikt og anbefalinger for fremtidig forskning, i tillegg til praktiske implikasjoner for utvikling og regulering.

Samhandling mellom syklist og automatiserte kjøretøy

Temaet samhandling mellom syklist og automatiserte kjøretøy tar for seg samspillet mellom syklist og bilister i dag og hvordan dette påvirker forventningene syklist har til automatiserte kjøretøy, samt potensielle endringer i implisitt og eksplisitt kommunikasjon ved innføring av automatiserte kjøretøy. Figur S.1N viser en oversikt over metodene og hovedfunn for *RQ1* og *RQ2*.

De overordnede funnene for *RQ1* antyder at syklist forventer bedre synlighet ved automatiserte kjøretøy. De forventer også at bilene kommuniserer tydelig, noe som til sammen understreker behovet for sensorer og algoritmer som identifiserer og imøtekommer syklisters atferd og sikkerhetsstrategier. Intervjudataene fra Norge og Nederland fremhevet også en preferanse for adskilt infrastruktur.

Når det gjelder viktigheten av implisitt kontra eksplisitt kommunikasjon (*RQ2*), indikerer dataene fra felteksperimentet at syklist legger mer vekt på implisitt kommunikasjon, som bilens plassering i veien og hastighet, for å tolke kjøretøys fremtidige kurs når bilen er på

avstand. I studien la ca. 30% av syklistene merke til fraværet av en sjåfør i det eksperimentelle kjøretøyet. Når de derimot ble bedt om å identifisere om en menneskelig sjåfør satt bak rattet, klarte deltakerne dette med 93% nøyaktighet. Imidlertid hadde syklistene lavere hastighet under disse forsøkene, noe som peker mot at identifisering av en sjåførs fravær eller tilstedeværelse krever ekstra oppmerksomhet.

RQ 1

Hvordan påvirker syklisters samhandling med sjåfører deres forventninger til fremtidig samhandling med automatiserte kjøretøy?

RQ 2

I hvilken grad påvirker implisitt kontra eksplisitt kommunikasjon samspillet mellom syklister og automatiserte kjøretøy?

Samspillet mellom syklister og automatiserte kjøretøy

KAPITTEL 2, 5 & 6



Metode

Semi-strukturerte intervjuer med 30 syklister og 8 trafikksikkerhetsekspertene i Norge og Nederland, analysert med tematisk analyse.

Feltekspériment med 36 syklister ikledd Tobii Pro Glasses 3. I analysen ble det benyttet en automatisk gjenkjenningssalgoritme, målinger av fartsintervaller og ChatGPT.

Hovedfunn

- Syklister forventer å bli sett og at automatiserte kjøretøy kommuniserer tydelig.
- Separat sykkelinfrastruktur foretrekkes.
- På avstand tolker syklister bilens intensjon via implisitt kommunikasjon.
- Å identifisere om det er en sjåfør i bilen krever ekstra oppmerksomhet.
- Behovet for brukergrensesnitt for å supplere kommunikasjon varierer ut ifra situasjon.

Figur S.1N. Oversikt over metoder og hovedfunn for RQ1 og RQ2.

Scenarier og atferdsmessige utfordringer

Temaet scenarier og atferdsmessige utfordringer fokuserte på å identifisere scenarier og automatisert kjøretøyatferd som kan påvirke syklisters sikkerhet og evne til kommunikasjon i automatisert trafikk.

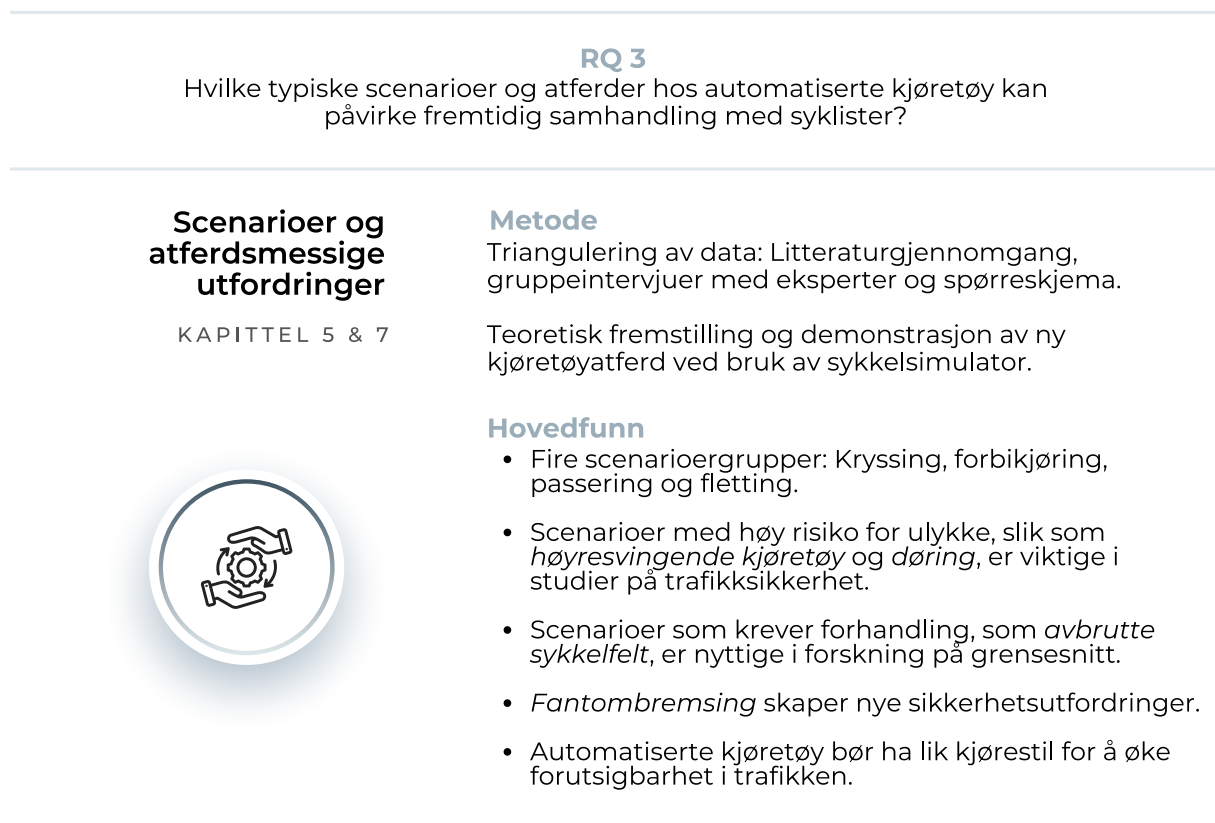
Det ble identifisert 20 scenarier som beskriver samspillet mellom syklister og automatiserte kjøretøy, gruppert i fire: Kryssing, forbikjøring, passering, og fletting. Scenarier med høy risiko for ulykke, slik som *høyresvingende kjøretøy* og *døring*, ble ansett som nyttige i studier av trafikksikkerhet, mens scenarier som innebærer mye forhandling og tvetydighet, slik som *avbrutte sykkelfelt* og passeringsscenarier, er egnet for forskning på brukergrensesnitt.

I studiene ble det også avdekket to automatiserte kjøretøyatferder som er særlig relevante for syklisters sikkerhet i fremtidig trafikk: Fantombremsing og kjørestil. Forekomsten av

fantombremsing, definert som automatiserte kjøretøys uventede bremsing eller stopp, forventes å øke med større grad av automatiserte kjøretøy på veien. Ved hjelp av *signal detection theory* og *the parallel human and automation altering system model* for teoretisk å skissere fantombremsing, ble fenomenet og dets potensielle implikasjoner for trafikk sikkerhet og atferdsendringer hos syklister demonstrert i en sykkelsimulator. Fantombremsing kan forklares som et biprodukt av et ufullkomment kjøretøysensorsystem, der kjøretøyet unngår ulykker på bekostning av potensielt å forårsake påkjørsler bakfra. Forekomsten av fantombremsing bidrar til å skape uforutsigbarhet i trafikken.

En annen atferdsmessig utfordring ved automatiserte kjøretøy er bilens implisitte kommunikasjonsstrategier, altså bilens kjørestil. Forskjellige kjørestiler blant automatiserte kjøretøy vil forme samhandlingen med syklister. Det anbefales at kjørestilen er ensartet på tvers av bilprodusenter for å sikre forutsigbarhet i trafikken, redusere mental belastning hos menneskelige trafikanter, og minske potensialet for misforståelser i scenarier som innebærer forhandling og tvetydighet.

Figur S.2N oppsummerer temaet scenarier og atferdsmessige utfordringer ved å gi en oversikt over metodene og hovedfunnene for RQ3.



Figur S.2N. Oversikt over metoder og hovedfunn for RQ3.

Etiske hensyn

Temaet etiske hensyn tar for seg de etiske aspektene ved å integrere automatiserte kjøretøy i trafikkmiljø med syklister. RQ4 tar sikte på å skape diskusjon og refleksjon rundt moralske forpliktelser og praktiske implikasjoner for policy som former utviklingen av

mobilitetsløsninger for å fremme sykkelsikkerhet. Metodene som brukes for å besvare *RQ4* er skissert i S.3N.

RQ 4

Hvilke etiske og praktiske hensyn bør tas ved tilrettelegging og regulering av sykling i en fremtid med automatiserte kjøretøy?

Etiske hensyn

KAPITTEL 2, 3 & 8



Metode

Semi-strukturerte intervjuer med 30 syklister i Norge og Nederland, analysert med tematisk analyse.

Systematisk litteraturgjennomgang.

Sammenfatning av resultater.

Hovedfunn

- Myndigheter burde prioritere og tilrettelegge for aktiv transport uten å plassere ansvaret for sikkerhet på syklister.
- Unngå automatiserte systemer som er avhengig av personlige enheter og grensesnitt for trygg samhandling.
- Behov for støtte til forskning og utvikling av løsninger som fremmer rettferdig mobilitet for alle trafikanter.

Figur S.3N. Oversikt over metoder og hovedfunn for *RQ4*.

Når løsninger for å forbedre samspillet mellom syklister og automatiserte kjøretøy utvikles, bør retningslinjer for design og policy innebære prioritering av trafikksikkerhet uten å pålegge ansvaret for sikkerhet på myke trafikanter. Den teknologiske samfunnsutviklingen innebærer økende omfang av tingenes internett, det vil si at tilkoblingsmuligheter til internett begynner å bli en standardfunksjon på nytt utstyr, inkludert sykler og tilbehør for syklister. Optimale intelligente transportsystemer som forutsetter tilkoblede trafikanter, for eksempel sykler som kan utveksle lokasjonsdata med andre enheter, er avhengig av bred adopsjon av denne type teknologi. Disse løsningene er ikke realistiske med det første. Forskningen peker heller mot løsninger hvor automatiserte kjøretøysensorer bør kunne oppdage syklister på egenhånd og eksplisitt kommunisere dette. Denne kommunikasjonen bør leveres gjennom kjøretøysbaserte grensesnitt, i stedet for å kreve at sykler og syklister utstyres med ekstra teknologi og enheter.

Brukergrensesnitt for syklister

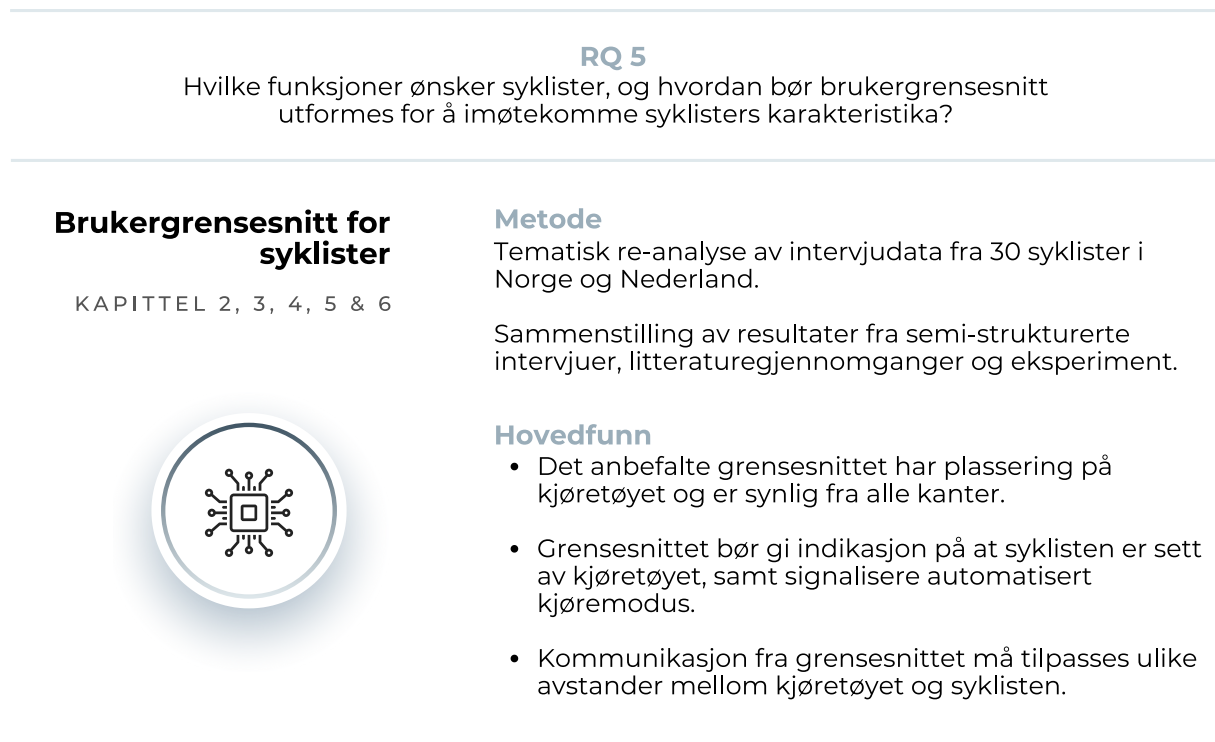
Innen dette temaet utforskes skjæringspunktet mellom syklister og teknologi ved å sette søkelys på design og potensialet ved menneske-maskin-grensesnitt for å forbedre samhandlingen mellom syklister og automatiserte kjøretøy. En viktig del av dette temaet er å utvikle designstrategier for brukergrensesnitt skreddersydd for syklister, design som imøtekommer deres kommunikasjonsbehov og atferdsmønstre (*RQ5*).

Analysen av intervjudata avdekket at syklisters hovedbekymring ved samhandling med automatiserte kjøretøy er å bli tilstrekkelig sett av disse kjøretøyene. I intervjuene kommer det også frem ønske om at automatiserte kjøretøy skal signalisere tydelig at de har oppdaget

syklistens tilstedeværelse. Andre ønskede funksjoner ved brukergrensesnitt for syklist er å motta informasjon om tilstedeværelse av andre veibrukere og hvor de befinner seg, informasjon om automatisert kjøremodus, og funksjoner som innebærer internettilkobling.

Når funn fra etiske hensyn kombineres med syklisters bevegelsesmønstre og blikkatferd, indikerer resultatene at syklist vil dra nytte av et grensesnitt plassert på utsiden av kjøretøyet, som har synlighet fra alle sider. Plassering av grensesnittet varierer ut ifra om det skal kommunisere på avstand eller i direkte nærhet til syklisten. På avstand burde grensesnittet være plassert på nedre del av bilen, mens meldinger som skal leveres når syklisten er på nærmere hold bør plasseres på høyde med panseret og i under vinduene.

Figur S.4N oppsummerer hovedfunn og metoder benyttet for å besvare *RQ5*.



Figur S.4N. Oversikt over metoder og hovedfunn for *RQ5*.

Fremtidig forskning og implikasjoner for policy

I denne avhandlingen understrekes behovet for fokus på sykkelsikkerhet og kommunikasjon innen fremtidig forskning på og policyutvikling for automatiserte kjøretøy. Det anbefales at fremtidige studier ser på realistiske og representative scenarioer av samspillet mellom syklist og automatiserte kjøretøy, og de endringene som vil oppstå ettersom teknologien utvikler seg. En annen anbefaling er fortsette utviklingen med å designe og teste etiske begrunnede brukergrensesnitt som ivaretar syklisters behov og atferdsmønstre.

I mer praktiske termer taler funnene for utviklingen av regulering av rammeverk som sikrer at automatisert kjøretøyteknologi alltid oppdager syklist, tydelig kommuniserer fremtidig atferd, og som reduserer forekomst av fantombremsing. Ensartet kjørestil på tvers av bilprodusenter anbefales også. Fra en syklists perspektiv bør det innføres en mer rettferdig fordeling av infrastruktur. Det anbefales økt søkelys på å utvikle retningslinjer for design og

policy som fremmer aktiv transport, og som ikke innebærer et behov for personlige enheter for å trygge myke trafikanter. Fremtidig forskning og myndigheter bør også fortsette arbeidet med å evaluere løsninger og sikkerhetstiltak som fremmer mobilitetsrettferdighet for alle trafikanter.

Ved å samordne forskningsinnsats og policyutvikling, kan vi sørge for at automatisert kjøretøyteknologi forbedrer sikkerheten og rettighetene til syklistene og andre myke trafikanter, noe som vil føre til tryggere og mer inkluderende trafikkmiljø.

Konklusjon

Oppsummert involverer hovedbidragene fra denne avhandlingen en gjennomgang av syklisters forventninger til fremtidig samhandling med automatiserte kjøretøy, understreket av syklisters behov for å bli sett av kjøretøyene og at ansvaret for sikkerhet ligger hos utviklere av automatiserte kjøretøy snarere enn hos syklistene selv. I avhandlingen presenteres både objektiv og selv-rapportert data som gir innsikt i samhandlingen mellom syklistene og automatiserte kjøretøy, samt en eksperimentell evaluering av hvorvidt syklistene visuelt kan oppdage tilstedeværelsen eller fraværet av en sjåfør. I tillegg introduseres en samling av 20 scenarioer av samhandling mellom syklistene og automatiserte kjøretøy, som fungerer som en ressurs for forskning på trafikksikkerhet og grensesnitt for syklistene. Det ble gjennomført en omfattende litteraturgjennomgang av eksisterende brukergrensesnitt for syklistene. I denne ble det identifisert 92 konsepter med plasseringer på kjøretøyet, sykkelen, syklistene og infrastruktur. Til slutt presenteres designretningslinjer og anbefalinger for brukergrensesnitt for syklistene, hvor det forslås at grensesnittet plasseres på kjøretøyet med synlighet fra alle vinkler. Grensesnittet bør gi indikasjon på at syklisten er sett av kjøretøyet, samt signalisere automatisert kjøremodus.

Chapter 1

Cycling in the age of automation

1.1 The rise of cycling in urban environments

Active transport, such as cycling, presents a partial but compelling solution to several pressing societal concerns. With the transport sector responsible for one-quarter of global CO₂ emissions (International Energy Agency, 2023), cycling may help reduce emissions (Mason et al., 2015). As the public is becoming increasingly sedentary (Park et al., 2020), a rise in cycling shares would benefit public health (Raser et al., 2018). There is political momentum in Europe promoting cycling adoption and infrastructure (European Parliament, 2023), but these goals are yet to be fully realised. Although trends indicate that cycling is rising in urban areas (Epinion Transport & Mobility, 2019; Harms & Kansen, 2018; OECD/ITF, 2013; Pucher & Buehler, 2017), empirical data does not support a substantial increase in cycling shares in Europe (Schepers et al., 2021). Still, cycling represents a sustainable alternative to driving, especially in urban environments where the use of personal cars has become unfeasible due to population growth and traffic congestion in cities (Pishue, 2023).

Cycling safety is paramount in promoting cycling as a viable everyday mode of transport. Safety is not just a statistic; it has real-world implications for the lives lost and altered due to traffic accidents. Cyclists are vulnerable road users with limited physical protection. Most cyclist injuries result from single-bicycle accidents – accidents occurring without other road users involved – but fatal accidents among cyclists are mainly caused by motor vehicle-bicycle impact (Schepers et al., 2015). In line with Vision Zero, a policy that aims at no fatalities or severe injuries in road traffic (Johansson, 2009; Tingvall & Haworth, 1999), increasing cycling

shares necessitates substantial investment in infrastructure and safety measures. Developing a continuous network of cycling infrastructure, separating cyclists from vehicles, is a promising safety measure: Cycling accidents can be reduced by about 45% with a separate lane compared to mixed traffic (Høye et al., 2015). However, constructing an extensive network of cycling infrastructure is a long-term or protracted process. Moreover, separate cycling infrastructure is not always a feasible solution and it is likely that cyclists will continue to share the roads with vehicles. Recently, a new type of motorised road user has emerged into traffic. Automated vehicles are progressively developing and becoming more capable (Parekh et al., 2022). With this newcomer, new challenges arise. How will the interaction between cyclists and vehicles change, and how do we ensure that cyclists are safe in future automated traffic?

1.2 The advent of automated vehicles

As the advent of automated vehicles looms on the horizon, so do the expectations of their societal impact and benefits. Automated vehicles have the potential to dramatically reduce road accidents and fatalities, minimise congestion, and change the way we travel (Fagnant & Kockelman, 2015). Early narratives even depict idyllic scenarios of drivers and passengers reading, working, or sleeping while the car takes on the task of driving (Volvo Cars, 2018). The reality of automated vehicles' integration into urban environments is far more nuanced.

By increasingly automating the task of driving, we are increasingly replacing the human driver with a machine. Today, commercial robotaxis (Public Utilities Commission, 2022; West, 2022) and advanced automated driving systems for personal and professional drivers (Nordhoff et al., 2023) operate on public roads. With these new systems come accounts of potentially hazardous behavioural adaptations among drivers, such as disregarding safety measures, complacency, overreliance, and skill degradation (Nordhoff et al., 2023). No longer opting for safety drivers and instead remote controlling robotaxis, media reports emerge of automated vehicles causing congestion and traffic jams, ignoring traffic regulations, and refusing to comply with police enforcement (Nordhoff, 2023; Pitts, 2023).

Although human factors researchers express scepticism regarding widespread adoption of fully automated vehicles in the decades to come (Tabone, De Winter, et al., 2021), automated vehicles may be engineered to operate completely independently in the future. While we anticipate full automation to be realised, road users have to grapple with a dual challenge. They must navigate interactions with human drivers as well as vehicles equipped with varying degrees of automation, ranging from partially automated driving systems, such as lane assist and adaptive cruise control, to highly automated systems that can operate, for the most part, without human intervention. We are yet to fully understand how the absence of a human driver in our current traffic system's complex interplay of social norms and interpretive cues will impact communication and safety, particularly in interactions between vehicles and vulnerable road users.

1.3 Road user interaction

A range of perspectives have been applied to describe the interaction between human road users, from traffic conflict theory (Svensson, 1998) and sociological theory (Renner & Johansson, 2006) to communication theory (Domeyer et al., 2019) and game theory (Elvik,

2014). Markkula et al. (2020) pragmatically combined these theories and defined road user interaction as a space-sharing conflict:

“A situation where the behaviour of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same region of space at the same time in the near future” (Markkula et al., 2020, p. 737).

A myriad of behaviours facilitate and solve a space-sharing conflict, all containing a form of communication between road users. The mechanism of road user interaction largely revolves around two types of communication: explicit and implicit.

“Explicit communication: A road user behaviour which does not affect own movement or perception, but which can be interpreted as signalling something to or requesting something from another road user” (Markkula et al., 2020, p. 742).

“Implicit communication: A road user behaviour which affects own movement or perception, but which can at the same time be interpreted as signalling something to or requesting something from another road user” (Markkula et al., 2020, p. 741).

Based on the definitions by Markkula et al. (2020), we can say that explicit communication involves social cues such as eye contact, head movements, and hand gestures (Al-Taie et al., 2022; Färber, 2016; Stanciu et al., 2018). In contrast, implicit communication relies on more subtle signals and motion cues, like speed or placement on the road (Berge, Hagenzieker, et al., 2022; Lee et al., 2020).

In academia, two schools of thought debate the necessity of supplementing explicit communication in the context of automated vehicles. Some argue that the importance of social cues in traffic is overrated (Lee et al., 2020; Moore et al., 2019). Studies with pedestrians show that their decision to cross in front of a vehicle depends on implicit cues like relative distance and speed (Pekkanen et al., 2022; Tian et al., 2023). Similar findings apply to cyclists; cyclists use speed (Mohammadi et al., 2023) and gap size (Nuñez Velasco et al., 2021) as implicit indicators of yielding to vehicles. On the other hand, some scholars argue that the interaction void that occurs when there is no longer a human driver to interact with is a major obstacle to automated vehicles' interaction with vulnerable road users (Rasouli & Tsotsos, 2020; Strömberg et al., 2018). This interaction void could be substituted with additional communication tools such as human-machine interfaces (HMIs).

1.4 Human-machine interfaces

In the human factors field, there is an emerging focus on external human-machine interfaces (eHMIs) as means to facilitate explicit communication between automated vehicles and other road users like pedestrians and cyclists (Bazilinsky et al., 2019; Dey, Habibovic, Löcken, et al., 2020; Rouchitsas & Alm, 2019). An *interface* can be defined as a relation between two distinct entities selectively allowing communication of information from one entity to the other (Hookway, 2014). In other words, an interface allows a user to interact with a device, program, or machine.

Several HMIs exist in all sorts of shapes and forms in traffic today. Traffic signals visually regulate traffic flow with red, yellow, and green lights, and we have tactile buttons for pedestrians to push, indicating their intention to cross the road. Moreover, pedestrian crossing light signals are equipped with audio to suggest it is safe to cross, and vehicles have turn indicators and brake lights. In the context of automated vehicles, an HMI bridges the social gap

created by the absence of a human driver. For instance, an interface could relay messages indicating the automated vehicle's planned actions and capabilities, whether the vehicle is stopping or going, or provide confirmation to vulnerable road users that they have been detected by the automated driving system.

According to Dey, Habibovic, Löcken, et al. (2020), current approaches to HMIs in the context of automated vehicles and vulnerable road user interaction can be broadly divided into two categories: (1) technical solutions, which include network and communication systems connecting road users, and (2) solutions oriented towards human factors, which concentrate on the ergonomic and interactive dimensions of the interface between automated vehicles and vulnerable road users. In this dissertation, both solutions and their implications for vulnerable road users are explored, with particular emphasis on cyclists.

1.5 The cyclist perspective

Previous research on automated vehicles and vulnerable road users has centred around pedestrian crossing behaviours (Rasouli & Tsotsos, 2020), acceptance and attitudes towards automation (Merat et al., 2017; Nordhoff et al., 2020), and eHMIs (Bazilinskyy et al., 2019; Dey, Habibovic, Löcken, et al., 2020; Rouchitsas & Alm, 2019). In their review of eHMI solutions for vulnerable road users, Dey, Habibovic, Löcken, et al. (2020) found that 91% of the concepts were geared towards pedestrians. It is important to note that the characteristics of cyclists differ from pedestrians: Cyclists have higher speeds and focus their attention differently in traffic (Trefzger et al., 2018). Compared to pedestrians, cyclists are likelier to share the road with vehicles, leading to close encounters both lengthways, headways, and at crossings (Berge et al., 2024). The research on pedestrians and HMI designs based on pedestrian attributes cannot necessarily be generalised to cyclists. With the implementation of new modes of transport, cycling has historically been oppressed as a result of political agendas, development of infrastructure, social conventions, technological advancements, energy access and international alliances. The emergence of automated vehicle technology is no exception (Gaio & Cugurullo, 2022).

A recurring theme of this dissertation is to shift the focus of research on HMIs in the context of automated vehicles to the cyclist's perspective, investigating cyclists' needs and how they interact with the emerging landscape of automated vehicles. Together, the studies presented in this dissertation explore the practicalities and implications of the proposed solutions for enhancing the interaction between cyclists and automated vehicles without imposing an automated vehicle- or pedestrian-centric perspective. The shift of focus is not just important; it is imperative for ensuring the safety and ongoing inclusion of cyclists in automated traffic while developing a sustainable transport system for the future.

1.6 Problem statement

Cycling safety is a growing issue in Europe (European Commission, 2021; SWOV, 2023). Traditional strategies to enhance cycling safety, including dedicated cycling lanes and infrastructure, appear efficient for safeguarding cyclists in conventional traffic. However, we lack knowledge about the appropriate measures to improve the safety of cyclists in the future of automated driving. Many solutions have been proposed, such as warning systems and eHMIs (Dey, Habibovic, Löcken, et al., 2020), connected vulnerable road users (Hasan & Hasan,

2022), and changes to the road environment (Tengilimoglu et al., 2023). The present state of knowledge of these solutions is fragmented and lacks a comprehensive overview, especially regarding cycling. Moreover, the solutions are largely technology- and automotive-oriented, with the knowledge concerning cyclists' needs and aspirations for HMIs and automated vehicles noticeably absent in the literature. To ensure academia and the industry are developing ethical and desired solutions for cyclists, cyclists' perspectives and viewpoints must be included in the process.

Focusing on the emergence of automated vehicles and their effects on cyclists, several questions and challenges arise. The multifaceted nature of cyclist-automated vehicle interactions, requirements of (e)HMIs in different traffic scenarios, and the overall implications for cycling safety in varying automated environments lack clear definition and understanding. These challenges extend to whether and in which prototypical scenarios cyclists miss vital communication cues from human drivers when encountering automated vehicles. Developing a cyclist-oriented understanding of the factors involved in cyclist-automated vehicle interaction and identifying relevant scenarios of the interaction will help address these concerns.

The ideal automated vehicle, with impeccable sensing and decision-making capabilities, is aspirational yet pragmatically utopic. The practical reality of automated vehicles entails potentially sub-optimal or erratic behaviour (Nordhoff, 2023; Pitts, 2023) and necessitates an exploration of how cyclists adapt and respond to this new road user and the situations that may arise. Although HMIs are offered as solutions to a prospective problem, the rudimentary question of whether substituting the lack of explicit communication cues is *necessary* remains largely unexplored. Establishing cyclists' use of and need for explicit communication from drivers and which cues – if any – to substitute with HMIs would benefit the literature base.

1.7 Research objectives

This dissertation takes a cyclist-centric approach to exploring the myriad of factors influenced by the increasing presence of automation on our roads. The previous sections have set the stage by introducing cyclists as an important road user group in the emergent landscape of automated vehicles. The sections have covered the basics of communication in traffic – implicit versus explicit – and seen current trends in human factors research focus on HMIs as support tools for vulnerable road users in future automated traffic. Against this backdrop, the following section outlines the four research topics shaping the forthcoming chapters of this dissertation. These overarching topics and subsequent research questions (*RQs*) cover the technological, psychological, and ethical considerations critical to safe cycling in the age of automation.

1.7.1 Cyclist-automated vehicle interactions

This topic is intended to examine the interaction dynamics between cyclists and automated vehicles holistically by combining multiple perspectives from everyday cyclists, traffic safety experts, previous literature, and field tests. By understanding how cyclists interact with vehicles today, exploring cyclists' communication needs, and the effects of gradually removing the human factor from driving, we can suggest and plan for future solutions from the cyclists' point of view. A key theme explored within this topic is the importance of implicit versus explicit communication between cyclists and vehicles. Exploring cyclist-automated vehicle interactions, the following research questions were derived:

RQ1: How do cyclists' interactions with human drivers shape their requirements and expectations of future interactions with automated vehicles?

RQ2: What is the role of implicit versus explicit communication in cyclist-automated vehicle interactions?

1.7.2 Scenarios and behavioural challenges

With the gradual removal of the human driver, new and unexpected behaviours and situations may arise in traffic. The topic of scenarios and behavioural challenges deviates from the others by focusing on vehicle behavioural changes relevant to cyclists. The research question centres around the real-world complexities that could surface as automation becomes more prevalent from the perspective of both cyclists and automated vehicles:

RQ3: What are common scenarios and automated vehicle behaviours likely to influence future interactions with cyclists?

1.7.3 Ethical considerations

Aiming to facilitate discourse on the prospect of automated vehicle-cyclist interaction, this topic covers the implications of the current HMI solutions promoted by industry and academia.

RQ4: What ethical and practical considerations should inform design and policy to accommodate cyclists in future automated traffic?

1.7.4 HMI solutions

Focusing on technological solutions, this topic aims to broadly evaluate the designs, devices, and systems available or under development that may facilitate safer and more efficient interactions between cyclists and automated vehicles:

RQ5: What key features do cyclists want in HMIs, and how should these HMIs be designed to accommodate the characteristics of cyclists?

1.8 Contributions

This dissertation contributes to the underrepresented area of studying automated vehicles from the cyclists' perspective, both from an academic and practical standpoint. By taking the cyclists' point of view, this dissertation enriches human factors in road traffic research, a field traditionally dominated by the needs and behaviours of drivers.

The academic contributions include mapping the terrain of the evolving needs of cyclists. Specifically, the studies in this dissertation outline the diverse and intricate requirements that cyclists will have as automated vehicles become more prevalent on the road. Through interviews with everyday cyclists, cycling safety experts, and empirical testing, our studies offer an in-depth examination of how traditional communication between cyclists and drivers might change. Our research uncovered novel situations that may arise in traffic with increasing degrees of automation, drawing particular attention to the subtleties of implicit versus explicit communication mechanisms, especially in the context of HMIs.

Moreover, this dissertation takes a pioneering role in instigating the ethical discourse around the responsibility of vulnerable road user safety of automated vehicles, a perspective often

lacking in academic papers. It questions the ethical considerations and implications of a more connected traffic environment, urging a rethinking of the solutions we offer vulnerable road users in the near future of automation. From the cyclists' point of view, our studies advocate for a more inclusive, less car-centred approach to urban traffic, aiming to shift the burden of safety away from vulnerable road users like cyclists.

Regarding practical contributions, the research outlined in this dissertation provides a series of resources for policymakers and researchers. It offers a collection of scenarios that can be used in future research focused on cyclists and automated vehicles. Furthermore, it presents an extensive inventory of technical solutions for cyclists, which provides a more precise overview of the solutions' attributes and functionalities with the potential to aid in future communication with automated vehicles. Additionally, the thesis outlines two HMI solutions specifically designed based on cyclists' requirements and desires in future traffic, contributing to the pool of practical, implementable solutions for improving cyclists' safety. Taken together, this dissertation fills the existing gaps in the literature and paves the way for future academic inquiry and real-world applications.

1.9 Methodology

Considering the intricate interplay of the social, psychological, environmental, and technological factors that shape the interactions between cyclists and automated vehicles, most of the studies presented in this dissertation adopt qualitative methodologies. Qualitative research allows for a richer and more nuanced understanding of a phenomenon than numbers (Braun & Clarke, 2013), and knowledge generated from these methods helps lay the foundation for future research.

The use of interview data in *Chapters 2, 4, 5, and 6* helps capture detailed accounts directly from cyclists, offering valuable insight into their perspectives and experiences both in understanding cyclist-automated vehicle interaction and designing HMI concepts, but also in developing design guidelines. Moreover, the literature reviews of *Chapters 3 and 5* systematise and contextualise previous research, while the triangulation in *Chapter 5*, combining different methods and sources of data, serves to strengthen the reliability of our findings, ensuring that the conclusions drawn are reflective of the multifaceted reality of cyclists. Additionally, the application of mixed methods, utilising eye-tracking and simulator data (*Chapters 6 and 7*), benefits from direct observations of behaviour and interaction, adding to the understanding of the phenomenon.

The methodologies applied in each study of this dissertation are outlined in their respective chapters. Together, the studies seek to illuminate the areas of cyclist-automated vehicle interaction, answer the research questions, and address the aforementioned knowledge gaps.

1.10 Dissertation structure

This section serves as a roadmap for the reader, offering a brief outline of each chapter and clarifying how they contribute to the overarching themes and objectives of the dissertation. Figure 1.1 illustrates the structure of the dissertation with the four overall objectives, their corresponding research questions, and the related chapters.

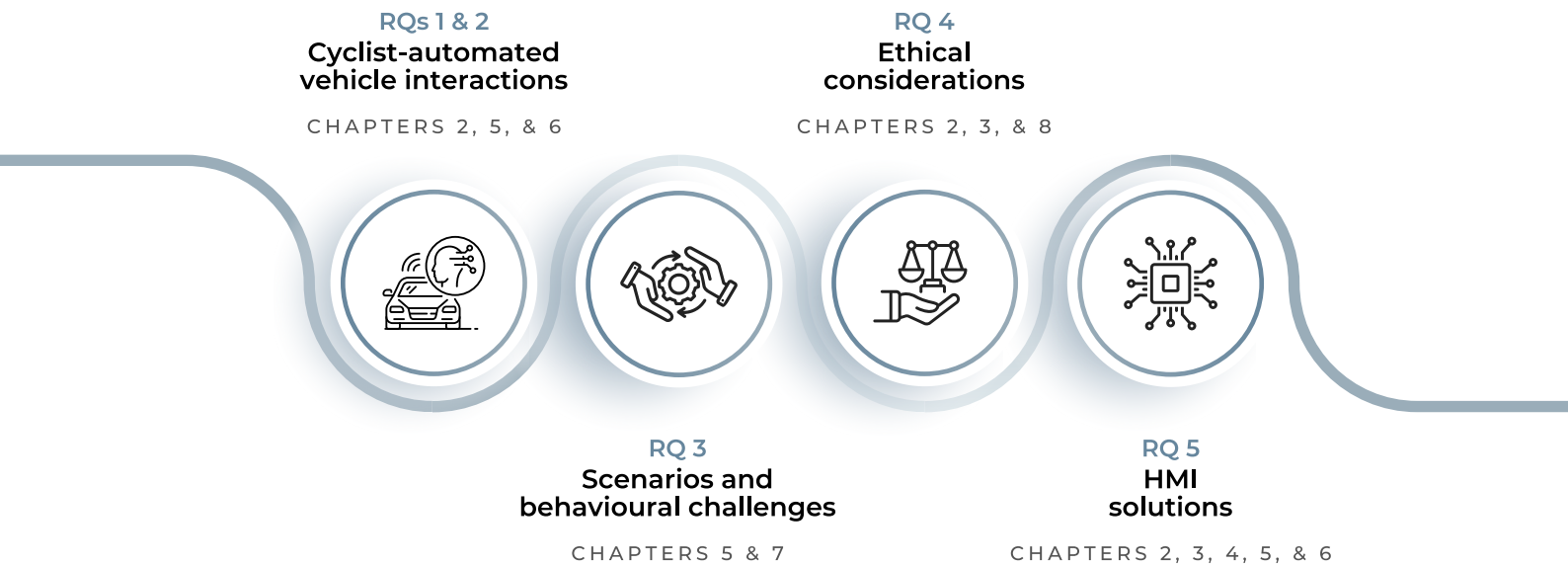


Figure 1.1. Dissertation structure

Note: RQ1: How do cyclists' interactions with human drivers inform their requirements and expectations of future interactions with automated vehicles? RQ2: What is the role of implicit versus explicit communication in cyclist-automated vehicle interactions? RQ3: What are common scenarios and automated vehicle behaviours likely to influence future interactions with cyclists? RQ4: What ethical and practical considerations should inform design and policy to accommodate cyclists in future automated traffic? RQ5: What key features do cyclists want in HMIs, and how should these HMIs be designed to accommodate the characteristics of cyclists?

Chapter 2 is based on an in-depth interview study with 30 cyclists. The factors that constitute cyclist interaction in traffic today and in the future of automated vehicles (*RQ1* and *RQ2*) were investigated with thematic analysis. The chapter also delves into potential design strategies of on-bike HMIs to enhance the interaction between automated vehicles and cyclists (*RQ5*). Moreover, it raises the topic of ethical considerations of HMIs for cyclists (*RQ4*).

Chapters 3 and 4 focus on HMI designs and design strategies (*RQ5*). Synthesising previous literature, **Chapter 3** presents an inventory of HMIs that have the potential to aid cyclists in automated traffic, categorising the designs according to attributes such as placement, functionality, and mode of communication. The study concludes with a discussion of connected road users (*RQ4*). **Chapter 4** goes deeper into the design strategies and proposes two HMI designs aggregated from a thematic re-analysis of the interview data outlined in Chapter 2 (*RQ5*).

Chapter 5 contains a collection of 20 scenarios identified through interviews with traffic safety and automation experts and previous literature on cyclists and automated vehicles (*RQ3*). Illustrating the movement patterns and proactive safety strategies of cyclists, the findings provide information for answering *RQ1* and *RQ5*. The chapter also introduces two behavioural traits of automated vehicles that might affect cyclist interactions (*RQ3*), including a discussion of the role of implicit versus explicit communication (*RQ2*).

Chapters 6 and 7 experimentally address the role and effect of implicit versus explicit communication in road user interaction (*RQ2*). **Chapter 6** focuses on the effect of the absence or presence of a driver on cyclists and examines cyclists' ability to detect a human driver behind

the wheel through eye-tracking and interviews with 37 field study participants. The results also provide an additional understanding of the necessity of distinguishing human-driven vehicles from automated vehicles (*RQ5*). Moreover, **Chapter 7** addresses the role of implicit vehicle communication by theoretically outlining and demonstrating the concept of ‘phantom braking’ in automated vehicles in a cycling simulator (*RQ2* and *RQ3*).

Finally, **Chapter 8** summarises the findings from the previous chapters and puts them into the context of the four broader research topics of cyclist-automated vehicle interaction, HMI solutions, scenarios and behavioural challenges, and ethical considerations. In particular, the chapter discusses the relevance of the studies’ results to the aggregation of insights and recommendations for policy development and future research (*RQ4*), consolidating the thesis and paving the path to a safer future for cyclists in the age of automated traffic.

Chapter 2

Do cyclists need HMIs in future automated traffic? An interview study

Cyclists are expected to interact with automated vehicles in future traffic, yet we know little about the nature of this interaction and the safety implications of automated vehicles on cyclists. On-bike HMIs and connecting cyclists to automated vehicles and the road infrastructure may have the potential to enhance the safety of cyclists. This study aimed to identify cyclists' needs in today's and future traffic and explore on-bike HMI functionality and the implications of equipping cyclists with devices to communicate with automated vehicles. Semi-structured interviews were conducted with 15 cyclists in Norway and 15 cyclists in the Netherlands. Thematic analysis was used to identify and contextualise the factors of cyclist-automated vehicle interaction and on-bike HMIs. From the analysis, seven themes were identified: Interaction, Bicycles, Culture, Infrastructure, Legislation, Automated vehicles, and HMI. These themes are diverse and overlap with factors grouped in sub-themes. The results indicated that the cyclists prefer segregated future infrastructure, and in mixed urban traffic, they need confirmation of detection by automated vehicles. External on-vehicle or on-bike HMIs might be solutions to fulfil the cyclists' need for recognition. However, the analysis suggested that cyclists are hesitant about being equipped with devices to communicate with automated vehicles: Responsibility for safety should lie with automated vehicle technology rather than with cyclists. A device requirement might become a barrier to cycling, as bicycles are traditionally cheap and simple, and additional costs might deter people from choosing cycling as a transport mode. Future studies should investigate user acceptance of on-bike HMIs among cyclists on a larger scale to test the findings' generalisability, and explore other, perhaps more viable solutions than on-bike HMIs for enhancing automated vehicle-cyclist interaction.

This chapter is based on Berge, S. H., Hagenzieker, M., Farah, H., & De Winter, J. (2022). Do cyclists need HMIs in future automated traffic? An interview study. *Transportation Research Part F: Traffic Psychology and Behaviour*, 84, 33-52. <https://doi.org/10.1016/j.trf.2021.11.013>

2.1 Introduction

Automated vehicles are expected to reduce the frequency of road accidents by removing the human factor from driving (Fagnant & Kockelman, 2015; Kröger, 2020). However, urban road automation is likely to be a prolonged transformative process (Rupprecht et al., 2018), and human road users can be expected to interact with vehicles of varying degrees of automation for decades to come (Litman, 2020; Owens et al., 2018).

Active transport like walking and cycling is beneficial to public health (Raser et al., 2018) and promises substantial reductions in CO₂ emissions (Mason et al., 2015). While automated vehicles are assumed to produce fewer emissions than conventional vehicles (Milakis et al., 2017), active transport remains more sustainable (Creger et al., 2019). Trends indicate that cycling is on the rise in urban areas (Epinion Transport & Mobility, 2019; Harms & Kansen, 2018; OECD/ITF, 2013; Pucher & Buehler, 2017), and it is likely that cyclists will be interacting with automated vehicles in future traffic.

Cyclists are vulnerable road users (Holländer et al., 2021), and a motorised vehicle colliding with a cyclist is likely to result in significant injury to the cyclist (Schepers et al., 2015). The way cyclists interact with human drivers cannot automatically be transferred to the context of automated vehicles, as cyclists might base their behaviour and interaction strategies on incorrect expectations of automated vehicle behaviour (Vissers et al., 2017). To ensure cyclists' safety in future traffic, exploring solutions for enhancing communication between automated vehicles and cyclists becomes vital.

Dey, Habibovic, Löcken, et al. (2020) suggested that present solutions for enhancing automated vehicle-vulnerable road user communication can be categorised in two broad terms: (1) technical, such as network and communication systems, and (2) human factors oriented, focusing on the ergonomics and interaction aspects of the interface between automated vehicles and vulnerable road users.

Among the technical solutions for enhancing automated vehicle-cyclist interaction, there are bicycle-to-vehicle connectivity and vulnerable road user beacon systems (Silla et al., 2017). As transport is increasingly becoming a part of the Internet of Things (Behrendt, 2019), several researchers have argued that connectivity between automated vehicles and vulnerable road users is essential to use vehicle automation to its full advantage (Farah et al., 2018; Owens et al., 2018; Sanchez et al., 2016). Cyclists could be connected to automated vehicles and the road infrastructure through their bicycles (Jenkins et al., 2017; Meinken et al., 2007; Piramuthu, 2017; Scholliers et al., 2017; Shin et al., 2013), or through wearables such as smartphones (Anaya et al., 2014; Engel et al., 2013; Liebner et al., 2013; Scholliers et al., 2017; Wu et al., 2014), and helmets (Hernandez-Jayo et al., 2015). However, little is known about the consequences of equipping cyclists with devices to communicate with automated vehicles in terms of reliance, liability, and responsibility of the automated vehicles and the cyclists (OECD/ITF, 2019; Owens et al., 2018).

Solutions for enhancing automated vehicle-cyclist interaction from a human factors perspective mainly revolve around on-vehicle eHMIs. eHMIs substitute the lack of explicit human-to-human communication cues with driverless automated vehicles by providing additional cues on vehicle displays, lights, or projections on the road. The eHMI research has focused primarily on physical interface elements like placement, colour, and textual versus non-textual messages (Bazilinskyy et al., 2019; Dey, Habibovic, Löcken, et al., 2020). Out of the eHMI concepts considered by Dey, Habibovic, Löcken, et al. (2020), 91% targeted pedestrians. Cyclists were, however, included as a multiple target user in 23% of the concepts. Cyclist behaviour differs from pedestrians in speed, glancing behaviour, and movement patterns (Hagenzieker et al., 2020; Trefzger et al., 2018). This points towards the necessity of considering these differences in the eHMI design process for cyclists and pedestrians. Similar viewpoints were expressed by Hou et al. (2020), as their findings for eHMIs for cyclists differed from pedestrians.

A cyclist-specific solution for enhancing communication between automated vehicles and cyclists could be combining the technical and human factors approaches by adding interfaces to the bicycle and connecting cyclists to a network of automated vehicles and infrastructure. Previous research on on-bike HMIs in conventional traffic has examined warning systems (Engbers et al., 2018; Jenkins et al., 2017; Prati et al., 2018), lane-keeping assistance systems (Matviienko, Ananthanarayan, Brewster, et al., 2019), turn indicators (Dancu et al., 2015), and navigation systems (Dancu et al., 2015; Pielot et al., 2012). For instance, Engbers et al. (2018) tested a front- and rear-view assistant system for cyclists and found that the front-view assistant resulted in less lateral distance to the approaching oncoming cyclist. In Prati et al. (2018), cyclists were more likely to decrease their speed if warned by an on-bike system. Other studies have investigated augmentation concepts like Augmented Reality (AR) glasses (Ginters, 2019; Von Sawitzky, Wintersberger, et al., 2020) and head-up displays (HUDs) (Dancu et al., 2015; Hou et al., 2020; Matviienko, Ananthanarayan, Brewster, et al., 2019) for cyclists. However, the potential of on-bike HMIs to enhance automated vehicle-cyclist interaction remains largely unstudied.

Investigating the factors that constitute cyclist interaction today might offer insight into cyclists' needs for automated vehicle interaction in the future. Utilising semi-structured interviews invites end-users to reflect on a topic (Gulliksen et al., 2003; Willig, 2008). In addition, by taking a qualitative and constructivist approach to the automated vehicle-cyclist interaction and on-bike HMIs, we aim to provide an in-depth description and understanding of the dynamics of these novel topics and lay a basis for further hypotheses development and testing.

The objective of the present study is to fill the knowledge gap of on-bike HMIs for automated vehicle-cyclist interaction by exploring the factors that constitute cyclist interaction in traffic, both in current environments and in future scenarios with automated vehicles. Moreover, we investigate whether on-bike HMIs are desired by cyclists and potential design strategies of on-bike HMIs to enhance the interaction between automated vehicles and cyclists.

2.2 Method

We conducted semi-structured online interviews with 15 cyclists in Norway and 15 cyclists in the Netherlands. The interviews were performed individually either in Norwegian or English by the first author via Microsoft Teams or Zoom from August to November 2020 and had an average duration of 50 minutes. The interviews started with a short introduction of the project

and demographic questions, followed by open-ended questions sectioned into three topics. Table 2.1 shows the interview topics and selected questions from the interview guide. For the complete interview guide please refer to Appendix A.

Table 2.1. Interview topics and a selection of questions from the interview guide

Topic	Question
Current traffic interaction	<i>I would like to know about your experience with cycling ...</i>
	Could you start by describing a typical cycling trip?
	How would you describe the interaction with motorised vehicles?
	Do you encounter any challenges while cycling? Please elaborate.
The future of cycling	<i>Imagine a future where cars are fully automated, and there is no longer a human driver behind the wheel ...</i>
	How will this impact you as a cyclist?
	How do you think [<i>challenge(s) already mentioned by the participant</i>] will change when cars are automated and driverless?
	As a cyclist, what kind of information would you need from an automated vehicle?
Bicycles and technology	<i>Imagine the future of cycling, with new and exciting technological progress. I want you to think of your perfect bicycle (it does not have to be realistic) ...</i>
	What would it look like?
	What kind of features would it have?
	<i>Imagine a system or device that helps you interact with automated vehicles ...</i>
	How should this device be designed?
	How should the device communicate with the cyclist?
	<i>If you could receive information about other road users, such as automated vehicles through a device or a system on your bike (like the one you just imagined) ...</i>
	What are the benefits of such a system?
	What kind of information about cyclists would be useful for the automated vehicle?
	What are the disadvantages of such a system?

Before participation, the interviewees received and signed an information sheet and consent form digitally through Adobe Sign. Participation was anonymous and voluntary. The study was approved by the Human Research Ethics Committee of TU Delft. Adhering to open science principles, the participants agreed to open access storage of anonymised written transcripts from the interviews.

2.2.1 Sample and recruitment

Aiming to gather a range of experiences among European cyclists, Norway was selected as a country with low shares of cyclists, and the Netherlands as a country with high shares of cyclists (Buehler & Pucher, 2012). By interviewing cyclists in two countries with different shares of cyclists and cycling culture, this approach allowed us to explore how cultural

differences may affect cyclist interaction and to what extent these differences play a role in the future of cycling.

The sample was recruited by invitations linking to a recruitment website shared on social media in the authors' personal and professional networks, LinkedIn, Facebook cycling interest groups², and Twitter³. Three of the interviewees were referred by other participants. In total, 66 potential participants were identified. The participants were contacted consecutively by e-mail with a request for an interview. The only prerequisite required was cycling experience in Norway or the Netherlands. A sample of 15 cyclists was selected from each country. Note that in thematic analysis, a sample size of 30 is regarded as sufficient, as 'thematic saturation' can be achieved with substantially smaller sample sizes (Fugard & Potts, 2015; Guest et al., 2006).

Table 2.2 provides an overview of the interview participants. The sample of 30 participants consisted of 11 females and 19 males.

² Syklistforeningen i Oslo and the Dutch Cycling Embassy

³ SWOV Institute for Road Safety Research

Table 2.2. Demographics of the interview participants

	n	Total	Norway	The Netherlands
Gender				
Female	11	37%	5	6
Male	19	63%	10	9
Age				
18-28 years	6	20%	0	6
29-39 years	8	27%	5	3
40-50 years	7	23%	5	2
51-61 years	4	13%	1	3
> 61 years	5	17%	4	1
Cycling frequency				
Daily	22	73%	11	11
Weekly	7	23%	3	4
Monthly	1	3%	1	0
Employment				
Employed	22	73%	12	10
Retired	4	13%	3	1
Student	3	10%	0	3
Unemployed	1	3%	0	1
No. of bikes				
0	1	3%	0	1
1	11	37%	6	5
> 1	18	60%	9	9
Type of bike				
City bike	11	37%	0	11
Electric	9	30%	7	2
Hybrid	13	43%	10	3
Road bike	6	20%	3	3
Other	25	83%	11	14
Approach to technology				
Early adopter	10	33%	3	7
Average	17	57%	11	6
Last to try	3	10%	1	2
Total	30	100%	15	15

The participants were evenly distributed across the age groups, with an average age of 43 years ($SD = 16$, $R = 53$). However, the age distribution differed between the two countries. All participants in the youngest age group were from the Netherlands, while most participants 62 years or older were Norwegian. Most of the participants (73%) cycled daily. The number of participants owning more than two bicycles was even between the two countries. A larger share of Norwegians (47%) owned an e-bike than participants in the Netherlands (13%). None of the Norwegians owned a city bike. Lastly, 70% of the early adopters of technology was interviewed in the Netherlands. Note that although we did not ask specifically about education and background, some participants had professional knowledge of automated vehicles and human factors.

2.2.2 Analysis

Thematic analysis adapted from Braun and Clarke (2006) was chosen as the methodological approach. Thematic analysis is a flexible and systematic approach for synthesising, linking, analysing and reporting patterns in interview data (Braun & Clarke, 2006) and has been shown valuable in previous transport research (Alyavina et al., 2020; Gössling et al., 2016; Liu et al., 2020; Pettigrew et al., 2020). Table 2.3 presents the six steps of our thematic analysis process.

Table 2.3. Six-step process of thematic analysis

Phase	Description
1	Familiarising with data
2	Generating initial coding
3	Searching for themes
4	Reviewing themes
5	Defining and naming themes
6	Reporting the findings

Audio from the interviews was recorded with Audacity and transcribed clean verbatim by a professional transcription company, removing repetitions and filler words as they were deemed of no relevance to the nature of the analysis. The transcripts were compared with the audio files to ensure their authenticity by the researcher who performed the interviews, and minor corrections were made to the transcripts. While the transcripts were transcribed in Norwegian and English, respectively, the thematic analysis was performed in English. Atlas.ti 9 was used to categorise, code, and analyse the interview data. The analysis was data-driven and emergent. The first author performed the coding process, based on the transcripts' semantic content, using raw quotes as codes. The codes were sorted into thematic categories based on repetition, similarities, and differences (Ryan & Bernard, 2003). Within each thematic category, the codes were further differentiated and sorted into sub-themes. The analysis was iterative, where codes and their allocation to each overarching theme were reassessed and merged during the initial phases. The emergent nature of the analysis necessitated using a single coder (Smith & McGannon, 2018). During the synthesis of the themes in phases 3 and 4, however, the authors discussed and reassessed the sub-theme allocation to the overarching themes.

As two or more codes could be allocated to the same data segment, there is some overlap (code co-occurrence) between the themes. Code co-occurrence can provide useful information on understanding the thematic domains beyond simple frequencies (Namey et al., 2008). Code co-occurrence is common in thematic analysis as the themes are not disjointed from the data, but rather a result of similarities and connections within and across the dataset (Braun & Clarke, 2006).

2.3 Results

2.3.1 Overview of results

Seven overarching themes and 47 sub-themes that constitute cyclist interaction today and in future scenarios with automated vehicles were identified in the analysis: Interaction, Bicycles, Culture, Infrastructure, Legislation, Automated vehicles, and Human-machine interface. Table 2.4 shows an overview of the seven themes and their respective sub-themes.

There are some code co-occurrences across the themes. As seen in Figure 2.1, Interaction had most code co-occurrences with the other themes. The overlaps of Interaction were most evident with Infrastructure (44 co-occurrent codes), Culture, and Automated vehicles (AVs) (28 co-occurrent codes each), implying that these themes are closely associated. Similar claims can be made for automated vehicles and HMI (35 co-occurrent codes), and Bicycles and HMI (30 co-occurrent codes).

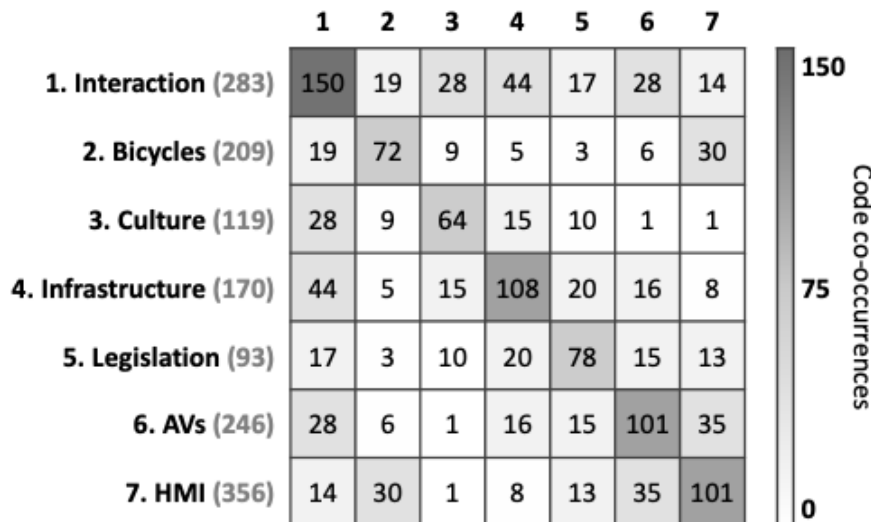


Figure 2.1. Code co-occurrence of the main themes

Note: The numbers on the diagonal indicate the total number of code co-occurrences for that theme. The numbers displayed after each theme indicate the total number of coded quotations within each theme.

Table 2.4. Overview of the main themes and sub-themes

Theme	Sub-theme	Category within Sub-theme
Interaction (30)	Cyclist behaviour (30)	Eye-contact (24)
		Motion cues (17)
		Hand gestures (12)
	Challenges (29)	
	Other road users (28)	Drivers (27)
		Mopedists (5)
		Pedestrians (4)
	Cycling (22)	
	Perceptions (19)	
	Safety (19)	
	Informal rules (6)	
Bicycles (30)	Features (30)	Electrification (21)
		Simplicity (14)
		Connectivity (8)
		Tailored (8)
	Utility (29)	
Culture (30)	The Netherlands (18)	
	Norway (14)	
Infrastructure (30)	Separated (29)	Safety (22)
	Challenges (26)	
	Future (16)	
	Traffic lights and signals (13)	
	Smart (4)	
	Parking (3)	
Automated vehicles (30)	Expectations and automated vehicle capabilities (30)	
	Cyclist needs (24)	
	Challenges (24)	
	eHMI (18)	
	Future applications of automated vehicles (6)	
Human-machine interface (30)	Functionality (30)	
	Perceptions and attitudes (30)	
	Design strategies (27)	Display (21)
		Audio (12)
		Haptics (10)
Legislation (30)	Planning and regulation (21)	
	Rule-breaking (14)	Red lights (11)
		Enforcement (4)
	Standardisation (9)	
	Privacy (9)	

Note. The numbers indicate the frequency of interviews each sub-theme occurred in.

In the following sections, the themes are presented with a selection of quotes from the participants, describing the thematic analysis's narrative direction.

2.3.2 Interaction

The theme Interaction encompasses perceptions of cycling, cyclist behaviour and informal rules, safety, interaction with other road users, and the challenges cyclists face related to interaction.

Cyclist interaction entails a certain degree of unpredictability and anarchy. Cyclists are described by the participants as having a high degree of freedom to move, even in congested traffic. Cycling in urban areas requires a high mental workload, and it may be challenging to predict other road users' intentions. In a group, however, cyclists can follow the crowd and pay less attention to motorised traffic. There is a group dynamic that seems to work well:

"It has something to do with the understanding that there is an interaction between many actors in a particular cityscape. Cyclists have the advantage that they can react flexibly".
(NO3)

"One of the paths I follow from my house to go to the train station is the busiest cycling road in the Netherlands. (...) It's like some thousands of bikes. To me, it's quite impressive that people can manage. It means that the system kind of works. People know how to cycle properly". (NL24)

Most of the interviewees described themselves as considerate and well-behaved, expressing gratitude and smiling to other road users, but it was also acknowledged that they could act carelessly and selfishly. Cyclists use a mix of eye contact, hand gestures, and motion cues to interact with other road users. They are likely to establish eye contact with drivers at intersections, crossings, and in ambiguous situations.

"I do use eye contact sometimes, for example, when I'm at a crossroads and the driver kind of slows down to let me pass or even, you know, uses his hand gestures to tell me to pass, I would usually look at them and like, wave and say thank you". (NL21)

"If a car approaches me, most of the time, I try to look at the driver to see if he sees me".
(NL29)

Eye contact can be particularly important when the cyclist is breaking the formal or informal rules of cycling. However, some interviewees said they tend to rely more on motion cues like change in speed and velocity to interpret other road users' intent than eye contact.

"Sometimes I wait to get an indication that they are going to slow down or they're going to let me pass - they know I'm there. Often that's if they slow down or they maybe move to the left a little, so to give me a little way, and then I know that they're aware of me, and then I'm fine". (NL20)

"Even if you do not see each other's eyes, I see how the car drives and the driver sees my posture and how I move". (NO12)

"I have to see that the car stops, that it slows down, I have to be sure of that". (NO2)

Hand gestures are used to signal intention and are often combined with alignment on the road and adjustment of speed to interact and negotiate with other road users.

Perceptions of cyclists and cycling varied across the interviewees. Cycling was perceived as mostly smooth and cooperative. However, some of the interviewees mentioned that they are

fearful of drivers, of not being seen, and of losing balance and falling. In urban areas without cycling infrastructure, the cyclists often cycle defensively and at lower speeds to avoid critical situations with cars and heavier vehicles.

“I have a rather defensive style of cycling. I never cycle so fast that I expose myself to, at least not consciously, any dangerous situation”. (NO1)

The consensus among the cyclists interviewed in the Netherlands was that cycling is safe and easy. Protective gear and equipment are seen as not needed because cyclists are cared for in traffic:

“In Netherlands, cyclists are meant to be cared about. I mean, the other users should take care of cyclists; they shouldn't take care of themselves. That's why they don't force you to wear helmets”. (NL19)

In regard to interaction with other road users apart from fellow cyclists, three types of road users were recurrently mentioned during the interviews: drivers, mopeds, and pedestrians. The interviewees perceived drivers as attentive, considerate, and aware of cyclists. For the most part, interaction with drivers is effortless. However, some drivers seem to be annoyed, drive aggressively, and apparently do not appreciate sharing the road with cyclists, sometimes to the extent where they are perceived to try to hinder cyclists in traffic deliberately. In addition, some drivers come too close, and are not aware of their vehicle size, misjudging the space needed for overtaking. Norwegian cyclists, in particular, mentioned that they sometimes feel disdained and not welcome by other motorised road users.

“When you look at motorists, you can get the impression that “it's just a cyclist, so we don't have to comply with the obligation to give way” (...). There is both uncertainty about whether they see me, or whether they simply don't care”. (NO11)

In the Netherlands, it is assumed that drivers are more considerate because they are often cyclists themselves.

“In other countries, you are either a cyclist or a driver. Here, drivers also cycle themselves. Maybe most of the time they cycle, but sometimes they drive or the other way around. So, they have experience of both, being a cyclist and driver. When they are driving, they understand the feeling of the cyclist in front of them”. (NL19)

Likewise, a Norwegian interviewee said he changed his view of cyclists from negative to positive after he started cycling regularly.

“In my experience, there are a lot of drivers who prevent cyclists by deliberately placing themselves all the way to the curb so you cannot... “no way in hell you are getting in front of me”, sort of. I have been a motorist for many years. I do not have a car anymore, but I was probably that type of driver. Now, I get these moments of realisation: I thought cyclists were in the way”. (NO13)

Traffic is, however, considered inherently dangerous, and with cyclists often being the losing party in a traffic accident, perceived safety was reported as higher when there is less interaction with other road users such as drivers. Some cyclists said they plan their routes to avoid mixed traffic and prefer taking the less busy and quieter roads.

“When I cycle with cars and other heavier vehicles, I cycle as if everything is a potential danger to my life. I ride my bike as if everything is a death threat”. (NO4)

“As a vulnerable road user, I try to be careful not to be hit by cars. I always think there is a risk when I bike on the road. Mostly I try to ride on bike and pedestrian paths”. (NO3)

"I will highly avoid cycling next to cars like I know some roads (...) are kind of mixed, so you have to be really close to cars. But I feel quite unsafe if I don't have my own cycle path. (...) I will maybe do a reroute myself to just make sure I don't have cars really next to me because you never know". (NL24)

Cyclists experience a wide range of challenges related to interaction. Unpredictable behaviour by other road users, such as rule-breaking, sudden braking or backing up, being cut off or experiencing tailgating or takeovers, was reported as a recurrent challenge. Parked cars and cars stopping and starting in bicycle lanes could also be challenging. Traffic with high complexity, combined with high speed at points of interaction, such as crossings and intersections, could be a challenge as well. Among the Dutch interviewees, interaction with mopeds and other cyclists were recurring challenges, especially when there are cyclist congestion or busy cycling paths, risk-taking cyclists and elderly e-bikers that might be unstable or react slow.

2.3.3 Bicycles

The theme of Bicycles encompasses bicycles as a mode of transport, desired features of today's and the future's bicycle, as well as bicycle theft.

Bicycles serve as a means of transport for commuting, errands, leisure activities, and recreation. In urban areas, in particular, cycling is an alternative to driving and saves travel time. Bicycles cover most everyday needs for transport, and with innovations such as e-bikes, cargo, and utility bikes, cyclists can transport children and goods on their bikes at longer distances. The cyclists interviewed saw cycling as a benefit to public health: Cycling is cheap, involves physical activity, and is beneficial to the environment.

"The more people who manage to use the bike for the bulk of their traffic or transportation needs, the better it is for city space utilization, noise levels, and traffic safety. In addition, it benefits public health. In every conceivable way, cycling is good". (NO4)

The perfect future bike could take many forms and shapes, and the participants suggested features such as self-stability, sensors, automated braking and gearing systems, improved traction, improved lights and signalling systems, and anti-theft and locking systems. The interviewees acknowledged that bicycles have versatile functionality and said they prefer a bicycle tailored to their individual needs. Half of the interviewees did, however, point out that the strength of the bicycle is its simplicity. The perfect future bicycle was often described as inexpensive and simple, with slightly improved features, such as better gears and brakes.

"I think the basic model, as the bike looks today, is how it will continue to look like. (...) Cars have had an enormous technical development, but bicycles have only been perfected using technology we already have. There is nothing about my bike I would want differently. It's perfect". (NO6)

"I definitely think that the perfect bike today is already the bike that exists and is being used. That's what's so liberating about cycling in general. It's simply the joy of transporting yourself. This freedom you have, it does not need the help of [additional] technology". (NO11)

Electrification was one of the most reoccurring sub-themes of bicycles in the interviews. While physical activity is an essential factor for many cyclists, it was acknowledged that electrification might be the future of cycling. E-bikes have the potential to increase personal mobility and make cycling more accessible to the public, including older persons. Electrification was reported useful for longer distances, and for cyclists who value travel time and comfort. On the other side, e-bikes are heavy and have a limited battery capacity. If the future bike is electric, some cyclists appreciate the option of turning the e-functionality off:

"Well, ideally, I would like to have the choice if the bike is electric or not, but I would like to still have the choice to exercise because cycling serves this purpose too for me. I like to keep myself healthy by cycling, but if I'm too tired or I want some boost, it would be nice to get some extra assistance". (NL24)

In a future where traffic has a high degree of automation, the interviewees were open to adding connectivity to their bikes, either through a simple sensor integrated into the bike, or a wearable, or a more elaborate cycling computer system used for navigation and communication with other road users and infrastructure. Some cyclists were, however, hesitant about adding new technology to bicycles. They argued that such systems will be excluding by no longer making bicycles affordable. Expensive bikes are also more prone to theft, some cyclists are wary of investing in extra equipment and features for their bicycles.

"Bikes getting lost is a thing in the Netherlands. Bikes are stolen. So, I would imagine having such technology already in the bike, isn't good (...) because when the bike is lost you lose a lot of money". (NL17)

"Everyone has had a lot of bikes, but everyone has also had a lot of bikes stolen. I think everyone I know has had a bike stolen and I think a bike like that would be really expensive with modern technology". (NL18)

2.3.4 Culture

As the cyclists were interviewed about cycling in Norway and the Netherlands, respectively, the theme Culture clusters around cycling culture in these two countries. Additionally, some of the participants had cycling experience from both, and several other countries, mostly in Europe.

Norway

The interviewees portrayed Norwegian road infrastructure as tailored to cars since the 1970s. Since then, cyclists have stereotypically been described as a nuisance to drivers. Cycling is permitted on sidewalks, and cyclists are in many instances forced to share the sidewalk with pedestrians as there is no viable alternative. If cyclists are using sidewalks, they typically lower their speed and cycle more carefully. It is, however, preferred to share the road with cars rather than cycle on sidewalks with pedestrians.

Cycling on the road can be a dangerous activity, where wearing protective gear and equipment is a must. There is a sense of anarchy among many cyclists, and rule-breaking seldom has legal consequences. For instance, it is common for cyclists to slow down and roll through an intersection, exploiting gaps in traffic, even if there is a red light. While waiting at a red light in mixed traffic, cyclists often start cycling before the light turns green, assumingly to make themselves more visible to drivers. Moreover, several of the Norwegian interviewees said cyclists have no clear role in traffic. This ambiguity enables cyclists to act as a vehicle in one moment and as a pedestrian in the next. Nevertheless, the lack of a clear role also adds frustration and confusion among cyclists and other road users:

"I think it prevents many from cycling. They often experience unpleasant situations. (...) When I cycle in the city and I'm in a hurry, I use the sidewalk, cross at pedestrian crossings, and I cycle on the road, whatever seems best in the moment. You always have to solve problems where there are no good solutions. I understand that this is frustrating for a lot of road users. I really do. It's the infrastructure that's lacking". (NO15)

Cycling innovation has previously revolved around creating more lightweight and racing bicycles, tailored to sports activity rather than everyday transport. Norwegian cyclists described

the past cycling culture in Norway as egocentric and aggressive. With increasing shares of cyclists and added diversity with e-bikes, cargo, and utility bikes, the interviewees said that the culture is changing, and that cycling is becoming increasingly available to the population. Particularly in urban areas, government officials and interest groups are working towards cycling as a viable mode of transport, focusing on more consistently designed cycling infrastructure and increasing access to cycling through shared city bikes- and bicycle subscription services.

“One thing that happened is that there are many more cargo bikes. (...) It’s more like the Dutch, shall we say, or the Danes. The proportion of racing cyclists is declining. Because they will now ride on e-bikes and cargo bikes. There are people with a basket on the handlebars, sitting upright and so on. I think that makes the traffic culture among cyclists a little more relaxed”. (NO12)

The Netherlands

The cyclists interviewed in the Netherlands saw cycling as a way of life and a big part of Dutch culture. Cycling is a natural part of childhood – bicycles and cyclists are everywhere, and cycling is the number one transport mode.

“Everybody cycles. Almost everybody has at least one bike, and a lot of people cycle at least once a week, I would say, but I also know [for] a lot of people, especially living in an urban area, it’s the quickest way to get from point A to point B by cycling”. (NL16)

“I would describe it more like a way of life, like in the Netherlands, like you get your keys, your phone, your credit card and your bike and you go. It’s a must-have”. (NL24)

Several participants pointed out that the Netherlands has been working towards a cycling culture since the 1970s. This has resulted in a network of continuous cycling infrastructure, including consistently designed cycling roads, traffic signs and signals for cyclists.

“I think it started in the 1970. Because a lot of accidents with cars were happening, like a lot of young children, also died of car accidents. And then there was this movement of people who really didn’t like cars because both those accidents and also the environment and then the government started to invest in the cycling structure and infrastructure, and it really paid off”. (NL22)

Combined with naturally flat terrain, cyclists can cycle for hours without stopping. Moreover, cyclists often have priority in urban areas, ensuring cycling as the fastest transport mode for short distances.

The interviewees portrayed Dutch drivers as patient and considerate. On the downside, cyclists who are used to be given priority may exhibit risky behaviour such as disrespecting traffic lights or misjudging a situation, leading to near miss encounters with other road users:

“I guess because it’s so normal to go by bike, a lot of people and also myself, I guess we think we are the bosses on the road. And sometimes people don’t wait or ignore the red lights or quickly go before a bus or a car”. (NL18)

Sports and recreational cyclists tend to invest in more expensive bicycles tailored to their interests. The average Dutch bike, however, was portrayed by the interviewees as simple and cheap.

2.3.5 Infrastructure

Infrastructure as a theme describes how infrastructure affects cycling, which challenges cyclists experience related to infrastructure, and how infrastructure might look like in the future of automation.

Separated infrastructure was one of the most reoccurring topics during the interviews. Cyclists prefer using bicycle roads and lanes over sharing the road with other road users:

“A dedicated space for bikes is paramount in my opinion. This makes me feel absolutely safe”. (NL21)

“It feels much safer with separate lanes. You are the losing party. You are a vulnerable road user, and if you are out on the road when something happens, you are essentially doomed”. (NO1)

However, a few interviewees noted that separation might lead to a higher speed of road users than in shared traffic; shared spaces are more chaotic and may slow down traffic, potentially increasing safety but reducing comfort in the process. Although preferred by most of the interviewees, infrastructure does not have to be completely separated; many are comfortable with a bicycle lane if the lane has sufficient width for overtaking or is separated from the road by a low curb or slight elevation.

“There must be wider cycle paths. And I appreciate bike paths that are much more separated from the road than they are today. It should not just be a red field with a white marking on the side [often used to indicate cycle lanes on roads in Norway], but that they are placed on a separate road”. (NO2)

“It would have been very nice with bicycle lanes and bicycle lanes elevated from car traffic on some of the roads (...). It’s almost like a sidewalk [for cyclists], I think. And then there is often a small, sloped curb towards the pedestrians so there is a clear separation”. (NO9)

Cyclists experience various challenges related to infrastructure. Particularly among the Norwegian cyclists, inconsistently or poorly designed cycling infrastructure was reported as challenging: Bicycle lanes suddenly ending at an intersection, narrow lanes, or lack of cycling infrastructure altogether, forcing the cyclists to choose between sharing the road drivers or the sidewalk with pedestrians.

“In Norway, it’s like “here is a bike lane, and here comes the intersection”. Snap, the bike lane is gone. You just have to figure it out yourself. Suddenly, the bike lane appears on the other side. It’s like “what happened in the middle there”? You are at the mercy of drivers”. (NO7)

Crossings, roundabouts, and intersections can be a challenge for cyclists in both countries, often due to low visibility and heavy traffic with road users coming from several directions. The cyclists tended to find signalised intersections less challenging than un-signalised intersections because traffic lights provide clear information.

“I try to position myself, so I can see the traffic lights and that I’m able to see ahead in the intersection, where the bike lane often disappears. I make sure to position myself behind the first car, so that I can see if the driver is using the turn signal to go right when I am going straight”. (NO10)

In a future where vehicles have a high degree of automation, most of the interviewed cyclists were sceptical about sharing the road and call for fully separated infrastructure to avoid interaction.

“Cyclists (...) are self-regulating and perhaps the closest humans can get to a flock of birds. It would require a lot before automated vehicles to function in coexistence with us. I

believe if we go for automated vehicles and this is the future of our transport system, it will require separate pathways and a large degree of separation". (NO4)

It was acknowledged that mixed traffic may be unavoidable and complete separation of cyclists and automated vehicles may not be realistic:

"In general, it's safe to assume that (...) as a cyclist you would [still] have places where you would have to interact with automated vehicles at some point. It's impossible to completely avoid that unless you just have bridges and tunnels everywhere. That's not realistic". (NL17)

However, a few of the interviewees were optimistic about sharing the road with automated vehicles. They argued that complete separation may delay the trust process between cyclists and automated vehicles. A few of them also pointed out that automated vehicles' implementation in the Netherlands might be more straightforward than in Norway, as there is already a larger amount of separated infrastructure available in the Netherlands.

Some of the interviewed cyclists mentioned smart infrastructure's potential, for instance, to inform cyclists about weather conditions, street pollution or for providing route advice. Smart infrastructure could also detect cyclists and inform automated vehicles about the cyclists' position. Other features suggested during the interviews were the ability to detect cyclists and change traffic lights to accommodate them, either by changing the light or by showing a countdown to the next green light on a sign or as a feature of an on-bike HMI.

2.3.6 Legislation

This theme describes how legislation is intertwined with cycling, the challenges cyclists encounter in traffic, and the implications legislation could have for cycling in a future of automation.

Several of the cyclists interviewed said that even though they strive to follow the traffic laws, rules are broken regularly. Running red lights was described as the most common rule to break. The chances of being caught are slim, as enforcement of traffic laws for cyclists was reported as rare. The fines are also expectedly lower than for drivers:

"I think that the fines are higher when driving my car through a red light, but also the police does not have enough people to check up on the cyclists who are going through the red lights". (NL16)

Some of the interviewees argued that the legislative focus should be on regulating the road user with the most significant damage potential, i.e., motorised vehicles. They claimed that investing in bicycling infrastructure would set precedence, and by prioritising vulnerable road users in legislation and law enforcement, cyclists would be more welcome in traffic.

"[We need] more bike paths, more bike traffic lights, more of specific things for cyclists to make you feel like you belong in traffic. Now we are sort of stuck between a rock and a hard place. Drivers do not want us, and pedestrians do not want us". (NO7)

In urban areas where vulnerable road users share the road with motorised vehicles, the interviewees suggested speed limits to be lowered, and priority given to cyclists at intersections. Moreover, regulating the speed would ensure road users using the same lane or road are on equal terms.

Legislation promoting standardisation among automated vehicle manufacturers was mentioned as important by several of the interviewees. In particular, standardisation is essential in designing intent indicators such as eHMIs and potential on-bike HMIs to correspond with colours, symbols, and signs road users are already familiar with in the current traffic environment. International agreements on standardisation of such indicators could cause less confusion and increase safety in a future where road users, to a greater extent, might depend on information from eHMIs, HMIs, and smart infrastructure.

"I think the issue here is just standardisation. Everyone can come up with like two hundred different concepts, but which are you going to choose". (NL23)

"If different manufacturers use different signals, or there is signal type that is otherwise used in traffic. Then it can get a little messy". (NO8)

With the trend of increasing connectivity in today's society, some of the interviewees had privacy concerns about sharing location data with connected automated vehicles, infrastructure, and other vulnerable road users. Any device used to detect or share data from cyclists should comply with privacy regulations.

"This would also trigger a big discussion about personal data, of course. I don't want people to know where I'm going, and this kind of stuff. So, I'm also not very happy or I'm reluctant, you know, sharing all of my personal thought just like that (...). But I would expect that there would be some rules about that and a certain amount of anonymity. In that case, I would say that it has quite a lot of positives". (NL21)

The interviewees suggested that data sharing should be anonymised, and that cyclists should only be detectable within a given radius. On the other hand, a few participants pointed out that most of us already are providing sensitive data to various tech companies and governments from devices such as wearables and smartphones. Assumingly, data sharing might be inevitable, and opting out may no longer be possible:

"How things are going at the moment, we are kind of doomed on privacy". (NL24)

2.3.7 Automated vehicles

The theme of Automated vehicles consists of cyclists' expectations and automated vehicle capabilities, the challenges they will encounter in a future of automated vehicles, as well as what needs cyclists have to safely interact in traffic with automated vehicles.

Some of the interviewees argued the transition period from semi-automated vehicles to fully automated vehicles will be longer than expected. Although they recognised that disruptive technologies force people to reconsider their current systems, some were sceptical if fully automated vehicles are the future. They argued that a change of focus to active transport like walking and cycling would be more desirable:

"If the car industry and tech bros define the mobility of the future, then you get something that is not egalitarian and that solves a very minority of its problems at the expense of everyone else. Because it taps funding from public transport and facilitation of vulnerable road users. (...) I do not think it is impossible to implement. But I think implementation comes at a social cost that is too high". (NO4)

However, in a future where motorised vehicles are fully automated, automated vehicles are expected to react faster and more rational, make fewer mistakes and be more predictable in traffic compared to humans. Automated vehicles would not overtake as often and be consistent in the use of turn signals, resulting in smoother interactions.

“You do not quite know what human drivers will do. If a car is automated, you kind of know how it will drive. Maybe it is better at using intent indicators. It would be easier to deal with”. (NO8)

“I think the technology of the future will be sufficient, that as a cyclist you do not have to think so much about it. The cars are good at detecting cyclists. In theory, there should not be any dangerous situations. It is possible that errors occur. But I think that it will be safer than having a [human] driver or steering wheel”. (NO5)

Some of the cyclists noted that they expect the ambiguity of today’s traffic to continue in the future. Automated vehicle algorithms reflect human input and may be shaped by the attitudes and prejudices of programmers. If automated vehicles are programmed to be normative, this will imply a change in traffic interaction as current cycling interaction follows informal rules and non-verbal cues. The interviewees claimed automated vehicles should mimic human behaviour, replicate subtle cues, and adapt to sudden movements.

The consensus among the participants was that it is the automated vehicles’ responsibility to ensure other road users’ safety. It was assumed that automated vehicle programming would be considerate and prioritise the safety of vulnerable road users. Some of the interviewees did, however, voice concern about safety during the transition period and fear there will be a decrease in car accidents, but an increase among vehicles and cyclists. One interviewee noted that automation adds a layer of uncertainty in traffic: Most humans have an inherent motivation not to hurt themselves and others, while automation does not. This unknown factor may add to the complexity of traffic interaction.

“As a vulnerable road user in traffic, automating other road users just adds more uncertainty. People who drive a car mostly have a desire to make traffic flow smoothly and not harm other people. That’s very straightforward and easy to relate to”. (NO10)

On the other hand, automated vehicles programmed to be conservative might lead to risk-taking and frustration, and traffic safety might be affected by automated vehicles’ exploitation:

“I can imagine some people exploiting the automated vehicle, knowing that it sees me and it’s going to stop for me, so I’m just going to keep on biking, I don’t care”. (NL17)

“If it continues with that level of conservative behaviour of safety [as today], that could lead to frustration of other road users and lead to risk-taking. In my view, I think it should behave as realistic as possible (...), not too aggressive and not too cautious”. (NL25)

In the end, there might be a trade-off between prioritising the safety of vulnerable road users and traffic efficiency:

“It boils down to the debate of the car being programmed to save vulnerable road users at all costs, whether you can really trust that. (...) If the car is programmed to be completely safe, then it wouldn’t move at all”. (NL23)

The cyclists did have very limited, if any, experience cycling with automated vehicles at the time of the interviews. There was an expectation that automated vehicles would be connected and share information about the environment with other road users and infrastructure. The interviewees assumed that future automated vehicles would be capable of receiving and transmitting information about the position, speed, and trajectory of other road users such as cyclists. Some cyclists suggested that the automated vehicle could adapt its driving style to the road user group, for instance, by driving slower or more conservatively in areas with cycling children.

The cyclists expressed scepticism about whether they would be comfortable or trust automated vehicles in mixed traffic. They were concerned about how automated vehicles would interpret rule-breaking behaviour and understand informal rules. A few cyclists questioned if automated vehicle intelligence will be advanced enough to adapt to cyclists' versatility and unpredictability and whether unexpected behaviour such as frequent stopping by conservative automated vehicles would affect safety and traffic flow.

Some cyclists prefer more distance between cyclists and automated vehicles than with human drivers. Being informed about automated vehicles' capabilities and limitations or receive training with automated vehicles might substitute this need, some cyclists suggested. The interviewees assumed that cycling with automated vehicles will be safer and more pleasant than today once the technology is sufficient, and trust is established.

One of the most reoccurring topics among the cyclists interviewed was the need to be seen in traffic, and acknowledgement that the automated vehicle detects the cyclist. With fully automated vehicles, the factor of eye contact between the driver and the cyclist will be lacking. Moreover, the eye contact gained with the passenger in the vehicle might add to more confusion. The interviewees preferred that the automated vehicle signals both detection and vehicle intent explicitly. While some interviewees said that the turn indicators of today's vehicles are sufficient, the majority called for additional on-vehicle eHMIs for automated vehicles:

"The major problem that I face, and my fellow cyclists and pedestrians face, is that you don't know what the car is going to do. (...) I think there needs to be some sort of tangible information that is conveyed to the bicyclist that lets him know if he should go or stop, whatever it is. But then it needs to be a very tangible thing from the end of the car, not from the end of the bicycle". (NL23)

"It would be nice to see that the car has identified me and is going to stop (...) a light or the same way to have a hand interaction with the driver to say: thanks". (NL24)

The interviewees portrayed on-vehicle eHMIs as a useful way for automated vehicles to display info in the initial stages of deployment. eHMIs offer an objective indicator of intention and are assumed to increase traffic flow. Described as particularly applicable in zones with much human-human interaction, the main challenge of eHMIs arises when conveying information to a group of road users. It might be preferred in such cases that a general message, such as vehicle status, is displayed.

"If automated vehicles also have displays that give instructions to the cyclists; that you may go first. I think then it becomes so important to know who that information is directed towards. If there's two cyclists, or three cyclists, not from one direction, but in opposing directions, but they see the same automated vehicle, how does that automated vehicle then customise personalised information for each of these cyclists that it's interacting with?" (NL17)

A few cyclists pointed out that automated vehicles should not be explicitly marked as fully automated, as this might make other road users try to exploit it.

Regarding design strategies for on-vehicle HMIs, the interviewees' preferences varied. Some would prefer the automated vehicle indicating intention or a message on display, others by a light strip or a light, with different colours indicating detection of the cyclist or the automated vehicle's intention. Some said that they prefer an eHMI as audio over a display, but the consensus was that audio might be hard to detect or cause distraction in traffic.

"It could be something as simple as a sound, auditory display, or maybe some displays, light flashes, indicators. There's a plenty of options". (NL23)

2.3.8 Human-machine interface

The dimension of HMI encompasses cyclists' perceptions and attitudes towards on-bike HMIs, along with HMI design strategies and desired HMI functionality. One of the most common sub-themes of HMI is the potential of an HMI to increase cyclist safety. A device could add more predictability, reduce human error, help automated vehicles understand cyclists' intention, and make the interaction more efficient and comfortable. Some cyclists did not see many disadvantages with a cyclist HMI and believed it might reduce mental workload, especially in urban areas where busy traffic requires constant attention.

"I think it helps in reducing human error. Sometimes I may see something from the corner of my eye. In the junction I cross, it doesn't only have an intersection this way, but also it cuts from the left, sometimes I miss the guy cutting from the left. So, having that information would be helpful to increase spatial awareness". (NL23)

Connectivity (bicycle-to-vehicle communication) was also a reoccurring topic. Being mutually aware of other road users' positions and intentions could benefit cyclists' situational awareness and reduce uncertainty in the traffic environment.

"I think from a safety point view, communication would be nice. (...) I think the advantage of communication is that the car can detect all the time the changes in the speed profile and acceleration, so it can detect easier if there is a potential for an accident". (NL25)

Among the interviewees, the consensus was that a device should not be mandatory. Some of the cyclists claimed a device would be of no advantage to the cyclist and only benefit the automated vehicle.

"The challenge is that [the HMI] will be one more thing to deal with, in a situation where you are already the vulnerable road user and the losing part. [It] should not exist". (NO10)

"I would be really annoyed if I had to buy that so other people can drive automated vehicles". (NL20)

If a device is needed to communicate safely in traffic, some interviewees claimed that it would become a barrier to the convenience of cycling: Devices break and need maintenance, or the cyclist might forget the device at home. There is also the matter of cost, which would affect the accessibility for all sorts of cyclists.

"I believe that having as little electronics on the bike as possible and make [bikes] easily accessible to the vast majority is better. The responsibility should be placed on the scary, heavy machines and those who manufacture these, not with the vulnerable road user". (NO15)

The consensus was that the responsibility of safety lies with automated vehicles: automated vehicle technology should be sufficiently able to detect cyclists before automated vehicles are released in traffic. If automated vehicles start relying on data collected from vulnerable road users' devices, some of the interviewees feared that this might decrease safety, as the automated vehicle could misinterpret the absence of data from non-users.

"It's problematic to plan for such a system (...). Because then, in a way, there is an expectation that the vast majority must have it, or that everyone has it". (NO12)

Several of the cyclists interviewed stressed that the simplicity of the bicycle is its advantage, and that they do not want an additional device to be safer in traffic:

"The bike is so technologically free from all gadgets; that's what gives it an advantage. Anything that has new regulations about how a cyclist should behave, or have equipment, I am definitely opposed to. This will make it more difficult for cyclists. (...) It will make it

easier and better for the automated vehicle, and that's the wrong way to look at it. Turn it around. It is not the cyclists or the pedestrians who should have to adapt to the automated vehicles". (NO11)

While a device could increase situational awareness, an HMI might also be distracting and make the cyclists unfocused. Additional information from a device could increase complexity in traffic. There is also the matter of trust. Placing too much trust in a device could cause less awareness.

"You start relying too much on technology and also that you tend to become lazy, in the way of sensing things. (...) Adding more of that technology can also give you a false safety, which causes you to do other things than being alert". (NL29)

"So unfocused that you (...) become a traffic hazard. You get so preoccupied with signals from the computer, vibration, light, everything". (NO1)

The most common HMI design strategy among the interviewed cyclists was an on-bike device. A detachable device mounted on the handlebars could be utilised across bicycles. On the other hand, an integrated, less conspicuous device or sensor system might deter theft. It could also have the potential to be used to track the bicycle if it gets stolen. Whether the device should be integrated or detachable depends on the functionality. Some cyclists noted that they do not like carrying extra accessories and that the device might be easily misplaced if it is detachable. Several of the cyclists envisioned an HMI as a wearable, by using an application on their smartphone or smartwatch, or as AR-glasses.

Design strategies identified in the analysis were divided into four main categories: audio, display, haptics, and lights. Most importantly, an HMI should be designed user-friendly and intuitive. Weather resistance and robustness are also key features. A device using audio was not preferred by most cyclists. The device could, however, have voice recognition and the possibility of voice commands.

The most commonly mentioned design strategy was a display or a screen. The display must be visible in sunlight and display vital information. The visual information should be simplistic, easy to read, and use colours and icons that road users are already familiar with.

"The visual part is very important. (...) I wouldn't put too much information on the screen, like not cluttered information, not things that are difficult to read because you're on the bike and especially if you drive with 20 kilometres per hour, you need to pay attention to the street". (NL21)

Changing display modes according to the purpose of the trip would also be desirable for some cyclists. For instance, the cyclist may require different cycling information in urban areas compared to rural areas.

A display could be combined with haptic feedback from the handlebars and seat. However, some cyclists prefer no display; instead, they opt for haptic feedback combined with a light or an LED light strip providing additional information. Haptic feedback would ensure full visual attention on the road while cycling. One interviewee noted that there might be too much vibration from the road for haptics to be feasible. A simplistic type of HMI envisioned by the interviewees was lights on the handlebars signalling detection by the automated vehicle. Lights could also be used to signal the intention of the cyclist, substituting hand gestures.

The cyclists envisioned a broad spectrum of HMI functionality. The main objective of an on-bike HMI is to enhance human communication. If connected to automated vehicles, the device

becomes the agent representing the cyclist. However, the device should provide additional information, not make decisions:

"It could just be for information acquisition, but not the deciding factor in decision making for the automated vehicle and the cyclist. Just get more information, that helps with reducing the uncertainty of the driving environment". (NL17)

It would be an advantage if both cyclists and pedestrians could utilise the device. The most common display type of functionality envisioned was a radar-like interface showing the location, trajectory, or intent of other road users such as automated vehicles.

"It's almost like a radar, I think. [The other road users] see which direction I'm riding, and the instrument shows those who are crossing in my direction – they could be visually presented on the screen. An arrow showing direction". (NO3)

A similar approach could be used for an AR glasses interface. The device could notify the cyclist if another road user is close to crossing the cyclist's trajectory. To not interfere with the cycling experience, the cyclists preferred to be notified by the device on rare occasions:

"Ideally, it will be nice to combine augmented reality. So, I can wear some smart glasses and I don't have to look on a screen to get information from my bike if needed. I just enjoy the nature and I look at the road (...). But then I can see my own speed, or I am signalled to be careful if a car is coming". (NL24)

A feature often desired by cyclists was also whether a car is approaching from behind or emerging from side/entryways with low visibility.

The interviewees envisioned the device's key functionality as connectivity: The device is most likely connected to automated vehicles and infrastructure. The device could provide each bicycle with a unique ID and broadcast info like the cyclist's speed and position to automated vehicles and infrastructure. With a display type of interface, the device could exchange this information between the bike and the automated vehicle. With connectivity, the device could show the remaining time until a green light ahead or help the cyclist arrive at an intersection at a green light by adjusting the bicycle's speed or changing the traffic light itself.

An on-bike HMI could also function as a cycling computer showing speed, elevation, and heart rate of the cyclist. As an integrated navigation system, the device could advise travel routes according to characteristics, such as the most scenic, fastest, or less congested cycling route.

The device has the potential to collect user data from bicycles. The cyclist could receive analytics and advice on their cycling and traffic behaviour based on smartness, travel, and personal historical data. Data collected could also be used in research and development, create maps of cities, and provide user data on other road users. The privacy issues related to connectivity and exchanging information in the theme Legislation overlaps with the theme of HMI.

2.4 Discussion

The thematic analysis resulted in seven themes constituting cyclists' experiences and challenges in today's traffic and how these might change in the future with automated vehicles: Interaction, Bicycles, Culture, Infrastructure, Legislation, automated vehicles, and HMIs. The following sections discuss the implications of the findings for cycling today and future interactions of cyclists with automated vehicles, followed by a discussion on whether on-bike HMIs and

connectivity are necessary or useful, or if a better solution would be to focus on detection by automated vehicles and infrastructure rather than connected bicycles.

2.4.1 Cycling today

From the analysis, experiences with and perceptions of cycling are described across several themes, mainly Interaction, Bicycles, Culture, Infrastructure, and Legislation. As a mode of transport, the theme of Bicycles shows how bicycles are versatile and cover most of the everyday needs for transport. While there are varied reasons why cyclists choose to cycle, some of our interviewees depicted cycling as *good* in every conceivable way. Compared to personal motorised vehicles, cycling is assumed to be better for the environment and beneficial to public health, contributing to a more sustainable transport system. These viewpoints have been addressed in previous research as well, emphasising the environmental effects (McDonald et al., 2015) and health benefits (Boschetti et al., 2014; Pucher & Dijkstra, 2003; Raser et al., 2018) of active transport and the fact that cycling is environmentally, socially and economically sustainable (Pucher & Buehler, 2017).

The theme Interaction describes cyclists' perceptions of cycling and how cyclist interaction is guided by eye contact, hand gestures, and motion cues corresponding to formal and informal rules. These aspects of interaction are reflected in previous research (Bjørnskau, 2017; Lundgren et al., 2017; Vissers et al., 2017; Walker, 2005).

More cyclists interviewed in the Netherlands indicated that they generally feel safe while cycling than participants from Norway. The analysis implies that the disparities in perceived safety might be related to differences in the themes Culture and Infrastructure between the two countries. Norwegian cyclists reported that they must wear protective gear and equipment to cycle in traffic. The same was not the case among the Dutch interviewees; a few noted that helmet usage is not encouraged in the Netherlands. In recent years, though, the sport-centred Norwegian cycling culture has been portrayed as changing to resemble the diversity of Dutch cycling culture, fuelled by a political climate promoting active transport, increased shares of cyclists, and bicycle infrastructure.

The need for designated cycling infrastructure was a prevalent sub-theme in the analysis. Bicycle infrastructure in the two countries still differs significantly. Dutch cities have invested heavily in cycling facilities since the 1970s (Pucher & Dijkstra, 2000). These investments have ensured a more consistently designed network of cycling infrastructure separating cyclists from motorised traffic. This is not the case in Norway. Note that inconsistently designed cycling infrastructure where bike lanes suddenly end or impede cyclists' traffic flow is not strictly a Norwegian phenomenon. A British interview study on cycling expressed similar findings (Christmas et al., 2010).

As suggested by our interview participants, investing in cycling infrastructure could set precedence and show that cyclists belong in traffic. Several of the interviewed Norwegian cyclists noted that they do not need fully separated cycling infrastructure to feel safe in today's traffic – they are satisfied with an integrated bicycle lane, preferably separated by slight elevation and sufficient width for takeovers. Previous literature is inconclusive whether completely separated cycling infrastructure is safer than bicycle lanes (Crompton et al., 2015; Melhuus et al., 2015). Schepers et al. (2011) indicated that bicycle lanes have 54% more cycling accidents in intersections than bicycle paths. Nevertheless, the effect of bicycle lanes versus

mixed traffic on accidents is evident; a meta-analysis of the effect of bicycle lanes on cycling accidents showed that there is a decrease of about 45% in accidents with a separate lane compared to cycling in mixed traffic (Høye et al., 2015). These findings give some validity to the viewpoints of the interviewees in our study: Completely separated infrastructure increases safety and could explain why the interviewees in the Netherlands generally felt safer than interviewees in Norway. In turn, bicycles lanes are safer than cycling in mixed traffic and, if invested in, would probably increase the perceived safety of Norwegian cyclists as well.

The differences in infrastructure and cycling culture in the Netherlands and Norway might affect how cyclists perceive interaction with other road users. While most of our interviewees reported interaction with others as smooth, more cyclists in Norway mentioned drivers as problematic compared to the Dutch participants: They reported that some drivers seem annoyed, drive aggressively, and do not appreciate sharing the road with cyclists. As Norwegian cyclists often do not have a clear place or role in traffic, they can make split-second decisions according to the situation, including cycling on sidewalks and pedestrian crossings. This unpredictability can be one of the main contributors to conflicts between cyclists and motorised vehicles (Bjørnskau et al., 2012). However, in another Norwegian study, drivers reported that the sudden role changes were not a significant issue, but rather cyclists often running red lights (Fyhri et al., 2012).

2.4.2 Future interaction: Expectations and cyclist needs

The theme of Infrastructure shows that our interviewees had a clear preference for completely segregated infrastructure in future traffic with automated vehicles. Segregation of cyclists and automated vehicles has been noted as ideal in other interview studies (Botello et al., 2019). However, our interviewees did argue that their scepticism towards sharing facilities with automated vehicles might change as they become more experienced with automated vehicles. This finding is in line with Blau et al. (2018), where cyclists were more likely to prefer protected facilities over sharing the road with automated vehicles.

The theme of automated vehicles depicts how our cyclists expect future automated vehicles to embody equal or better capabilities than human drivers. Automated vehicles are assumed to be capable of replicating and understanding the implicit, subtle cues of human road user interaction. Human motorists tend to deviate from traffic rules by yielding to cyclists regardless of priority (Bjørnskau, 2017; Van Haperen et al., 2018), which indicates that automated vehicles following familiar, non-normative interaction patterns might be necessary when interacting with cyclists. The challenge, however, is that the informal communication cues of cyclists can be subtle and unambiguous and might be difficult to anticipate or decipher by automated vehicles (Kooij et al., 2019; Vissers et al., 2017).

In the theme of Interaction, the cyclists described eye contact as a part of how cyclists negotiate in today's traffic. Some interviewees expressed concern that eye contact would be lacking when there is no longer a human driver present in the automated vehicles. As a behavioural cue, eye contact of the driver may encourage cyclists to continue pedalling (Bazilinskyy et al., 2021). However, some of the interviewees claimed that they do not use eye contact at all but instead rely on vehicles' motion cues. Risto et al. (2017) identified movement gestures as the vehicles' primary mode of expressing intent. Indeed, in future automated vehicle-cyclist interaction, interpreting automated vehicles' motion cues and movement patterns might suffice (Habibovic et al., 2016; Lee et al., 2020; Moore et al., 2019; Sripada et al., 2021).

Our analysis indicated that cyclists prefer automated vehicles to communicate recognition explicitly. Similar findings are shown in Merat et al. (2018), where cyclists and pedestrians reported that they would prefer to receive communication about automated vehicles' status and behaviour, particularly about detecting vulnerable road users. Proposed solutions by the interviewees in the present study included eHMIs or vehicle-to-bicycle technology, which is in line with the current development of eHMIs to enhance road user interaction (De Clercq et al., 2019; Habibovic et al., 2018; Lundgren et al., 2017; Mahadevan et al., 2018; Merat et al., 2018; Rouchitsas & Alm, 2019). However, another issue brought up in a few of our interviews was how eHMIs would communicate recognition when there is more than one recipient. A solution could be an eHMI conveying the automated vehicles' current state rather than instructing vulnerable road users what to do (Tabone et al., 2021).

The dynamic and versatile nature of cycling points toward a need for new types of eHMIs, for example, eHMIs that can be perceived omnidirectionally, as suggested by Eisma et al. (2019), or directional eHMIs that can address specific road users, as suggested by Dietrich et al. (2018).

2.4.3 On-bike HMIs: Potential and design strategies

Electrification was one of the most recurring bicycle features mentioned in the interviews. While our interviewees said they enjoy the physical activity involved in cycling, they argued that the future of cycling is likely to be electric. Market trends confirm this notion: E-bike use is on the rise, and shares of e-bikes in the Netherlands are expected to increase from 19% to 37% by 2025 (KiM, 2020).

Previous literature suggests that on-bike HMIs can accommodate cyclists' needs for detection and communicate that the automated vehicle has recognised the cyclist (Schieben et al., 2019; Tabone et al., 2021). The theme of HMI describes how the interviewees proposed that an on-bike device might increase safety. An ideal device would result in more predictable interactions, reduce human error, and help automated vehicles understand cyclists' intentions. Connectivity would be a key functionality of on-bike HMIs—being mutually aware of other road users' positions and intentions could benefit the cyclists' situation awareness and reduce uncertainty in the traffic environment.

Some of the cyclists we interviewed were interested in using an on-bike HMI to communicate with automated vehicles if the utility value is beyond guaranteeing their safety. For instance, the device could function as a navigation system or a cyclo-computer. As noted by several of our interviewees, a detachable HMI might be more feasible than a device integrated into the frame or handlebars. Still, with cyclist accessories such as helmets, bags, and e-bike batteries, a few interviewees noted that carrying extra devices is a hassle to be avoided. The utility value of bicycles, costs, and potential theft imply that the most apparent solution as to HMI design strategies is to use devices already available to cyclists, such as their smartphones, cyclo-computers, or other wearables. A wearable HMI design fits well with previous research on vulnerable road user connectivity, where most solutions involve using smartphones or wearables (Dasanayaka et al., 2020; Scholliers et al., 2017).

Positive aspects aside, the majority of the cyclists in our interview study were hesitant about on-bike HMIs. A major dilemma is that a device would have to be mandatory and universal as the absence of data will not inform the automated vehicle of vulnerable road users' presence, potentially putting these road users in increased danger. Most of the interviewed cyclists, however, said that a device should *not* be mandatory for communication with automated

vehicles. Our interviewees disapproved of a device merely connecting automated vehicles and infrastructure by broadcasting the cyclist's location or ID tag. They argued that there should not be a need for on-bike HMI and connectivity between vulnerable road users and automated vehicles with sufficient development of automated vehicle technology before its employment on a large scale in traffic.

Another concern voiced in the interviews was that an on-bike HMI requirement might become a barrier to cycling. The interviewees reasoned that an on-bike device might reduce the accessibility of cycling, as cycling is traditionally a cheap and simple mode of transport. One could argue that simplicity is not a universal desire among cyclists: The average price of a Dutch bicycle is among the highest in Europe⁴. Moreover, 60% of the interviewees said they own more than one bicycle and choose their type of bicycle according to the purpose of the trip. Even so, additional bicycle costs are undesired, as theft is common. On average, half a million Dutch report bicycle theft worth €600 million yearly (Kuppens et al., 2020).

In summary, the consensus among our participants was that the primary responsibility of safety lies with the automated vehicle. Being dependent on a device that might malfunction, be misplaced or stolen was not desired. There were also concerns about how automated vehicles interpret the absence of data from non-users and about road user privacy. Similar arguments were made by academic, industry, and government experts in an interview study on automated vehicles and planning for active transport, where they expressed concern about a vulnerable road user device requirement for recognition by automated vehicles: While a device might increase safety, a requirement might not be egalitarian and could pose privacy issues (Botello et al., 2019).

The ethical aspect of safety and responsibility of automated vehicles versus vulnerable road users is reflected in previous literature proposing connectivity among all road users (OECD/ITF, 2019; Owens et al., 2018). Worst case scenario, we could end up with a second-class citizen society, where only people who can afford these devices can safely leave their homes in urban areas with automated vehicles. This issue draws parallels to the ethical issues debated in the light of the COVID-19 pandemic, i.e., whether the population will be needing a vaccine pass to access certain services or be allowed to travel freely (Voo et al., 2021).

Even though our interview participants were hesitant about on-bike HMIs to enhance communication with automated vehicles, this does not necessarily mean that on-bike HMIs should be rejected immediately. The public does not always welcome traffic safety measures. For instance, most drivers recognised that vehicle safety belts effectively reduce or prevent driver injuries, but seat belt usage was not prevalent when first implemented. Similarly, while the Dutch safety belt mandate increased seat belt usage from 20% to 50% in 1975 (Hagenzieker, 1992), it took another 35 years before seat belt use became nearly universal (SWOV, 2012).

Acceptance of new technology to enhance road user safety might increase with more experience and knowledge (Nordhoff et al., 2020), and this might also be the case with on-bike HMIs. With e-bike use on the rise (KiM, 2020) and increased connectivity and smart travel in the future transport system (Behrendt, 2019), it is plausible that at least some future bikes will be connected via (low-cost) Wi-Fi. By placing the responsibility of safety on the automated vehicles, cycling connectivity may become an option rather than a requirement. Various simple,

⁴ According to [Statista](#) (2020)

inexpensive, and optional on-bike HMIs can be envisioned as a starting point, such as a vibrating handlebar or integration with existing cyclo-computers.

2.4.4 Future studies

A possible limitation of the present study, originating in the qualitative nature of the research, is a lack of generalisability. Whether the viewpoints depicted in our study can be generalised to the general public should be explored on a larger scale in future studies, along with potential other solutions than on-bike HMIs for enhancing automated vehicle-cyclist interaction.

Future studies should further investigate to what extent additional, explicit behavioural cues of automated vehicles, such as eHMIs, are necessary to ensure safe and desired interaction between cyclists and automated vehicles. For instance, exploring whether on-bike HMIs are necessary or useful in a naturalistic setting might bring insight into their feasibility as a traffic safety measure. Moreover, exploring other solutions that do not require connected cyclists via additional devices is essential, such as improved detection sensors in automated vehicles, on-vehicle eHMIs, and smart infrastructure systems.

2.5 Conclusion

Our analysis showed that cyclists' primary need in automated vehicle-cyclist interaction is sufficient detection by automated vehicles. Moreover, cyclists prefer that the automated vehicles communicate recognition explicitly. The findings strengthen the notion that on-bike HMIs are potential solutions for enhancing interaction between cyclists and automated vehicles. Previous studies on enhancing automated vehicle-cyclist interaction tend to focus on the technical feasibility of such devices and their effect on safety, without considering the actual end-users. Our analysis yielded that the interviewees particularly favoured HMI functionality, informing them about other road users' location, and road user connectivity.

The analysis also uncovered that cyclists are hesitant about on-bike HMIs, mainly in terms of unclear utility value and the ethical aspect of imposing the responsibility of safety on the more vulnerable road user. Moreover, a device requirement might become a barrier to cycling, as increased costs are undesired, and theft is common. Even if we are utilising ubiquitous devices in the future, we should be careful about adding restrictions or requirements that may discourage the population from choosing active transport, as cycling and walking is beneficial to public health and the environment. Future studies should investigate user acceptance of on-bike HMIs among vulnerable road users on a larger scale to test the findings' generalisability and explore other, perhaps more viable, solutions for enhancing automated vehicle-cyclist interaction.

Chapter 3

Support systems for cyclists in automated traffic: A review and future outlook

Interaction with vulnerable road users in complex urban traffic environments poses a significant challenge for automated vehicles. Solutions to facilitate safe and acceptable interactions in future automated traffic include equipping automated vehicles and vulnerable road users, such as cyclists, with awareness or notification systems, as well as connecting road users to a network of motorised vehicles and infrastructure. This chapter provides a synthesis of the current literature on communication technologies, systems, and devices available to cyclists, including technologies present in the environment and on motorised interaction partners such as vehicles, and discusses the outlook for technology-driven solutions in future automated traffic. The objective is to identify, classify, and count the technologies, systems, and devices, extrapolate the potential of these systems to aid cyclists in traffic with automated vehicles, and stimulate discourse on the implications of connected vulnerable road users. We analysed and coded 92 support systems using a taxonomy of 13 variables based on the physical, communicational, and functional attributes of the systems. The discussion frames these systems into four categories: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems, and highlights the implications of the visual, auditory, motion-based, and wireless modes of communication of the devices. The most common system was cyclist wearables (39%), closely followed by on-bike devices (38%) and vehicle systems (33%). Most systems communicated visually (77%). We suggest that interfaces on motorised vehicles accommodate cyclists with visibility all around the car and incorporate two-way communication. The type of system and the effect of communication modality on performance and safety needs further research, preferably in complex and representative test scenarios with automated vehicles. Finally, our study highlights

the ethical implications of connected road users and suggests that the future outlook of transport systems may benefit from a more inclusive and less car-centred approach, shifting the burden of safety away from vulnerable road users and promoting more cyclist-friendly solutions.

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3.1 Introduction

Before the large-scale deployment of highly automated vehicles, these vehicles must understand the social aspect involved in road user interaction. Specifically, interaction with vulnerable road users in complex urban traffic environments remains a significant challenge for automated vehicles (Rasouli & Tsotsos, 2020; Schieben et al., 2019). One proposed solution for supporting vulnerable road users in future automated traffic is equipping automated vehicles and vulnerable road users with HMIs that display notification messages and warnings (Berge, Hagenzieker, et al., 2022). Another solution, substituting the lack of explicit human-to-human communication by driverless vehicles, is on-vehicle eHMIs, providing communication cues to other road users through displays, lights, or projections on the road. eHMIs have been widely researched, including the effect of the physical shape and appearance of the interfaces, such as placement, colour, and the use of text, symbols, or lights (Bazilinskyy et al., 2019; Dey, Habibovic, Löcken, et al., 2020).

Research on automated vehicle-vulnerable road user interaction focuses primarily on the effects of eHMIs on the crossing behaviours of pedestrians (Dey, Habibovic, Löcken, et al., 2020; Rasouli & Tsotsos, 2020), on designing the interaction of automated vehicles (Schieben et al., 2019) and on automated vehicle acceptance (Merat et al., 2017). When cyclists are included in eHMI studies, they are rarely the main subject of study: None of the eHMI concepts identified by Dey, Habibovic, Löcken, et al. (2020) solely targeted cyclists, and only a few empirical studies focus specifically on cyclist interaction with automated vehicles (Bazilinskyy et al., 2023; Berge, Hagenzieker, et al., 2022; Hagenzieker et al., 2020; Hou et al., 2020; Kaß et al., 2020; Nuñez Velasco et al., 2021; Rodríguez Palmeiro et al., 2018; Utriainen & Pöllänen, 2021; Vlakveld et al., 2020). Cyclists are vulnerable road users (Holländer et al., 2021), but differ from pedestrians in eye-gazing behaviour. Trefzger et al. (2018) found that cyclists are more preoccupied with looking on the road and gaze less frequently at vehicles than pedestrians. Cyclists also differ in speed and movement patterns compared to pedestrians: While pedestrians usually interact with vehicles at crossings, cyclists regularly share the road and travel parallel to vehicles, experiencing passing, merging, and overtaking situations (Berge et al., 2024). To ensure the safety of cyclists in automated traffic, targeting them as a specific road user group in research is vital. Currently, there is no overview of technologies and solutions for cyclists to improve their interaction with automated vehicles.

With transport systems increasingly becoming part of the Internet of Things (Behrendt, 2019), it has been suggested that interconnectivity between infrastructure, automated vehicles, conventional vehicles, and vulnerable road users is essential for the successful full-scale deployment of automated vehicles (Farah et al., 2018; Sanchez et al., 2016). Interconnectivity could increase visibility among road users, making them mutually aware of each other's locations and trajectories, which in turn could be a significant safety improvement (Owens et al., 2018), resulting in a reduction in conflicts and better traffic flow (Papadoulis et al., 2019).

At the same time, the rising security and privacy issues accompanying vulnerable road user connectivity tend to be overlooked and understudied (Hasan & Hasan, 2022). Although some researchers have questioned whether vulnerable road users should depend on additional devices for safety in traffic with automated vehicles (Berge, Hagenzieker, et al., 2022; Tabone, De Winter, et al., 2021), the discussion in academic and media circles regarding the ethical considerations surrounding connectivity for vulnerable road users remains limited. In light of the proliferation of IoT and technological advances, it is plausible to expect that most new devices will have some form of connectivity in the near future. Therefore, we argue that a technological approach to support systems for cyclists merit further investigation in research, to establish a foundation for future studies and to promote ethical discourse.

The present study provides a synthesis of existing literature and a comprehensive overview of the state-of-the-art support systems for cyclists to encourage the discussion of technological devices and connectivity for vulnerable road users such as cyclists in future automated traffic environments. The objectives of the study are three-fold:

- To identify, classify, and quantify the various communication technologies, systems, and devices that have the potential to aid cyclists in automated traffic.
- To align the support systems with knowledge about human factors related to cycling and to discuss the systems' potential in the context of automated vehicles.
- To provide a reflection on the prospect of automated vehicle-cyclist interaction and recommendations for future research.

The overall goal is to enhance the understanding of automated vehicle-cyclist interaction, promote discourse and research by identifying gaps in current literature, and discuss strategies for optimising cycling in future traffic environments with automated vehicles.

3.2 Method

This chapter presents an exploratory synthesis and descriptive analysis of systems designed for cyclists and bicycles with the potential to affect cyclist interaction in automated traffic systems. We collected concept descriptions of the technologies, systems, and devices from the literature and taxonomically coded and analysed them descriptively. For simplification purposes, we refer to the descriptions of the identified technologies, systems, and devices as 'concepts' throughout the analysis.

3.2.1 Selection of literature

We performed literature searches in Scopus and Google Scholar to collect relevant academic articles. In addition, we used Google to identify informal or commercial concepts from the industry. The literature searches were dynamic as the field of support systems for cyclists in the context of automated vehicles is new and emergent. When reviewing a topic with limited academic literature, the inclusion of grey literature and commercial publications can provide valuable insights and perspectives that may not be found in academic literature alone (Paez, 2017). Commercial concepts can offer practical, real-world examples of support systems for cyclists that have not been studied by academia but may still help understand the systems' application and impact on cyclists in the context of automated vehicles. As the field currently lacks a standardised nomenclature, we performed keyword searches combining words across four categories:

- Target road user: cyclist, vulnerable road user, vulnerable road user.
- Location: bike, bicycle, car, vehicle, infrastructure.
- Function: interface, interaction, communication, detection, connect*.
- Automation: autonomous, automated, self-driving, driverless.

The criterion for selecting the study sample was set to transport-related concepts capable of transferring messages or information among road users through technology, or the ability to be developed or adapted for use in the context of vehicles with automation capabilities beyond SAE level 2 (Shi et al., 2020). The publication had to indicate at least one cyclist or bicycle as the target user of the concept. For the searches in the scientific databases, the titles, and abstracts of the first 100 results were assessed for inclusion. When a relevant article was located, a search with the *related articles* function of Google Scholar was performed.

3.2.2 Sample

We identified 62 publications that fit the inclusion criteria. Out of the 62 publications, 40 of the articles were from academia, with 13 journal articles, 25 conference papers, one book section, and one poster. The remaining 22 publications were from industry, with 18 commercial or industry articles and four patents. Several of the publications contained descriptions of more than one concept description, adding up to 92 descriptions of concepts in total. Most of the concepts originated from Europe: Germany (20), the Netherlands (17), Italy (11), Sweden (9), France (3), the United Kingdom (2), Latvia (1), and Spain (1). Moreover, 12 concepts were published in the United States, followed by Canada with 9 concepts. Two concepts originated in Australia and Japan, and one concept from Colombia, Chile, Israel, and Taiwan, respectively. The oldest concepts identified were published in 2007, and the most recent in late December of 2021. See Appendix B for a full list of the identified publications.

3.2.3 Analysis and coding of concepts

The study sample was analysed systematically using a taxonomical coding system outlined in section 2.4. The taxonomy was developed in an iterative process. First, we established the dimensions and definitions based on the classification taxonomy of eHMIs by Dey, Habibovic, Löcken, et al. (2020). The publications were analysed, and the identified concepts were initially coded based on their physical and functional characteristics in line with Dey, Habibovic, Löcken, et al. (2020). Throughout the initial coding, the suitability of each dimension was consecutively evaluated and modified per concept by creating cyclist- or bicycle-appropriate sub-categories and removing the original sub-categories that did not sufficiently describe our study sample. In cases where the original eHMI taxonomy dimensions did not depict all appropriate aspects of the identified concepts, the dimensions were merged or removed entirely, and new variables were created. For instance, variable 9. *Functionality* is inspired by and covers in part the dimensions *Message of Communication in Right-of-Way Negotiation* and *Covered states* Dey, Habibovic, Löcken, et al. (2020). The taxonomy was further refined through discussions within our research group.

The full classification taxonomy was applied to each of the 92 identified concepts. The physical and functional characteristics of the concepts were coded based on the descriptions or information available in the publications, varying from text and illustrations, to photos, animations, and videos demonstrating the concept in use. Certain concepts had multiple features, e.g., a concept could have HMI placements as an on-bike device and a cyclist wearable and utilise more than one modality of communication. Each of these features was recorded with

separate values divided by commas within the applicable sub-categories. The variables pertaining to usability and realism in real-world traffic, such as *11. Complexity of implementation*, required interpretation during coding and relied on the coder's knowledge and understanding of the feasibility of the technology available today. The data from the 92 concepts were analysed descriptively using frequency counts and pivot tables in Microsoft Excel.

3.2.4 Taxonomy definitions

The taxonomy separates the concepts into four categories according to interface placement: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems. The concepts were further differentiated according to their physical characteristics, intended functionality, modality of communication, communication strategies, and evaluation method based on a refined version of the classification taxonomy of eHMIs proposed by Dey, Habibovic, Löcken, et al. (2020).

In total, there are 13 taxonomical categories used for coding the concepts: terminology, target road user, HMI placement, number of interfaces, number of messages, modality of communication, communication strategy, connectivity, functionality, type of concept, the complexity of implementation, support for people with special needs, and finally, concept evaluation. Table 3.1 shows an overview of the variables and their definitions. The variables directly adapted from Dey, Habibovic, Löcken, et al. (2020) are noted in the table. A full description and rationale of the variables can be found in Appendix C.

Table 3.1. Taxonomy definitions

	Variable	Definition
1	Terminology	The words used to describe a concept.
2	Target road user	The type of road user targeted by a concept.
3	HMI placement	The location of the interface or location of the message conveyed to its intended recipient.
3.1	Cyclist wearables	The interface is located on the cyclist.
3.2	On-bike devices	The interface is located on the bicycle.
3.3	Vehicle systems	The interface is located on or within the motorised vehicle.
3.4	Infrastructural systems	The interface is located on infrastructure.
4	Number of interfaces	The number of modalities capable of communicating a piece of information between the system and the human road user(s).
5	Number of messages	The number of messages communicated through an interface. Adapted from Dey, Habibovic, Löcken, et al. (2020).
6	Modality of communication	The way communication is achieved by a concept.
6.1	Visual	The concept communicates through visual perception and sight.
6.1.1	Colour	The colour of visual modalities.
6.2	Auditory	The concept communicates through the sense of hearing.
6.3	Motion	The concept communicates through the action or process of moving or being moved.
6.4	Wireless	The message is delivered through a signal transmission on a frequency spectrum.

7	Communication strategy	The way the system addresses road users when communicating its message. Adapted from Dey, Habibovic, Löcken, et al. (2020).
7.1	Unicast	The system communicates and delivers its messages targeted to a single road user.
7.2	Broadcast	The system broadcasts its messages to non-targeted road users.
7.3	Multicast	The system targets and delivers its message to multiple road users at the same time.
8	Connectivity	The concept has the capacity for interconnection by signal transmission between systems or users.
9	Functionality	The intended functionality or purpose of the message(s) communicated to its recipient(s).
9.1	Information systems	Systems informing road users about a particular arrangement or sequence of events.
9.2	Warning systems	Systems intending to convey messages of caution or urgency to their users.
9.3	Support systems	Systems conveying messages with a behavioural component of the cyclist or bicycle to its user, such as information about a cyclist's current or future behaviour.
10	Type of product	The concept stage of development (i.e., whether it is conceptual, a prototype, or an end product).
11	Complexity of implementation	The complexity of implementing a concept in real traffic scenarios. Adapted from Dey, Habibovic, Löcken, et al. (2020).
11.1	Ready to use	Technology is ready to use today.
11.2	New technology required	The concept requires new technology but does not depend on widespread implementation or infrastructural changes to function.
11.3	New technology and large-scale changes required	The concept requires new technology but depends on widespread implementation or infrastructural changes to function.
11.4	Highly aspirational	The concept uses technology that is not yet developed or available.
12	Support for people with special needs	The concept accommodates the special needs of visually, auditory, or cognitively impaired persons through multimodal communication. Adapted from Dey, Habibovic, Löcken, et al. (2020).
13	Evaluation of concept	The concept has been evaluated in a scientific publication. Adapted from Dey, Habibovic, Löcken, et al. (2020).

3.3 Results

This section presents the results from the descriptive analysis of the coding and categorisation of the 92 communicative technologies and concepts identified in the literature search. See Appendix B for the full list of publications from the literature search.

3.3.1 Terminology

We investigated the terminology used in the 62 articles. 55% of the articles used the word *system* to describe their technology, while about one in five referred to their concept as an *interface* or *HMI*. Other reoccurring terms were *communication* (13%), *warning* (11%), *safety* (6%), and *smart* (6%).

3.3.2 Target road user

As inherent to the study's search strategy, cyclists were the target road user in all 92 concepts; however, cyclists were the sole target road user in 63% of the concepts. This means that the remaining 37% (34 of the concepts) were multi-agent systems involving the communication of messages to cyclists, pedestrians, or drivers/vehicles. Seven of the multi-agent concepts targeted cyclists and drivers/vehicles, 14 concepts targeted cyclists and pedestrians, and 13 concepts targeted all three groups of road users.

3.3.3 HMI placement

The most common placement of the system or interface was cyclist wearables (39% of all concepts), closely followed by on-bike devices (38% of all concepts) and vehicle systems (33% of all concepts). About one in four concepts had placements on infrastructure or projections on infrastructure. One out of three concepts was categorised as having more than one placement. For instance, De Angelis, Stuiver, et al. (2019) describe a multi-agent system with a display mounted on the bicycle's handlebars and a display placed on infrastructure. Another example by Matviienko et al. (2018) portrays a wearable system with interfaces embedded in the cyclist's helmet and on the bicycle's handlebars. Figure 3.1 shows an overview of the HMI placement of the concepts categorised as cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems.

Cyclist wearables 36 concepts



AR glasses (13)



Smartphone (11)



Helmet (11)



Other (5)



Head-up display (4)



Beacon (4)

On-bike devices 35 concepts



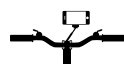
Handlebars (22)



Mounted display (9)



Unspecified (6)



Head-up display (5)



Frame (4)



Rear (5)



Seat (4)

Vehicle systems 30 concepts



Side (7)



Hood (6)



Roof (5)



Windshield (5)



Bumper (3)



All around (2)



Rear (1)



Unspecified (10)

Infrastructural systems 21 concepts



On road (9)



Projection (7)



Traffic sign (4)



Side of road (1)

Figure 3.1. An overview of the 92 concepts categorised according to their placement on the cyclist (wearables), bicycle, vehicle, or infrastructure.

Note: As a concept could be a multi-agent system, a concept can be categorised into more than one category.

3.3.4 Number of interfaces and messages

Table 3.2 shows the number of interfaces and messages identified in the analysis. The analysis showed 41 concepts (45%) with one interface conveying messages to a recipient. The other half of the concepts used more than one interface for communication: two (25 concepts, 27%), three (10 concepts, 11%), four (8 concepts, 9%), and more than four (4 concepts, 4%). It was not possible to count the exact number of interfaces for four concepts, which were marked as unclear.

Table 3.2. Number of interfaces and messages of concepts

	Number of interfaces	Number of messages
One	41	45
Two	25	16
Three	10	13
Four	8	2
More than four	4	1
Unclear	4	15

Note: n = 92.

Regarding the number of distinct messages delivered by the interfaces, half of the concepts delivered only one message. Of the remaining concepts, 16 concepts (17%) delivered two messages, 13 concepts (14%) delivered three messages, two concepts (2%) delivered four messages, and only one concept delivered more than four messages. We could not count the number of messages for 15 concepts, which were marked as unclear.

3.3.5 Modality of communication

The most common communication modality was visual with abstract/light (54% of visual concepts). For instance, a concept coded as visual and abstract/light could describe a light blinking on the bicycle's handlebars or an abstract shape that does not resemble text, symbols, or anything anthropomorphic projected on the ground. As seen in Figure 3.2, four out of five concepts communicated their message visually. For visual interfaces, red (19%), green (18%), and yellow (13%) were the most common colours used (see Figure 3.3).

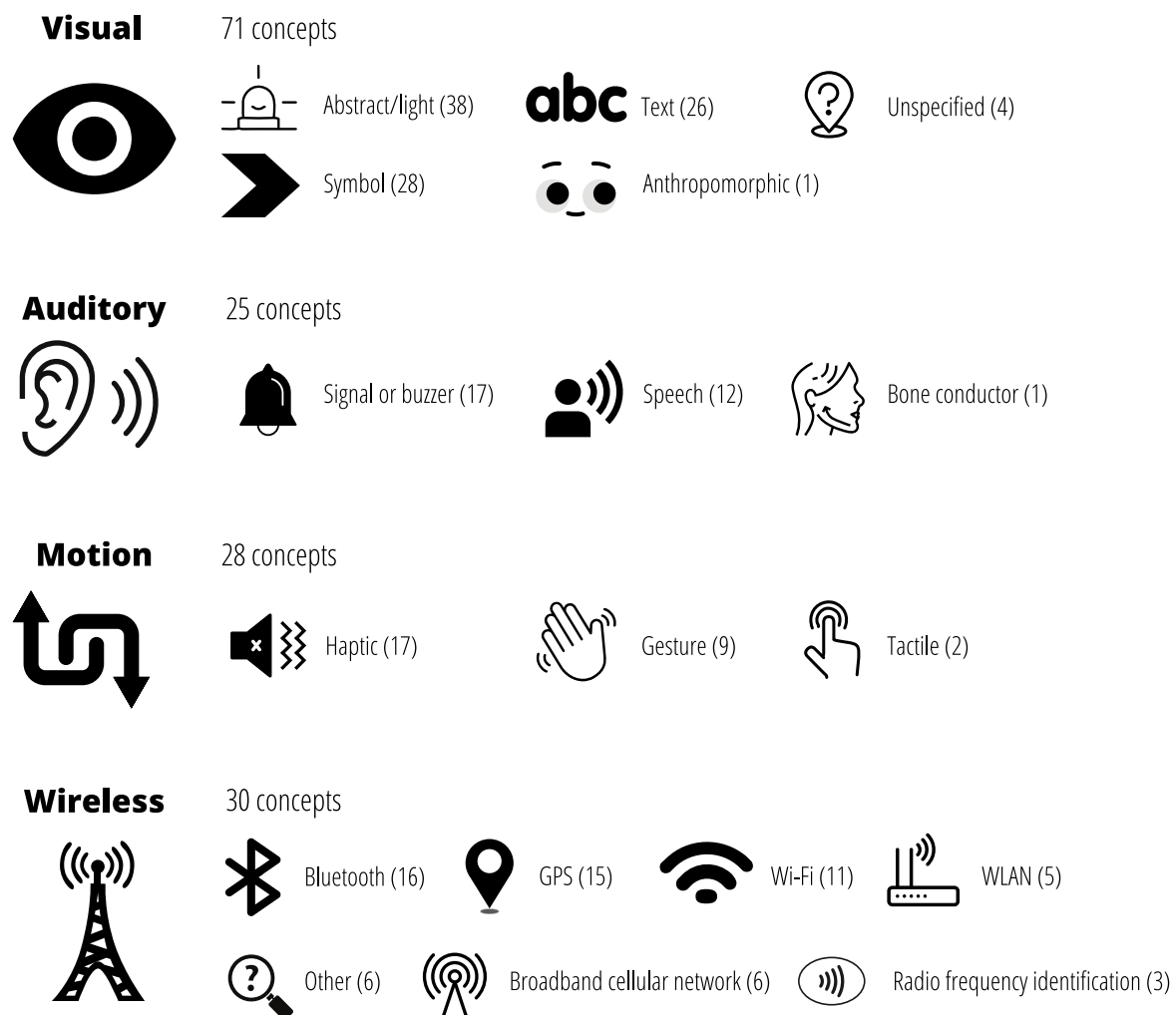


Figure 3.2. An overview of the modalities of communication identified in the concepts

Note: $n = 92$. As a concept could communicate through more than one interface, a concept could be categorised into more than one category. Four concepts coded as having an unspecified mode of communication are not represented in the figure.

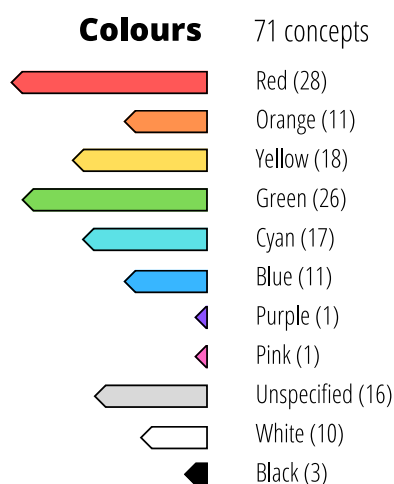


Figure 3.3. The colours used in the 71 visual concepts

Note: A concept could be coded with more than one colour.

Approximately one in three concepts used auditory and motion-based communication modalities. The most common way of auditory communication was a signal or buzzer (17 concepts, 68% of auditory concepts), typically as an alert or warning to the cyclist. In about two out of three motion-based concepts, the communication modality was haptic feedback, such as vibrating handlebars. Nine concepts used gestures, typically to control AR glasses.

There is potential for road user connectivity in 41% of the concepts: 38 of 92 concepts described a connectivity feature or technology with the potential of connecting multiple agents to transmit messages. As seen in Figure 3.2, concepts specifying wireless communication utilised technology such as Bluetooth (53%), GPS (50%), and Wi-Fi (37%). Six concepts had wireless as their only communication mode and were typically cooperative communication systems or vehicle-to-everything systems.

Table 3.3 shows the results from the pivot table analysis of the concepts' HMI placement and modality of communication. Almost all concepts with interfaces on infrastructure used a visual mode of communication. Visual mode of communication was the most common modality for on-bike devices (77%, 27 out of 35 concepts) and vehicle systems (77%, 23 out of 30 concepts). Wireless and visual were the most common modes of communication for cyclist wearables (64%, 23 out of 36 concepts, respectively). When opting for a motion-based mode of communication, the interface of choice was mainly on bicycles (78%, 18 out of 23 concepts).

Table 3.3. Pivot table of HMI placement and modality of communication

HMI placement	Modality of communication			
	Visual 71 concepts	Auditory 25 concepts	Motion 28 concepts	Wireless 30 concepts
Cyclist wearables 36 concepts	23	16	13	23
On-bike devices 35 concepts	27	12	18	11
Vehicle systems 30 concepts	23	5	4	13
Infrastructural systems 21 concepts	20	1	4	5

Note: n = 92. Note that four infrastructural systems are classified as using motion and one as using auditory as the mode of communication due to concepts with more than one interface. The coding system did not distinguish the modality of different interfaces within the same concept.

3.3.6 Communication strategy

We investigated whether the concepts used targeted or non-targeted communication strategies and whether they address single or multiple road users. Table 3.4 shows that half of the concepts targeted a single road user (47 out of 92 concepts), while 41% (38 out of 92 concepts) broadcasted their messages, and 23% (21 out of 92 concepts) targeted their communication to multiple users. The majority of cyclist wearables and on-bike devices delivered messages to a targeted, single road user. About two out of three vehicle systems broadcasted their messages to multiple road users in a non-targeted manner.

Table 3.4. Pivot table of HMI placement and communication strategy

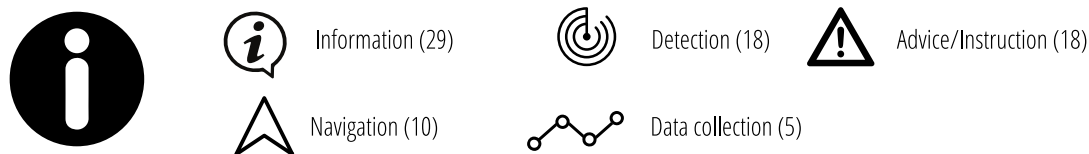
HMI placement	Communication strategy		
	Unicast 47 concepts	Broadcast 38 concepts	Multicast 21 concepts
Cyclist wearables 36 concepts	30	2	6
On-bike devices 35 concepts	25	11	11
Vehicle systems 30 concepts	4	19	10
Infrastructural systems 21 concepts	6	12	4

Note: n = 92. The coding system did not distinguish the communication strategy of different HMI placements within the same concept, i.e., a concept could be coded with more than one placement and communication strategy.

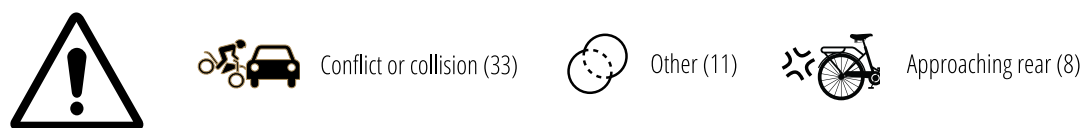
3.3.7 Functionality

The 92 concepts were categorised into three groups of systems based on their functionality: information systems, warning systems, and support systems. A system could be classified as having more than one function and, therefore, coded within more than one system sub-group. Figure 3.4 shows an overview of the functionality of the concepts.

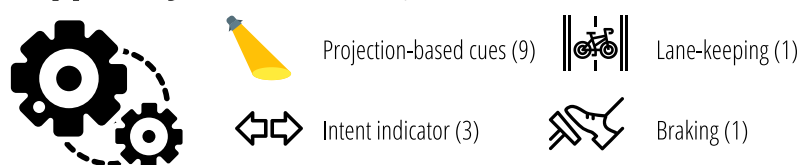
Information systems 61 concepts



Warning systems 46 concepts



Support systems 11 concepts

**Figure 3.4. Overview of the coding results for functionality**

Note: n = 92. As a concept could have more than one function, a concept can be categorised into more than one category.

As seen in Figure 3.4, two-thirds of the concepts were coded as information systems. However, the most common functionality among the concepts was a warning system communicating an alert of an imminent or potential conflict or collision (36% of all concepts). For instance, the smart bicycle helmet concepts by Von Sawitzky et al. (2021) warned the cyclist of the potential

door opening of parked cars on the side of the road, while Matviienko et al. (2018)'s helmet and bicycle warning concept for children warned the user of a potential left or right collision at junctions, as well as vehicles appearing from behind obstacles. Eight of the concepts (17% of the 46 warning system concepts) were warning systems about other road users approaching from the rear. Engbers et al. (2018)'s front and rear-view assistant concept for older cyclists was coded as both conflict or collision and approaching from the rear, as the concept involved a bicycle equipped with a radar detecting road users from the front of the bicycle, as well as a camera detecting road users approaching the cyclist from behind.

One out of four concepts was categorised as a warning system and the sub-category *other*, see Figure 3.4. These concepts describe systems that warned the user of an unspecified event without indicating that the event is a collision or conflict.

Only 11 of the concepts had the functionality of a support system, and nine of these systems were concepts that projected signals onto infrastructure. For instance, in a concept by Hou et al. (2020), a vehicle projected a cyclist symbol coloured red or green next to the cyclist, indicating whether the cyclist can change lanes, while in Dancu et al. (2015), cues for navigation or the intended trajectory of the cyclist were projected onto the road.

Table 3.5 shows the results of the pivot table analysis of HMI placement and functionality. Almost all vehicle systems (97%, 29 out of 30 concepts) and infrastructural systems (85%, 18 out of 21 concepts) had functionality coded as an information system. The main functionality of information systems concepts is to inform the user or other agents in the system of an entity, object, or event. For instance, the six-vehicle system concepts by Dey et al. (2018) all aimed to inform vulnerable road users about the vehicle's current or future behaviour. De Angelis, Stuiver, et al. (2019)'s concepts involved different types of interfaces placed on infrastructure, showing countdown timers for a green light.

Table 3.5. Pivot table of HMI placement and functionality

HMI placement	Functionality		
	Information system 61 concepts	Warning system 46 concepts	Support system 11 concepts
Cyclist wearables 36 concepts	23	20	4
On-bike devices 35 concepts	13	25	5
Vehicle systems 30 concepts	29	11	2
Infrastructural systems 21 concepts	18	7	6

Note: n = 92. The coding system did not distinguish the functionality of different HMI placements within the same concept, i.e., a concept could be coded with more than one placement and functionality.

Most of the on-bike devices (71%, 25 out of 35 concepts) were warning systems. In an on-bike concept by Oczko et al. (2020), the cyclist is warned by haptics in the handlebars and through speakers if the system estimates a collision or close-miss encounter with a vehicle.

3.3.8 Type of concept

Of the 92 concepts, 43% were conceptual, e.g., created digitally for research purposes or as an aspirational patent. Close to one in five concepts were end products ready for commercial use, and the remaining 39% of the concepts were prototypes.

3.3.9 Complexity of implementation

The results from the descriptive analysis show that almost half of the concepts (see Table 3.6, 38 out of 92 concepts) require new technology that depends on large-scale deployment or infrastructure changes to function in future roads with automated vehicles. About one in five concepts require new technology without large-scale deployment or changes, and 34% (31 out of 92 concepts) can use technology today. Only 4% of the concepts are highly aspirational, awaiting the development of novel technology. As seen in Table 3.6, more concepts using wireless communication require large-scale deployment or changes to work (63%, 19 out of 30 wireless concepts).

Table 3.6. Pivot table of the modality of communication and complexity of implementation

Complexity of implementation	Modality of communication			
	Visual 71 concepts	Auditory 25 concepts	Motion 28 concepts	Wireless 30 concepts
Ready to use 31 concepts	28	5	10	8
New technology required 19 concepts	15	6	8	2
New technology and large-scale changes required 38 concepts	26	13	9	19
Highly aspirational 4 concepts	2	1	1	1

Note: n = 92. The coding system did not distinguish the modality of different interfaces within the same concept, and more than one modality of communication could be applicable to each concept. For instance, four concepts were coded with highly aspirational complexity of implementation, where one of the concepts had two modalities of communication.

3.3.10 Support for people with special needs

More than half of the concepts had multimodal ways of communication. However, based on the results from the mode of communication category, we considered only 23% (21 out of the 92 concepts) to have support for people with special needs.

3.3.11 Evaluation of concepts

Out of the 92 concepts, 50 were evaluated in a scientific publication. About half of the concepts were evaluated quantitatively, while 38% used mixed methods involving objective data as well as qualitative data like interviews or observations. Table 3.7 provides an overview of the results from the descriptive analysis of eight coded categories for the evaluation of the concepts.

Table 3.7. The method, type of data collection, scenario setup, task of cyclist, time of day, weather conditions, cycling infrastructure, and road condition used in the evaluation of the concepts

Method		Data collection		Direction of movement		Task	
Naturalistic	14	Automatic recording	29	Same/parallel	12	Adjust speed	9
Controlled outdoor	5	Eye-tracking	2	Perpendicular	16	Cycle normally	17
Simulator (screen)	11	Questionnaire	41	Opposite	6	Anticipate behaviour	14
Simulator (VR headset)	11	Interview	13	No interaction	13	Other	3
Video/animation	12	Observation	2	Unspecified	25	Unspecified	13
Photo	2	Video recording	1				
Time of day		Weather conditions		Cycling infrastructure		Road condition	
Daylight conditions	25	Direct sunlight	2	Mixed traffic	22	Clean road	32
Evening conditions	1	Indirect sunlight	28	Bike lane	3	Water on road	0
Night-time conditions	1	Rain or snow	0	Separated bike path	13	Snow on road	0
Unspecified	24	Unspecified	24	Unspecified	18	Unspecified	17

Note: n = 50. An evaluation could involve the use of more than one method, type of data collection, setup, and task.

Most concepts were evaluated in a simulated, virtual, or digital environment, with a total of 72% of the concepts evaluated in one of these environments. In half of the evaluations, the type of scenario was not specified. 26% of the scenarios identified had no interaction with other road users. Out of the scenarios with interaction, the most common scenario was a vehicle approaching the cyclist from a perpendicular direction. When specified, almost all concepts were evaluated in daylight, most in indirect sunlight with clean roads, meaning there was no rain or ice on the road (see Table 3.7). It was most common to test concepts in non-segregated traffic; there was no bike lane in 44% of the concepts. About one in four evaluations had scenarios with a separate bike path.

Table 3.8 shows that the scenarios used for prototype evaluation were relatively simple; only 6% involved more road users than the cyclist and a vehicle, and 12% involved two vehicles or more throughout the entire scenario. Interestingly, 12% of the evaluations did not involve a cyclist. These concepts were evaluated using photos of infrastructure and the bicycle's handlebars, with no cyclists or vehicles present, such as the concepts by De Angelis, Stuiver, et al. (2019).

Table 3.8. The number of simultaneous road users and vehicles per trial

	Number of simultaneous road users per trial	Number of vehicles per trial
0	12%	14%
1	8%	28%
2	28%	6%
>2	6%	6%
Unspecified	40%	40%

Note: n = 50.

Regarding the sample sizes of the evaluated concepts, the samples ranged from five to 2389 participants, with an average of 310 participants. Not all evaluations were performed on cyclists due to the nature of the data collection methods, e.g., studies using crowdsourcing surveys to collect data. The average age of the participants in the studies was 31 years old. Two studies were carried out on children with a median age of nine and ten, while three included elderly cyclists with an average age of 70.

3.4 Discussion

This study synthesises the current literature on communicative technologies, systems, and devices available to support cyclists. The overall goal is to pinpoint knowledge gaps in the literature and develop strategies for optimising cycling in future traffic environments with automated vehicles. The following sections are divided into three: We first discuss the type of cyclist support systems categorised according to HMI placement: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems. The next section addresses the different modalities of communication and their potential for cyclists, before finally, a section providing a broader reflection on the prospects of future automated vehicle-cyclist interaction presented as knowledge gaps in the literature and recommendations for future research on cyclist support systems.

3.4.1 Type of systems

Cyclist wearables

From the 92 concepts, the most common systems were cyclist wearables and on-bike devices. Cyclist wearables are usually lightweight and can be utilised across bicycles. One in three cyclist wearable concepts was embedded in a helmet. HindSight, for instance, is a concept in which a camera on the cyclist's helmet notifies the cyclist of approaching road users outside the cyclist's field of view (Schoop et al., 2018). Moreover, thirteen of the cyclist wearable concepts in this study used AR to communicate with the cyclist, and five of these concepts were already commercially available AR glasses (Cosmo Connected, 2022; EverySight, 2022; Garmin, 2022a; Julbo, 2022; Solos, 2018). AR technology enhances the real-world environment by adding a virtual layer of computer-generated perceptual information in real-time (Milgram & Kishino, 1994). Among the academic conceptual concepts, Von Sawitzky, Wintersberger, et al. (2020)'s augmentation concepts create a digital overlay of a smart bicycle path indicating

whether the gap allows for safe crossing, while a later concept warns the cyclist of a potential vehicle door opening ahead (Von Sawitzky et al., 2021).

Wearable obstacle detection systems like HindSight (Schoop et al., 2018) and academic AR concepts (Von Sawitzky et al., 2021; Von Sawitzky, Wintersberger, et al., 2020) depend on several data sources (e.g., vision data and motion data) and cannot detect a hazard on their own (Hasan & Hasan, 2022). This means that they would have to be a part of a multi-agent system to function in real-life traffic. The accuracy of wearable obstacle detection systems also relies on correct positioning and calibration (Hasan & Hasan, 2022). Trusting a wearable system for safe interaction with automated vehicles may pose another challenge: The device might malfunction, be stolen, or simply not be worn by the user. For example, self-reported helmet use among cyclists varies from 2% in the Netherlands to 80% in Norway (Haworth et al., 2015). If the system is integrated into devices already available to most vulnerable road users, such as a smartphone or other types of wearables that may become ubiquitous in the future (e.g., AR glasses or chip implants), universal usage might be less of an issue.

On-bike devices

An HMI placement on the handlebars was the most common among our on-bike devices. The handlebars are likely a favourable place out of practicality and convenience, as they are located in the centre of a cyclist's focal view between traffic and the road. A range of commercial on-bike products like cyclocomputers placed on the handlebars already exist. Often paired with wearables such as AR glasses, smartwatches, and fitness trackers, on-bike devices are popular among sports cyclists. Today, these types of devices are typically performance-based, providing cyclists with real-time heart rate, speed, and cadence data. In the future, they have the potential to be programmed to aid cyclists with automated vehicles.

Vehicle systems

Almost all concepts categorised as vehicle systems (97%, 29 out of 30 concepts) were information systems. Most of these were eHMIs targeting pedestrians and cyclists, and only seven concepts were omnidirectional — two were visible from all around the motorised vehicle, and five were placed on the vehicle's roof. Cyclists differ from pedestrians in terms of movement patterns, speed, and eye-gazing behaviour (Trefzger et al., 2018). For cyclists, it is likely vital that the interfaces are omnidirectional to accommodate the differences in movement patterns and that the message can be observed at high speeds. When anticipating their needs in future automated traffic, interviewed cyclists' main concerns were visibility and confirmation of detection by the automated vehicle (Berge, Hagenzieker, et al., 2022). Some of the concepts identified in our study have the potential to cover these needs. For instance, CommDisk, a 360° rooftop-mounted eHMI providing omnidirectional two-way communication (Verstegen et al., 2021), and The Tracker, a band of light surrounding the vehicle illuminating a small segment in the spatial proximity of the detected vulnerable road user (Dey et al., 2018), both show promise in accommodating the characteristics and needs of cyclists.

Infrastructural systems

Out of the 92 concepts identified in our study, 21 were infrastructural systems that communicated with the system's user through interfaces on the road surface, projections, or traffic signs. Eighteen of the infrastructural systems were coded as information systems, aiming to inform the user about a particular arrangement or sequence of events. The main function of these systems was to detect elements or entities in the cyclist's environment or advise or instruct

the cyclist on desired behaviour through normative messages. Traditionally, traffic lights, signs, and markings regulate road users' normative behaviour. In a survey on the effect of text, colour, and perspective of eHMI, egocentric interfaces instructing the user to “walk” or “stop” were regarded as clearer than allocentric displays informing the user of the vehicle's intended behaviour (e.g., the vehicle displaying it “will stop” or “will not stop”) (Bazilinskyy et al., 2019). Communicating through designs and interfaces familiar to users, such as traffic signs or road markings, may relieve cognitive load and shorten the learning process and is in line with the design principles of consistency (Constantine & Lockwood, 1999; Norman, 2013). When designing a system to support cyclists in automated traffic, it would be recommended to rely on the modes of communication and messages the cyclists are familiar with. Nevertheless, incorporating messages about automated vehicle behaviour into normative infrastructural systems may have legal implications from a liability point of view: Advising an action from vulnerable road users based on automated vehicles' behaviour may be particularly challenging when the automated vehicle encounters multiple cyclists or pedestrians as there can be confusion as to which road user the automated vehicle is addressing (Bazilinskyy et al., 2019; Tabone, De Winter, et al., 2021).

3.4.2 Modality of communication

Visual communication

From the analysis, the concepts' most common modality of communication was visual (77% of all concepts). The majority of the visual communication used abstract types of light, while approximately one in three concepts used text. Lights and light signals are typical modes of visual communication in traffic. The most common colours used by the concepts (red, green, and yellow) resonate with the colours used in traffic today. In our study, most of the infrastructural systems concepts also use a visual mode of communication, such as different types of countdown timers for a green light (De Angelis, Stuiver, et al., 2019), an interactive crossing system that responds dynamically to road users by lighting up large displays on the ground to increase awareness (Umbrellium, 2017), and a light system alerting vehicles of nearby cyclists crossing the road (Heijmans, 2022). Infrastructural concepts using visual communication modes included systems communicating through projections on the road surface. Broadcasting visual messages by projecting them on the road enables the system to reach multiple road users simultaneously. On the downside, projection-based and infrastructural systems are vulnerable to weather. In particular, fog, ice, and snow might obstruct the line of sight and reduce efficiency.

The majority of the cyclist wearables communicated visually. AR glasses communicating visually offer unicast and individualised messages to the user, alleviating the uncertainty as to which road user is addressed when a message is broadcast by an on-vehicle eHMI. The functionality of academic AR prototype concepts could potentially be integrated into commercially available AR glasses and be utilised to improve the interaction of cyclists and vehicles, both conventional and automated. Although no differences in perceived safety or mental workload were noticed, augmented warning messages caused cyclists to increase their distance from a potential hazard earlier than swerving when a hazard occurred (Von Sawitzky et al., 2021). Similar augmentation concepts for supporting pedestrians' crossing behaviour in automated traffic have been suggested (Hesenius et al., 2018; Tabone, Happee, García, et al., 2023; Tabone, Lee, et al., 2021).

Close to half of the on-bike concepts in our study involved a type of visual display on the bicycle's handlebars. Using an on-bike display to communicate messages from automated vehicles could be a potential solution for cyclists: Transmitting and receiving signals from other road users and being mutually aware of each other's location and trajectory in traffic, e.g., via a radar display, is a functionality desired for an on-bike system (Berge, Hagenzieker, et al., 2022). However, adding tasks or demands by prompting cyclists with cues or messages about automated vehicles through an on-bike display might negatively impact cyclists' performance and increase their mental workload. Although other modalities of communication may increase mental workload as well, visual cues could be particularly distracting because they prompt cyclists to place their attention elsewhere than on the road. For instance, the use of a touch screen negatively affected cycling behaviour and resulted in worse visual detection performance (De Waard et al., 2014). In another study, the use of mobile phones while cycling negatively affected cycling performance, and visuotactile tasks such as texting were more distracting than listening to music (Jiang et al., 2021).

Cyclists' mental workload can also be higher in complex compared to simple traffic situations, despite cyclists compensating with a reduction in speed (Vlakveld et al., 2015). In that sense, visual or visuotactile support systems might be more appropriate for use in rural environments with fewer other road users than in complex, urban traffic environments. The effect of a visual and visuotactile mode of communication on cyclist distraction and mental workload in traffic with automated vehicles should be explored further in future research.

Auditory communication

Auditory communication was the least popular way of transmitting messages among the concepts in our study, with 25 out of 92 concepts using sound. Auditory messages were mostly delivered as a signal or buzzing sound (68% of auditory concepts). It is questionable whether audio is a feasible option for cyclists in a busy traffic environment with multiple sources of sound and noise, reducing detection accuracy (Hasan & Hasan, 2022). This concern resonates with an interview study on cyclist HMIs, where some of the cyclists pointed out that they prefer on-vehicle eHMIs with audio over a visual display, but a device using audio was generally not preferred by most cyclists. The consensus was that audio might be hard to detect or cause distraction in traffic (Berge, Hagenzieker, et al., 2022). If a concept can deliver targeted messages to the user without interfering with or disturbing other road users, an auditory feature may be feasible. In our study, most cyclist wearables used a unicast communication strategy, meaning that they offered targeted communication. The efficiency and feasibility of auditory devices for cyclists could be a focus of future research; however, as auditory-based systems elicit limited information about the hazard or nature of obstacles (Hasan & Hasan, 2022), a device using auditory communication will likely have to be multimodal.

Motion-based communication

Half of the on-bike concepts in our study use motion-based communication, mostly through the use of vibro-haptic feedback in the handlebars or bicycle seat. While visuotactile communication methods like touch screens may not be a feasible cyclist support system, combining visual cues with haptic feedback may be a solution for complex situations with a high mental workload: Visuo-haptic, multimodal communication was found to be more effective for multiple tasks in high workload conditions (Burke et al., 2006). Eight of the concepts identified in our study were categorised as warning systems for alerting the cyclist of another road user approaching from behind, and half of these concepts used motion-based communication to alert the cyclist. Engbers et al. (2016) found that haptic feedback had a higher

acceptance rate than visual warnings. The system received similar positive feedback in a later study, where haptics was described as intuitive and easy to distinguish from vibrations caused by the cycling itself (Engbers et al., 2018). Using haptics to warn about other road users approaching from the rear may benefit situational awareness, particularly in rural areas where other road users do not frequently approach from behind. In urban environments with a higher sensory input, however, cyclists may find a passive system that does not notify the user less strenuous: In a study on passive versus active on-bike warning systems, the participants preferred a passive system alerting the vehicle rather than the cyclist over a system eliciting audio-visual or haptic warnings (De Angelis, Fraboni, et al., 2019).

Nine of the concepts in our study used gestures as a mode of communication. Most of these concepts are AR glasses, in which the cyclist controls the device by swiping a touchpad embedded in one of the spectacle rods. Other systems use head movements as a way of communication, e.g., an eHMI concept attempting two-way communication by blinking if the vulnerable road user nods at the sensor (Verstegen et al., 2021), and a smart helmet sensing head tilt to enable turn indicators (Jones et al., 2007). The advantage of such systems is that they allow the cyclist to maintain eye contact with the road and other road users instead of looking at a display.

Wireless communication

Future transport systems will likely depend on interconnectivity, and there is much potential in utilising digital infrastructural systems to aid road users in becoming a part of IoT. Today's infrastructure is often equipped with sensors, e.g., road infrastructure and junctions are fitted with low-power transponders that are detectable by vehicle sensors, in preparation for the intelligent transport systems of tomorrow. There are also traffic cameras and roadside units collecting traffic data, which can provide essential information about other road users and the environment that may be missed by automated vehicle sensors (Rebsamen et al., 2012).

Automated vehicles' main challenge in urban traffic today is the interaction with pedestrians and cyclists. Equipping and connecting all road users with sensors may seem like a plausible solution to this challenge. Fifteen of the concepts in our study used GPS, which enables obstacle detection without relying on line-of-sight (Hasan & Hasan, 2022). In terms of functionality, two-thirds of the concepts analysed in this study were categorised as cyclist wearables, and on-bike devices were warning systems detecting a nearby entity and alerting the cyclist of a potential conflict. Moreover, almost all vehicle systems (97%) aim to inform the cyclist about the vehicle's current or future behaviour. Combining these concepts by utilising the wireless mode of communication by connecting the cyclist or bicycle to a network of automated vehicles and infrastructure might enhance visibility and sufficiently acknowledge the cyclists.

3.4.3 Knowledge gaps and recommendations for future research

On-vehicle eHMIs targeting cyclists

With conventional vehicles equipped with intelligent transport systems like detection, lane-keeping, and braking systems, and automated vehicles with their lidar and radar sensors and continuously developed algorithms, the necessity of on-vehicle cyclist support systems like eHMIs can be questioned. In their position paper, De Winter and Dodou (2022) conclude that road users seem to want and accept eHMIs, as eHMIs can add to implicit communication and fill the void of social interaction with driverless vehicles in terms of eye contact. Moreover,

eHMIs have the potential to communicate multifaceted messages, indicating the vehicle's functional state, both in terms of sensors and whether the automated system is active (De Winter & Dodou, 2022). In sum, vehicle systems such as eHMIs seem to be a welcomed addition that could potentially enhance vulnerable road user interaction with automated vehicles.

The next step is likely to be the standardisation of eHMIs across car manufacturers. In that case, it is vital to consider cyclists in the design and evaluation process, as the needs of cyclists and how they affect the interaction with automated vehicles are understudied topics to date. We suggest that eHMIs for cyclists should be designed with visibility all around the vehicle and with messages observable at the higher speeds of cyclists compared to pedestrians. Incorporating two-way communication, allowing the cyclist to receive confirmation of detection by automated vehicles, is also likely a desirable feature of a cyclist support system. The exact configurations and attributes of a cyclist-oriented eHMI still require additional research.

The effect of modality on performance and safety

More than half of the concepts analysed in this study were evaluated by previous research. The evaluation method and measurement variables varied from study to study, ranging from preference and acceptance to usability and bicycle speed and trajectory adjustments.

It is not possible to draw conclusions about the effects or usability of the systems based on these evaluations, particularly as few of the concepts were evaluated in the context of automated vehicles. Moreover, most of these concepts were evaluated in simulated, virtual, or digital environments. However, simulators and virtual reality are common methods in user studies in automotive research, providing a safe, controllable, and immersive test environment for the participants (Hock et al., 2018). Real-world experiments also raise legal and ethical concerns pertaining to automation. Although simulations do not entail all details of real-world traffic environments, virtual reality has been found to be useful for investigating pedestrians' behaviour when interacting with automated vehicles (Nuñez Velasco et al., 2019). Considering that the field of automated vehicle-cyclist interaction is still in early stages, performing research in virtual environments is a reasonable approach.

We propose that investigating the effect of visual versus auditory and motion-based modes of communication on cycling performance, safety, situational awareness, and mental workload are important directions for future research. In particular, augmentation concepts and head-up displays for cyclists, although already commercially available as AR glasses, remain largely unexplored by academia.

Increased complexity and representative test scenarios

Most of the concepts were evaluated using relatively simplistic scenarios. If there was an interaction between a cyclist and another road user in the evaluation, the most common scenario was a vehicle approaching the cyclist from the left or right side in broad daylight on clean, dry roads. Future research on cyclist interaction with automated vehicles could benefit from more complex and realistic scenarios to increase the ecological validity and generalisability of the findings, including scenarios with more than one cyclist and vehicle, and cluttered urban environments with varied weather and lighting conditions. Moreover, the development of standardised test scenarios for automated vehicle-cyclist interaction would be a welcomed addition to the literature base.

The implications of connected vulnerable road users and inclusive transport systems

The number of devices connected to the internet has increased significantly in recent years (Lombardi et al., 2021), and with the transport system increasingly becoming part of the IoT (Behrendt, 2019), connected bicycles and cyclists are likely the future of cycling. The assumption is that equipping bicycles or the cyclists themselves with sensors will ensure that smart infrastructure and automated vehicles are aware of the cyclists' location, increasing their safety. One of the key challenges with this solution is that only the connected cyclists will be detected if automated vehicle programming depends on data from these sensors. Human road users without sensors, whether for economic or privacy reasons, may be at increased risk due to the absence of data. The ethical implications of equipping vulnerable road users with beacon systems are rarely considered in research, and issues pertaining to user privacy and security arising from vulnerable road user safety systems are typically retroactively addressed (Hasan & Hasan, 2022). Shifting the burden of safety to the cyclists by requiring them to invest in or wear additional devices to be safe from automated vehicles is one of the main reasons cyclists are hesitant about using HMIs in automated traffic (Berge, Hagenzieker, et al., 2022).

Silla et al. (2017) investigated the effect of intelligent transport systems on preventing cyclist injuries and fatalities. With a 100% penetration rate, pedestrian and cyclist detection systems paired with emergency braking and bike-to-vehicle communication had the highest positive effect on cyclist-vehicle accidents, while vulnerable road user beacon systems had the lowest effect. Without a near-perfect prevalence of connected bicycles, the vehicle-based systems (detection system and emergency braking) showed the highest reduction in fatalities and injuries. The effect of on-vehicle eHMIs was not considered in this study. While more research is required, the findings still suggest the necessity of high penetration rates of cyclist support systems to increase the safety of cyclists in future traffic and indicate that vehicle systems, such as improved sensors and programming, possibly paired with on-vehicle eHMIs, may perform better in terms of safety if connected vulnerable road users is not universal.

Historically, the drive for new mobility paradigms in transport has been auto-oriented, oppressing active modes of transport for the benefit of motorised vehicles (Gaio & Cugurullo, 2022). Considering that cyclist wearables or on-bike devices may be stolen, malfunction, or be misplaced, we hypothesise that the sensors connecting human road users will likely have to be embedded in the human body to ensure everyone's safety. Members of transhumanist and biohacking communities have demonstrated the potential of implantable technologies such as neodymium magnets, radio-frequency identification chips, and sensors for human enhancement (Yetisen, 2018). In the future, such implants may become ubiquitous. While the Internet of People may be a possible way forward, the privacy and safety implications of prospective mass surveillance are of major concern. It is highly debatable whether connected road users through implants is an acceptable solution to the automated vehicles' challenges of interacting with vulnerable road users in complex, urban environments.

The acceptance of road user connectivity should be explored in future research. While interviewed cyclists expressed uncertainty about systems that provide information about critical safety situations in connected traffic (Berge, Hagenzieker, et al., 2022), the participants in a study conducted by Von Sawitzky et al. (2021) indicated a willingness to use such systems. Additional knowledge of current situations in the traffic environment may improve cyclists' situational awareness. For instance, a system that alerts cyclists about critical situations through modalities that do not interfere with visual attention or mental workload may prevent accidents and increase cyclist safety. Situational awareness-enhancement systems may prove to be feasible solutions during the transition period between conventional and automated vehicles

and should be further investigated. In terms of the burden of safety, these systems will not shift the burden onto cyclists as long as the use of such systems is voluntary and not a requirement of safe automated vehicles in future traffic.

In the forthcoming years, a critical direction for automated vehicle-cyclist interaction will be the development of eHMI technology tailored to the specific needs of cyclists. In the context of road user connectivity, allocentric on-vehicle eHMIs – interfaces informing vulnerable road users about the automated vehicles' intended behaviour – will not require additional sensors or vulnerable road user beacon systems. However, we also suggest that exploring other solutions, essentially shifting the car-centred and technology-driven perspective towards a more inclusive and multimodal transport future, might be equally important to investigate. As suggested by Gaio and Cugurullo (2022), future advancements in mobility should prioritise mobility justice and mode choice rather than primarily promoting a single transport mode such as automated vehicles. Policy-driven initiatives that promote active transport and more inclusive urban environments, such as reducing the speed of automated vehicles in urban areas, reallocating urban road infrastructure to active transport, and separating automated vehicles from vulnerable road users to a greater extent, may be a viable direction forward.

3.4.4 Limitations

While this chapter provides a comprehensive overview of the communicative technologies and solutions identified for cyclists, we cannot claim it is a complete and fully systematic review. The literature searches showed that the research field on communicative solutions for cyclist interaction with automated vehicles is relatively new and emergent, and there is presently no widespread agreed-upon terminology to describe these concepts. The lack of nomenclature in the field warrants an explorative approach to the literature review rather than a systematic approach. Thus, we do not provide detailed information about the search strings used to identify publications, but rather the categories of keywords combined in the searches. Moreover, only some of the coding taxonomy variables used to categorise the concepts were based on previous research (Dey, Habibovic, Löcken, et al., 2020). Our coding taxonomy has not been formally validated nor tested for internal reliability. In light of these limitations, the results from the analysis should be interpreted and considered as indicative of trends rather than definitive conclusions.

Most of the concepts identified in our study have not been tested or evaluated with automated vehicles. Interpreting the need for and necessity of the systems based on the results from evaluations with or without other road users is challenging. However, in the new and emerging field of automated vehicle-cyclist interaction, we argue that the inclusion of concepts not primarily designed for vehicle interaction is beneficial if the concept technology is deemed to have the potential to be adapted for use with vehicles. In our study, we define potential as the ability of the technology or device to be developed or adapted for use in the context of vehicles with automation capabilities beyond SAE level 2. For instance, the Bicycle Light Communication System by Westerhuis et al. (2021) is intended to support cyclists in traffic with other cyclists by displaying their speed, braking, and turning intentions. Although the concept was tested and evaluated in the context of cyclists, the information emitted by the light communication system could be interpreted by automated vehicle sensors and used to calculate cyclists' behaviour and trajectories. Other concepts, such as the on-bike warning system by Erdei et al. (2021), were evaluated in the context of testing signal perception and the effects of communication modalities among cyclists. The authors argued that warning systems could increase cycling safety by informing the user of imminent critical situations related to other

road users or high-risk cycling conditions, but they did not specify the exact functionality of their warning system. Still, such proof-of-concept studies show the potential for further development of cyclist support systems in the context of conventional motorised vehicles and automated vehicles. The inclusion of concepts that have not been tested nor evaluated with automated vehicles in the present study provides a broader overview of the technologies available to cyclists. A broader overview contributes to uncovering more knowledge gaps in the literature and may be beneficial to future research, testing, and development of concepts for supporting cyclists in future automated traffic.

3.5 Conclusion

The findings from this study provide a synthesis of the present literature on automated vehicle-cyclist interaction and an overview of the state-of-the-art cyclist support systems. We aligned this overview with knowledge about cyclists and their behaviour from a human factors perspective and explored whether the solutions meet cyclists' needs in future automated traffic. Focusing on technology-driven solutions, we propose that the future of cyclist support systems may be a passive beacon or chip system that connects cyclists with vehicles, other road users, and infrastructure. This system could be paired with on-vehicle eHMIs that are visible from all around the vehicle and incorporate two-way communication if deemed feasible. However, drawing conclusions based on the evaluations of the concepts identified in this study or recommending a particular type of system is not feasible before the concepts are tested and evaluated in the context of automated vehicles or vehicles. Testing the type of system and the effect of communication modality on performance and safety in more complex and representative scenarios involving automated vehicles would be beneficial. Investigating the effect of visual versus auditory and motion-based modes of communication on cycling performance, safety, situational awareness, and mental workload are important directions for future research. In particular, augmentation concepts and head-up displays for cyclists, although already commercially available as AR glasses, remain largely unexplored by academia. Finally, our study promotes ethical discourse by highlighting the ethical implications of connected road users and suggests that the transportation system may benefit from a more inclusive and less car-centred approach, shifting the burden of safety away from vulnerable road users and promoting more cyclist-friendly solutions.

Chapter 4

User interfaces for cyclists in future automated traffic

In future traffic, intelligent user interfaces may aid cyclists in interpreting the behaviour of automated vehicles. Cyclists can be equipped with obstacle-detecting sensors, and an interface could display relevant information or use audible alerts to warn or inform cyclists of other road users' intent and potential hazards. Researching user interfaces for cyclists is vital for understanding how users can efficiently and safely interact with automated vehicles. This study presents the development of two human-machine interfaces (HMIs) for cyclists in future automated traffic. To develop the interfaces, we re-analysed interview data from 30 cyclists in Norway and the Netherlands. The analysis resulted in two interface concepts: the app CycleSafe and an omnidirectional on-vehicle interface capable of communicating cyclist recognition and vehicle intent. This preliminary design study sets the stage for future empirical research by identifying cyclists' requirements and HMI design considerations to enhance cyclists' interactions with automated vehicles. Investigating the effects of different communication modalities on cyclist performance, safety, and situational awareness remains an important direction for future research.

This chapter is based on an extended version of Berge, S. H., De Winter, J., & Hagenzieker, M. (2023). User Interfaces for Cyclists in Future Automated Traffic. In *Companion Proceedings of the 28th International Conference on Intelligent User Interfaces* (pp. 91-94). <https://doi.org/10.1145/3581754.3584140>

4.1 Introduction

Integrating automated vehicles into the transport system raises concerns about the potential impact on vulnerable road users such as cyclists. As cycling is an increasingly popular mode of transport (Schepers et al., 2021), it is crucial to understand how automated vehicles and cyclists interact to ensure the cyclists' safety and continued inclusion in the transport system.

Human-machine interfaces (HMIs) allow users to interact with a device, program, or machine. The electrification of bicycles and the introduction of HMIs can potentially revolutionise the cycling industry and enhance the overall cycling experience, including cyclists' interaction with automated vehicles. Regarding safety, bicycles can be equipped with self-balancing technology (Wintersberger et al., 2022; Wintersberger et al., 2021) and sensors detecting obstacles or conflicts (Englund et al., 2019). An HMI for cyclists could include a display showing cyclists relevant information or warning signals of potential collisions or other hazards (Kreißig et al., 2022; Lindner et al., 2022; Von Sawitzky et al., 2021; Von Sawitzky, Wintersberger, et al., 2020).

Additionally, HMIs can support cyclists in a range of modalities: on infrastructure (De Angelis, Stuiver, et al., 2019), vehicles (Dey, Habibovic, Löcken, et al., 2020), and wearables such as augmented reality (AR) glasses (Von Sawitzky, Wintersberger, et al., 2020), mobile phones (Lindner et al., 2022), and helmets (Matviienko et al., 2018). With the advent of intelligent interfaces and connected transport systems, researching HMIs for cyclists is essential for understanding how users can efficiently and safely interact with these technologies.

In this study, we apply an exploratory, qualitative approach by analysing interview data to develop HMI concepts improving cyclist interaction with automated vehicles. For the analysis of the interview data, we derived the following research questions:

- What type of information do cyclists require from automated vehicles?
- What types of design strategies are applicable to cyclist-oriented HMIs?

The goal is to develop HMI concepts for cyclists tailored to improve their interaction with automated vehicles.

4.2 Method

This study uses qualitative data collected by Berge, De Winter, et al. (2022), available at the 4TU.ResearchData repository (Berge, De Winter, et al., 2022). The dataset contains 30 transcripts from interviews with 15 cyclists in Norway and 15 in the Netherlands. The semi-structured interviews were conducted online via Microsoft Teams or Zoom. To compile a variety of experiences from European cyclists, the Netherlands and Norway were chosen as the countries with high and low percentages of cyclists (Schepers et al., 2021). The countries also differ in cycling infrastructure and culture (Berge, Hagenzieker, et al., 2022). Fifteen cyclists from each country were recruited through social media advertisements shared in the authors' personal and professional networks. The sample consisted of 19 males and 11 females with an average age of 43 years ($SD = 16$). Most participants (73%) cycled daily, and one-third identified themselves as early adopters of technology. The transcripts from the Norwegian interviews were in Norwegian, while the Dutch interviews were in English.

The chosen methodology was thematic analysis adapted from Braun and Clarke (2006). Thematic analysis is a method for organising and analysing qualitative data, which enables

researchers to find patterns or themes in datasets (Ibrahim, 2012). We sectioned the transcripts and analysed data from the following interview guide questions:

- As a cyclist, what kind of information would you need from an automated vehicle?
- Imagine a system or device that helps you interact with automated vehicles. How should this device be designed? How should the device communicate with the cyclist?
- If you could receive information about other road users, such as automated vehicles, through a device or a system on your bike: What kind of traffic information would be useful to receive? What kind of information about cyclists would be useful for the automated vehicle?

The six-phase, inductive, data-driven analysis was carried out in Atlas.ti 9. During phase 1 of the analysis, the analyst read the transcripts numerous times to identify the sections of the transcripts with information from the selected interview questions. In Phase 2, the selected text portions from the transcriptions were coded to create the first coding. Using raw text as codes, the codes were created based on the semantic content of the text segments. Phase 3 involved reviewing and readjusting the codes before categorising them thematically based on their repetition, similarity, and difference (Ryan & Bernard, 2003). Phase 4 of the analysis involved examining the thematic divisions, wherein the codes were classified into sub-themes. Checking the transcripts and continuous re-evaluation of the codes and their alignment with the overarching themes is a part of the thematic analysis' iterative process, where each step is revisited throughout the analysis (Braun & Clarke, 2012). Phase 5 involved identifying and labelling the topics before the final production of the analysis report in Phase 6. A selection of exemplary quotes from the transcripts highlights each theme. The first author of this study translated the Norwegian quotes into English.

Combining the results from the thematic analysis with previous literature, we created mock-up designs of two HMIs. The designs were based on already-available technology identified in the literature (Berge et al., 2023) and took the interviewed cyclists' desired HMI functionality and communication modalities into consideration.

4.3 Results

The results are divided into two sections. The first section outlines the results from the thematic analysis, while the second describes the development of two user interface concepts: a mobile application and an omnidirectional external human-machine interface (eHMI).

4.3.1 Thematic analysis

Our analysis resulted in two main themes: Design strategies and Modality of communication. Each theme has two and four sub-themes, respectively. The following sections outline the themes and their sub-themes, illustrated with quotes to describe the narrative direction of the analysis. Table 4.1 shows an overview of the themes and the sub-themes and the number of interviews the respective themes occurred in.

Table 4.1. Overview of the themes and sub-themes

Theme	Sub-theme
Design strategies (30)	Functionality (30) Cyclist needs (27)
Modality of Communication (30)	Auditory (11) Visual (25) Haptic (7) Vehicle interfaces (28)

Note: The numbers in the parentheses represent the number of interviews in which the theme occurred. For instance, sections with codes allocated to the theme Modality of communication were identified in all 30 interviews. Still, only 11 of the interview transcripts contained codes grouped in the sub-theme of Auditory. This means 19 out of 30 transcripts were not coded with codes allocated to the sub-theme Auditory.

Design strategies

Functionality

Functionality was the most prominent theme in the analysis and contains ideas for human-machine interface (HMI) design strategies and desired HMI features. The system was envisioned as an app or a cyclo-computer, a system embedded into the handlebars, or as wearables such as augmented reality (AR) glasses, smartwatches, and helmets. One of the most commonly mentioned functionalities of a cyclist HMI was to receive recommendations such as information about congested roads, changes in navigation, speed, or weather.

"A kind of speed advice would be nice. [The system] gives me advice on what kind of speed to go, until you reach the intersection, because for cars in some kind of models, if you keep going 50 then you always have green lights. So, if I also have something on my bike that tells me what the speed should be to always reach green". (P19)

"Maybe the gadget could give an estimate: 'You won't make it to the roundabout now, with the speed you've had the last few meters. You shouldn't change lanes now because there is too much traffic.' You could get information like that". (P2)

Another potential HMI feature recurrently identified in the interview data was the ability to detect and predict the trajectories of other road users.

"On a narrow and winding road, I don't always know if a car is coming around the next bend. It would have been nice to know that. And also, if there are any cars coming, if there are any cars coming behind you, I would have liked to know that too". (P2)

"Let's say a car is speeding next to you and they are probably going to turn (...) right just in front of you (...). Basically, they want to cut you off, so your smartphone will tell you: OK, this car is going to turn. Yeah, that would be great".. (P21)

"You have a device that sends signals to a self-driving car, so that the car knows that there is a bike at a distance, and it has time to turn without slowing down or to avoid an accident. Like GPS systems on ships that plot other ships while are sailing, and then you can sit and look at the radar: 'Now the ship is approaching on a collision course, so you have to turn, or something will happen'. You could have one of those on a bike too, that's probably not a bad idea. Then you could give signals to each other, and the bike could also receive that now a car is coming up behind you". (P1)

In the interviews, several of the cyclists recognised that device features such as detecting other road users would require connectivity between road users in the transport system.

“I would expect that maybe bikes would also have some kind of transmitters on them because I for sure expect that cars will be able to discuss with each other. Exchange information and exchanging information about whatever accidents or traffic jams or these kinds of things, but also being aware of each other's location and position. And maybe that would be in the future of bikes too where they have some kind of a GPS transmitter as well that would make them visible through the GPS to the cars as well. So instead of only being based on the visuals of cameras and maybe some of the lidars that some cars have, you would also have a more direct connectivity between them”. (P21)

“I could imagine that [the device] can talk with cars in its vicinity, and it could also tell me that a car is in my area or close to me or maybe within one meter (...). And then, I can get on my display a sign, a blinking red or whatever, that a car is closing in on me. It could be helpful”. (P27)

The most frequently mentioned functionalities relevant to vehicle interaction can be seen in Table 4.2.

Table 4.2. The most frequently coded HMI functionality

#	Functionality	Description	n
1	Recommendations during cycling	A device providing real-time recommendations or information while cycling, e.g., navigation and route changes, information about traffic congestion, accidents, speed, cadence, and weather.	23
2	Detecting other road users	A system detecting other road users and conveying their speed, trajectories, and intention (e.g., yielding) to the cyclist, most commonly suggested through a radar-like display.	15
3	Detection indicator	A system indicating that the cyclist is detected by the automated vehicle.	14
4	Connectivity	A system that connects bicycles or cyclists to automated vehicles.	10
5	Warning system	A warning system prompting the cyclist in case of close proximity to an obstacle, critical situations, or vehicles approaching from behind or the side.	9
6	Smart infrastructure	A system incorporating information from smart infrastructure, e.g., a countdown timer for a green light or a system that changes the light in favour of the cyclist.	7
7	Augmentation	A system that displays augmented information, most commonly mentioned as a function of AR glasses.	6
8	Intent indicator	An intent indicator, e.g., on-bike turn signals.	4
9	Crash/fall sensor	A crash or fall detector alerting emergency services.	2

Note: The n indicates the number of interview transcripts containing codes associated with each functionality. The prevalence of a certain functionality does not indicate whether the functionality was regarded as a positive or negative feature of an HMI concept.

Cyclist needs

The sub-theme of Cyclist needs covers the design strategies and functionalities the interviewed cyclists preferred and might need in future traffic with automated vehicles. One of the most frequent topics among our participants was the need to be seen in traffic. Most participants also indicated a preference for explicit communication of recognition by the automated vehicle.

“I'm just thinking about interactions... because it's challenging when cycling. (...) That I know the car has seen me or has registered me. That if I get feedback on that, [it] would make it easier to cross an intersection”. (P8)

“I would like the car to show very clearly that he's going to the right direction or the left direction, but I guess that's what they will show [through intent indicators]. It would be nice if they can have some special light so that they know that I'm next to them, or near them”. (P16)

The analysis indicated that an HMI should be designed as simple and intuitive. The device's benefit must be clear to its users. Some of the interviewees expressed that cycling is an attractive mode of transport due to bicycles' simplicity and relatively low price: Adding more technology, and technology to ensure safe interaction with automated vehicles, in particular, was not desired. Vulnerable road user safety should not be contingent on devices or HMIs, and a device should not be mandatory.

"The disadvantage? It's expensive. And then there might be a bit of a class divide. Those who can't afford a bike with all that [equipment], would still have to deal with traffic in a regular way. So, it might become a crutch in the sense that you depend on that system. Otherwise, you are on your own. You are at risk". (P7)

"It could be an idea to have something on the bike that makes it easier for the car to see the bike. But I don't think you'll get everyone to have [a device]. Say there are 700,000 inhabitants in Oslo, and there are 600,000 bikes. You can't sell 600,000 of one thing when the cyclists understand it as something that is only there to help car drivers and to sell cars. In principle, it could make the cyclist safer. But the problem is that if not everyone has it, (...) it is deadly". (P15)

"I see no reason why a car should be allowed to have a lower standard than what is required by a human driver today. It should not be necessary to upgrade the bike's technology to be detected, or for the car to have worse technology than what a human driver represents. (...) The challenge is that it becomes one more thing to deal with, in a situation where you are already a vulnerable road user and the weaker party. I have no input on something I believe shouldn't exist". (P10)

Modality of communication

Auditory

Audio was generally not preferred as a modality of communication. Audio can be difficult to perceive due to traffic noise and cyclist equipment (e.g., helmet), which might be distracting. However, audio allows cyclists to keep their visual attention on the road compared to a visual modality. Audio has potential if combined with haptic feedback and for universal design purposes.

"I think sound would be very annoying. Maybe. If you think about it, if there are almost only self-driving cars, it will be a lot of noise all the time". (P8)

"If it was up to me, I would probably want vibrations. I think... along with some kind of light. It's better than sound because sound can startle you or be distracting". (P1)

Visual

The analysis indicated that visual information should be simple, symbol-based, and visible in direct sunlight. A display should be small and convey vital information only. For some participants, light-based signals were preferred over auditory modalities.

"I think the key here is to display only vital information that doesn't notify you too often. Yeah, a map that doesn't change every second - you know where you are; you don't need to see it every two seconds. You check it at every crossroad or every summit". (P21)

"I think that having a screen mounted on the handlebar is a very good device. It gives you information about the surroundings (...), other traffic participants that are crossing in my direction. It will be almost like a radar, I think. That they can see which direction I am cycling, and that device should know those who are crossing my direction, they could come up visually on the screen". (P3)

“I would like to have it like a display. And then on this display could also be my route, if I need to go somewhere, and then with a small light on it, when there is a vehicle approaching me, or which vehicles are approaching me”. (P16)

Haptic

With haptic feedback, cyclists can keep their visual attention on the road.

“Some sensory feedback... If you think about a screen, it's something to see. I think if it was handlebars with vibrations, you would feel it right away. You don't have to move your gaze. You could keep an eye on everything around you but feel in your hands that ‘something is there’”. (P8)

Natural vibrations from the pavement and bike may interfere with a haptic modality. When prompted, the participants preferred haptics from the handlebars rather than the seat.

Vehicle interfaces

According to our analysis, the most critical requirement of a vehicle system is to detect cyclists and predict their trajectories. This type of functionality will likely require connected road users.

“I think it helps to have connected vehicles. Like platooning and car platooning, they're coming up with a lot of technologies where cars communicate with each other. And if bicycles could be added to that network (...). I think that would be very beneficial. It's as simple as having the bicyclist's smartphone connected to a certain network, so the car knows that there is someone at the junction”. (P23)

The interviewed cyclists suggested that vehicles should be equipped with an objective indicator of automated vehicle behaviour, e.g., on a display, light, or LED lightbar, with different colours indicating the detection of the cyclist or the automated vehicle's intention.

“It would be nice to see that the car has identified me and is going to stop, if there is a light or the same way to have a hand interaction with the driver to say thanks. Maybe the car can do those signalling, and it will give the green light to me to acknowledge that the car has seen me, and I can proceed”. (P24)

“Maybe it would have been practical to have a light signal, for example. Not on the pedestrian crossing but on the car. Indicating that it [the vehicle] has seen me, and it is braking. Otherwise, it would not be very smooth if I have to wait until the car has stopped completely”. (P9)

“[I would like to know the vehicle's] intention, what they want. If I'm approaching an intersection, the car is approaching from a distance, I think the same motion cues would be helpful if it's given in the same way as it is today. If the driver is slowing down or accelerating. But it might maybe benefit the traffic if, for example, this intention is communicated by other means that could be visible to pedestrians or cyclists from a distance. It means that I can cross, and the car still doesn't need to decelerate that much, so you can increase the traffic efficiency”. (P25)

“The drivers can flash their light or something like that, to signal: ‘Hey, you can go first’. I would really appreciate that. Or maybe indicators. Any form of a signal rather than the hand wave from the inside of the car. That would make me feel a little bit safer”. (P23)

“If they get some technology that can use the outside of the car as a display, or something. Instead of turn signals, there could be a big LED screen on the back of the car”. (P7)

4.3.2 Interface development

On-bike and wearable HMI: CycleSafe

The interface concepts were developed to accommodate cyclists' needs and characteristics extrapolated from the thematic analysis. The analysis uncovered that cyclists' primary need in traffic with automated vehicles is to be seen. Cyclists also prefer explicit communication of detection from the automated vehicle. However, as seen in Table 4.2, the three most frequently mentioned features of a cyclist-oriented HMI were a system detecting other road users – including vehicles and other cyclists – and conveying information about their trajectories and intentions to the cyclist while also providing an option for real-time recommendations about navigation, speed, and traffic information. The communication modality of choice varied among the interviewees, but a visual interface was the most recurring modality in the analysis. The first interface concept, CycleSafe, aspires to meet these criteria. CycleSafe (see Figure 4.1) is a mobile application that utilises bicycle, vehicle, and infrastructure sensors combined with mapping technology to detect the presence and location of other road users and display this information on the screen.

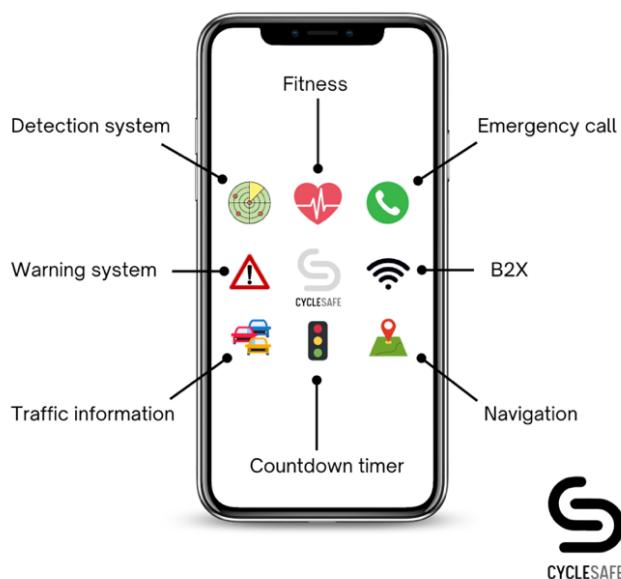


Figure 4.1. A mock-up of the mobile application CycleSafe

The application also includes an alert system for critical or urgent situations, such as an imminent conflict with a vehicle, e.g., an approaching vehicle, a vehicle in the cyclist's blind spot, or a vehicle attempting to overtake the cyclist, as well as features like speed tracking and turn-by-turn navigation. See Figure 4.1 and Table 4.3 for other proposed features, such as emergency calls and traffic light countdown timers.

Table 4.3. The features of CycleSafe

Feature	Description
Fitness	Opens the user's selected fitness app, e.g., Strava or Wahoo Fitness.
Emergency call	Crash or fall detector system, alerting emergency services if the set parameters are met.
B2X	Bicycle-to-everything communication.
Navigation	Opens the user's selected navigation app, e.g., Google Maps or Bikemap.
Countdown timer	A feature incorporating data from smart infrastructure, showing a screen with a countdown timer for a green light.
Traffic information	Informs the user of traffic congestion or changes a predetermined route.
Warning system	A system that warns the user of urgent or critical situations requiring immediate action.
Detection system	A system that detects other road users in the environment and displays their trajectories on the screen.

Omnidirectional eHMI

Vehicle interfaces were discussed in 28 of the 30 interviews. About half of the interviewees suggested that on-vehicle interfaces should be designed as an objective indicator of automated vehicle behaviour, such as display, light, or LED lightbar, with different colours indicating the detection of the cyclist or the automated vehicle's intention. Cyclists have higher speeds than pedestrians and interact with vehicles longitudinally and in crossing and merging situations (Berge et al., 2024). To accommodate cyclists' behavioural characteristics, movement patterns, and desire for explicit detection communication, we developed the second concept: an omnidirectional eHMI placed on the vehicle (see Figure 4.2).

Building on the principle of minimal information access cost (Wickens et al., 2014), our proposed eHMI concept uses an LED light strip visible around the vehicle. The LED strip is capable of communicating whether the car is in automated driving mode, yielding or not yielding, and can provide cyclists' feedback on detection. As an omnidirectional concept, the eHMI applies clear and unclear multicast, as well as broadcast, communication strategies (Dey, Habibovic, Löcken, et al., 2020): By being visible from all around the vehicle, the concept can target multiple specific road users at a time through its proximity indicators, communicate the vehicle's yielding and non-yielding states to non-targeted multiple road users, and broadcast its automated driving state omnidirectionally. Adhering to the design principle of familiarity and top-down processing (Wickens et al., 2014), we propose that the LED light strip uses colours traffic participants are already familiar with for communicating the detection of cyclists: The light strip changes colour from cyan to yellow, orange, and red depending on the proximity of the cyclist to the vehicle.

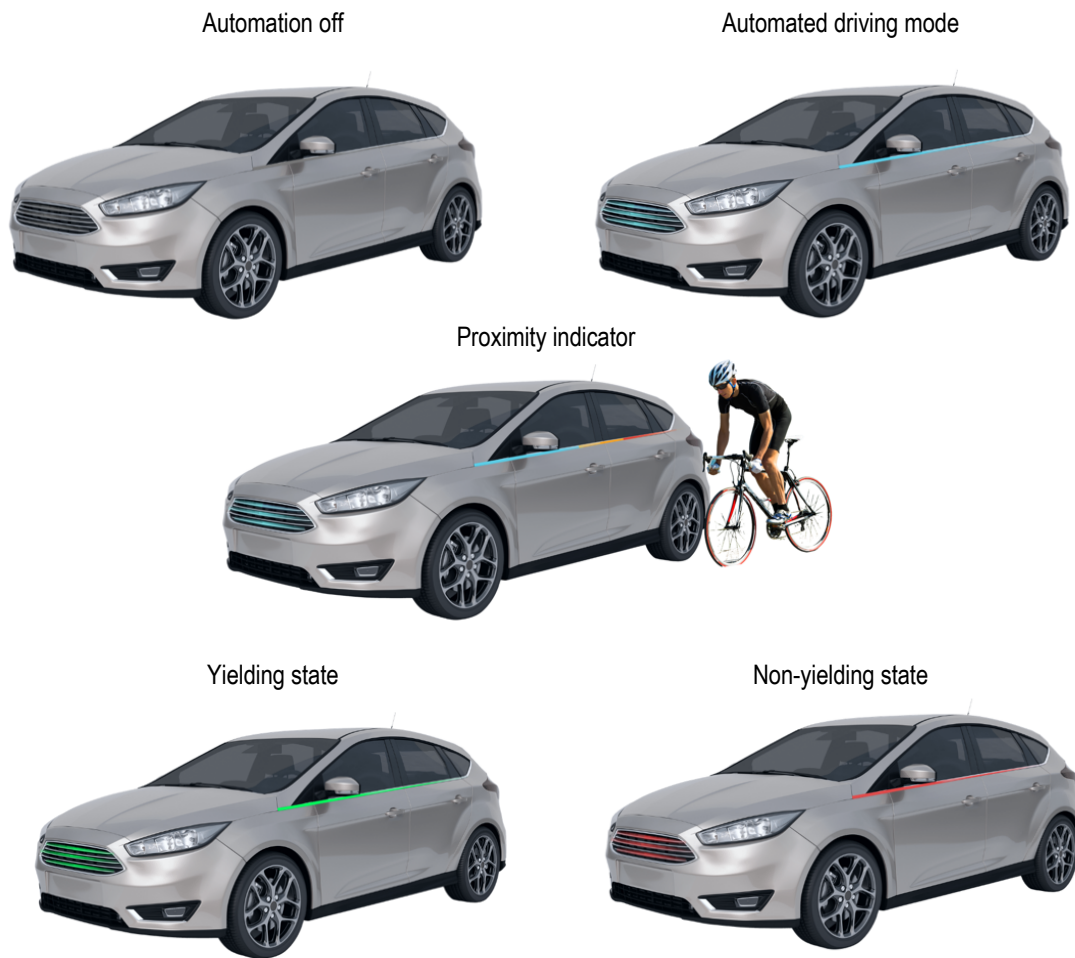


Figure 4.2. The omnidirectional eHMI concept

As cyan is easily visible, perceptible to colour-deficient individuals, and not yet used in traffic signs (Dey, Habibovic, Pfleging, et al., 2020; Werner, 2019), the light strip is cyan when automated driving is active. This is in line with recent developments in the automotive industry: the use of cyan as automated driving marker lights has been approved for Mercedes-Benz in the US (Mercedes-Benz, 2023).

The light strip of our concept can change colours to indicate intention. For example, in a yielding state, the colour could turn solid green or solid red if the vehicle is assertive and taking its right-of-way. Green was chosen as the colour indicating the vehicle is yielding and that it is safe for the cyclist to continue pedalling, as the colour was indicated as the most intuitive for communicating crossing (Bazilinskyy et al., 2020). A green light indicating yielding also adopts an egocentric perspective, as the cyclist is told they can continue pedalling, which is in line with previous research on pedestrians (Bazilinskyy et al., 2019; Dey, Habibovic, Löcken, et al., 2020). Research on pedestrians also indicates that a red bar communicating the vehicle yielding was perceived as safe if activated early rather than late in the interaction (Bazilinskyy, Kooijman, et al., 2021).

The eHMI system must likely be connected to the vehicle's lidar and camera sensors for the detection component. The use of lights and colours moving along the LED strip aims to satisfy the interviewed cyclists' requirement to communicate detection and vehicle intent.

4.4 Discussion

The objective of this study was to develop cyclist-oriented user interfaces to improve cyclists' interaction with automated vehicles by exploring the type of information cyclists want and require from automated vehicles and the appropriate design strategies for a cyclist-oriented HMI. Based on the results from the interviews, we developed two concepts that have the potential to aid cyclists in future automated traffic. CycleSafe is an HMI concept that utilises ubiquitous devices such as smartphones. The app's proposed features reflect the most prevalent suggestions from the sub-theme Functionality. As suggested by our interview participants, incorporating a similar concept into AR glasses might be a more feasible option, depending on how widespread the technology becomes in the future (Tabone, De Winter, et al., 2021).

Our thematic analysis revealed that on-bike HMIs such as CycleSafe should not be mandated as a safety measure in traffic environments that include automated vehicles. The ethical implications of shifting the burden of safety onto vulnerable road users are further discussed in Berge, Hagenzieker, et al. (2022) and Berge et al. (2023). Nevertheless, cyclists might be more inclined to adopt on-bike HMIs if they are offered utility beyond improved safety. CycleSafe provides value through features that serve multiple purposes, not as a mere warning tool aiding automated vehicles. The inclusion of detection and warning systems along with bicycle-to-everything functionality are supplementary benefits to the other features, provided the user's smartphone and bicycle are equipped with the necessary technological capabilities to support these functions.

In the interviews, a frequent concern raised by the cyclists was the need to be detected by the automated vehicle. Besides improved vehicle sensors and technology, detection could be enhanced through road user connectivity, such as bicycle-to-everything communication. Filling the potential void of social interaction with driverless vehicles, the cyclists we interviewed also preferred detection to be communicated explicitly, which aligns with previous research (De Winter & Dodou, 2022; Merat et al., 2018). Recognition could be indicated through the CycleSafe app; however, for cyclists who prefer bicycles to be void of such technology, an eHMI is a more viable option. Our previous studies suggested that an eHMI should be designed omnidirectionally and be visible all around the vehicle to accommodate cyclists' movement patterns and eye-gazing behaviour (Berge et al., 2024; Berge et al., 2023; Berge, Hagenzieker, et al., 2022).

The eHMI concept presented in the current study aims to cover cyclists' need for recognition and their movement patterns by an omnidirectional design and lights changing colour to indicate the proximity of the cyclist to the vehicle. Similar concepts have been proposed in previous literature, e.g., "The Tracker" by Dey et al. (2018), inspired by Nissan's IDS concept (Nissan Motor, 2015). Similarly, our eHMI concept illuminates a corresponding section of the light band around the vehicle in spatial proximity to the vulnerable road users detected. Our concept differs as it functions as an inverted proximity sensor, indicating the distance to the road user with a gradient of yellow to red, where red indicates the closest proximity of the cyclist or pedestrian. Moreover, the LED band illuminates in full solid green or red to indicate to single or multiple road users that the vehicle is yielding or not yielding in ambiguous situations, such as an unsignalized intersection or if outside road users are blocking the vehicle's path. The use of the colour cyan to indicate that automated driving systems are active does not involve the same bias as towards the colours red and green, but it may appear confusing (Dey, Habibovic, Pfleging, et al., 2020). The use of green and red to indicate yielding and non-yielding states, respectively, might also lead to some confusion about whether the message is

allocentric or egocentric, meaning the recipient might be unsure if green means the car is going or telling the vulnerable road user that it is safe to cross (Bazilinskyy, Kooijman, et al., 2021). It is important to note that many of these studies are performed online via photos or videos, and usually from a pedestrian's perspective. The choice of colours and intensity of the LED band to indicate the different messages for cyclists need further investigation.

Regarding the modality of communication, the interview participants disregarded auditory messages as they might interfere with surrounding traffic. Instead, the most common suggestion was a visual HMI. However, a visual HMI may be distracting as it prompts cyclists to place their visual attention away from traffic. Previous studies on cyclist HMIs point towards an auditory modality as the most efficient modality of communication (Erdei et al., 2021; Strohaecker et al., 2022). Whether audio is a viable modality for cyclists in busy traffic environments with multiple sources of sound and noise is questionable. In situations with a high mental workload, multimodal communication, such as visual-haptic, might be a more efficient solution (Burke et al., 2006). Comparing visual and haptic feedback, cyclists slightly preferred haptic (Engbers et al., 2016). Our interview participants suggested that haptic signals might be challenging to distinguish from vibrations originating from the road, which is in line with Erdei et al. (2021). However, in Engbers et al. (2018), haptic feedback from the bicycle was considered intuitive and easy to distinguish from vibrations caused by cycling.

The HMI concept CycleSafe mainly communicates messages visually through a display on the bicycle. Previous studies on HMIs for vulnerable road users indicate that *redundant cues*, communicating messages through multiple modalities, such as text, icons, and intuitive colour schemes, can promote informed user decision-making (Bazilinskyy et al., 2019; Tabone, Happee, Yang, et al., 2023). Moreover, in perceptually degraded environments, the concurrent presentation of visual and auditory messages is more likely to ensure the correct perception of warnings (Wickens et al., 2014). Given that traffic presents a high level of sensory stimuli, which may overwhelm cyclists' abilities to perceive their surroundings accurately, urgent messages displayed on CycleSafe could be communicated with more than one modality, e.g., visually, auditory, or as haptic feedback. The efficiency of single and multimodal communication on cyclists in different traffic environments should be explored in future research.

4.4.1 Limitations

A limitation of the present study is that none of the HMI designs have been tested or evaluated in a real or simulated environment. They were also designed retrospectively from interview data without user input during the design process. Without visual prompts, the interviewees could only speculate about design elements such as the communication modes, placement, colours, patterns, and intensity of the messages conveyed by the HMI. Involving the user in the entire design process could lead to more optimised HMIs tailored to cyclists, potentially increasing their effectiveness and safety. It is crucial that our HMI concepts are further developed through empirical evaluation with end-users.

The HMI concepts presented in this chapter were designed to accommodate cyclists' requirements in future traffic with automated vehicles. However, the practicalities and legalities of implementing such designs in real-life traffic were outside the scope of this study. The designs must likely be aligned with the vehicle's existing lighting scheme and altered to comply with legal constraints dictating luminosity, colour, and light patterns to avoid interfering with traffic safety. Moreover, as we based the designs on data from interviews performed in Norway

and the Netherlands, the HMI concepts are principally developed with Northern European traffic environments in mind. Consequently, the design criteria established in this study might not translate to regions where cycling culture and infrastructure considerably differ. Future iterations of the designs would benefit from more diverse perspectives.

4.5 Conclusion

This study investigated user interfaces aiming to improve cyclists' interaction with automated vehicles. The results from the interview data indicated that cyclists require accurate detection and explicit confirmation of detection from automated vehicles. Moreover, an HMI must be intuitive, and its benefit must be clear to its user. Our findings indicated that cyclists tend to favour visual communication cues. The analysis resulted in two HMI concepts: the smartphone app CycleSafe, incorporating various features ranging from traffic information, navigation, and warning systems, and an omnidirectional eHMI providing cyclists confirmation of detection and additional information about the automated vehicle's intentions. Utilising a multimodal approach is likely feasible to ensure clear and effective communication in urgent situations, considering the sensory-rich urban traffic environment of cyclists. Overall, this preliminary design study sets the stage for future empirical research to determine efficient and safe HMI design considerations for cyclists. Investigating the effects of different communication modalities on cyclist performance, safety, and situational awareness remains an important direction for future research.

Chapter 5

Triangulating the future: Developing scenarios of cyclist-automated vehicle interactions from literature, expert perspectives, and survey data

Automated vehicles pose a unique challenge to the safety of vulnerable road users. Research on cyclist-automated vehicle interaction has received relatively little attention compared to pedestrian safety. This exploratory study aims to bridge this gap by identifying cyclist-automated vehicle scenarios and providing recommendations for future research. In this study, we triangulated three sources: a systematic literature review of previous research on cyclists and automated vehicles, group interviews with eight traffic safety and automation experts, and questionnaire data. The resulting scenario collection comprised 20 prototypical scenarios of cyclist-automated vehicle interaction, grouped into four categories based on the road users' direction of movement: crossing, passing, overtaking, and merging scenarios. The survey results indicated that right-turning vehicles, dooring scenarios, and more complex situations have the highest likelihood of accidents. Passing and merging scenarios are particularly relevant for studying automated vehicle communication solutions since they involve negotiation. Future research should also consider phantom braking and driving styles of vehicles, as well as programming proactive safety behaviours and designing on-vehicle interfaces that accommodate cyclists.

This chapter is based on Berge, S. H., De Winter, J., Cleij, D., & Hagenzieker, M. (2024). Triangulating the future: Developing scenarios of cyclist-automated vehicle interactions from

literature, expert perspectives, and survey data. *Transportation Research Interdisciplinary Perspectives*, 23, 100986. <https://doi.org/10.1016/j.trip.2023.100986>

5.1 Introduction

Automated vehicles present a unique challenge for the safety of vulnerable road users (vulnerable road users). Human road users exhibit unpredictable behaviour and interact according to social and cultural norms (Tabone, De Winter, et al., 2021). Programming the social aspect of human behaviour is challenging, particularly in complex urban traffic environments (Rasouli & Tsotsos, 2020; Schieben et al., 2019). vulnerable road users are a diverse road user group, further complicating their interactions with automated vehicles (Holländer et al., 2021). In the human factors field, research on automated vehicle interaction with vulnerable road users has focused on safety, with key focus areas on the crossing behaviours of pedestrians (Rasouli & Tsotsos, 2020), vehicle acceptance (Merat et al., 2017; Nordhoff et al., 2018), and infrastructure planning (Blau et al., 2018; Botello et al., 2019). Additional attention is given to external human-machine interfaces (eHMI), which serve as communication tools between automated vehicles and other road users like pedestrians and cyclists (Bazilinskyy et al., 2019; Dey, Habibovic, Löcken, et al., 2020; Rouchitsas & Alm, 2019).

Cyclists differ from pedestrians in eye-gazing behaviour as they focus more on the road and perform fewer shoulder checks (Trefzger et al., 2018). Cyclists also differ from pedestrians in movement patterns and speeds. Cyclists are more likely to share the road with vehicles, leading to close encounters when travelling longitudinally as well as at crossings: In the majority of same-direction cyclist-to-vehicle accidents analysed by Díaz Fernández et al. (2022), cyclists and vehicles were travelling in the same direction without intending to cross each other's trajectory. However, studies indicate that most accidents occur when the vehicle approaches the cyclist from a perpendicular direction (Kuehn et al., 2015; Kullgren et al., 2019; Utriainen & Pöllänen, 2021). The most prevalent type of cyclist-vehicle crashes in Europe involved vehicles approaching from the left or right direction of the cyclist, accounting for 38% of all fatal cyclist accidents (Brown et al., 2021).

Targeting cyclists as a specific road user group in research is vital to better understand and plan for safe cycling in the future of automated traffic. Representative test scenarios are necessary for realistic and comprehensive assessments of the interaction between cyclists and automated vehicles. A *scenario* can be defined as “a description of the sequences of actions and events performed by different actors over a certain amount of time. The scenario specifies goals, objectives, and environmental information related to the different actors” (Wilbrink et al., 2018, p. 13). By simulating real-world scenarios, it is possible to identify the potential challenges and limitations of automated vehicle technology and assess the vehicles' ability to navigate complex traffic environments with vulnerable road users. Moreover, research using representative test scenarios can help uncover safety concerns and identify areas of improvement, ultimately ensuring that automated vehicles are safe and effective for use on public roads. More specifically, representative test scenarios of cyclists' interaction with automated vehicles can be used to explore cyclists' perceptions of and responses to automated traffic, test the efficiency of communication interfaces on vehicles, bicycles, cyclists, or infrastructure (Berge et al., 2023), and perform safety assessments of automated vehicle systems.

Though it is anticipated that by 2030, most new vehicles will be equipped with automated driving systems (Winton, 2022), researchers in human factors are sceptical about introducing fully automated vehicles in the coming decades (Gaio & Cugurullo, 2022; Tabone, De Winter, et al., 2021). In the meantime, cyclists encounter vehicles with varying degrees of automation, ranging from partially automated, such as lane assist and adaptive cruise control, to highly automated systems that can operate without human intervention in certain conditions. Previous cyclist scenario development studies have focused on building scenarios from accident data (Camp et al., 2016; Díaz Fernández et al., 2022; Kuehn et al., 2015). As of early 2023, reports of 546 automated vehicle collision reports were publicly available online (State of California Department of Motor, 2023). Car manufacturers' accident and incident databases involving automated vehicle systems beyond SAE level 2 systems (Shi et al., 2020) are mostly unavailable in the public realm. In general, there is a lack of knowledge on how automation changes vehicle behaviour from the cyclists' perspective and the behavioural markers needed to define automated vehicle behaviour in empirical studies.

In this exploratory scenario development study, we apply a mixed methods approach by triangulating data from a systematic literature review, group interviews, and a questionnaire with traffic safety and automation experts. The objectives are three-fold:

- To identify the types and characteristics of scenarios used in previous research on cyclists and automated vehicles.
- To identify the typical behavioural characteristics of automated vehicles and the types of novel situations that may arise with increasing degrees of vehicle automation.
- To provide recommendations for future research on cyclist-automated vehicle interaction.

The overall goal is to generate representative and realistic test scenarios of cyclists' interaction with automated vehicles and to provide recommendations and guidelines for defining automated vehicle behaviour in future research on cycling in automated traffic.

5.2 Method

In this chapter, we present the development of scenarios to test the interaction between cyclists and automated vehicles. The methods section consists of three parts: the systematic literature review of previous research on automated vehicles and cyclists, group interviews and the analysis of the interview data, and the survey used to evaluate the previously identified scenarios.

5.2.1 Systematic literature review of automated vehicle-cyclist interaction

We performed searches on the titles, abstracts, and keywords in Scopus and Web of Science with the following keywords, combined with AND/OR Booleans: **cyclist**, *automated*, *driverless*, *autonomous*, *self-driving*, *vehicle**, *experiment*, and *scenario*. In addition, we conducted searches on ResearchGate and Google Scholar with similar keywords to locate preprints and grey literature. The initial search was performed on July 5th 2022, and updated to include new publications as of October 21st 2022.

To be included in the analysis, the publications had to satisfy the following inclusion criteria:

- Academic publication: Journal article, conference paper, book, or report.

- Empirical or scenario development study involving the interaction between at least one cyclist and one automated vehicle.
- The study must indicate that the vehicle has automation capabilities beyond SAE level 2, i.e., studies examining the effect of one particular automated support system (e.g., automatic braking or adaptive cruise control systems) were excluded.
- The study must involve a cyclist or bicycle, i.e., studies on powered two-wheelers, such as motorcycles, scooters, or mopeds, were excluded unless the results were disaggregated by road user group.

Figure 5.1 shows the number of identified publications and the screening process following PRISMA (Page et al., 2021). The first step of the identification process involved reading the title and abstract of the publication. If the publication met the inclusion criteria, it was sought for retrieval. The full-text publications were subsequently assessed for eligibility. As seen in Figure 5.1, 30 publications were excluded for two reasons:

- The publication did not describe a specific scenario of automated vehicle-cyclist interaction ($n = 28$).
- The publication contained identical scenarios and variables as another publication in the study sample ($n = 2$).

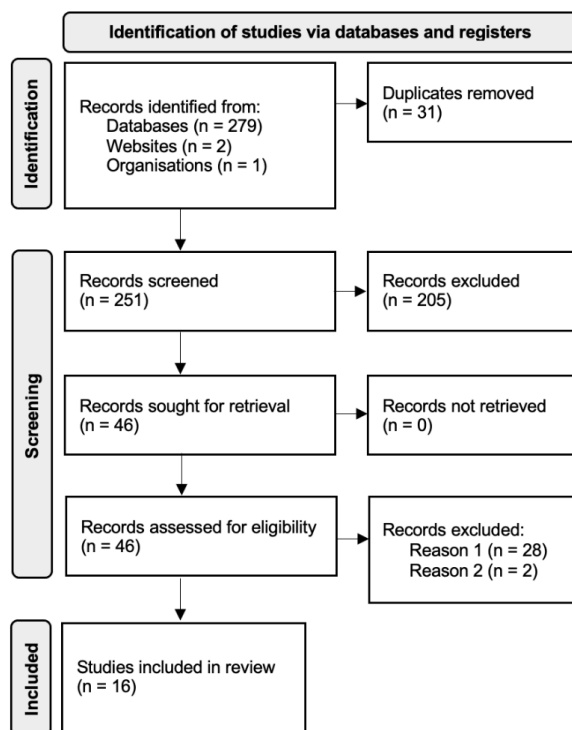


Figure 5.1. PRISMA flow diagram of the literature review

The literature sample was analysed and coded using a taxonomy of 17 variables that describe the scenarios' environmental, spatial, and temporal characteristics of the interaction between the cyclist and the automated vehicle, such as the infrastructural layout, weather, and the direction of movement. The taxonomy also included variables describing factors related to the road users themselves, such as the number of road users involved in the interaction, line of sight, and right of way. The taxonomy was developed iteratively, drawing on the attributes and value facets in Fuest, Sorokin, et al. (2018) and the three attribute clusters in Wilbrink et al. (2018). The variables *Time of day*, *Weather condition*, and *Road condition* were adapted from

Dey, Habibovic, Löcken, et al. (2020). The variable *Point of impact on the bicycle* was adapted from Englund et al. (2019) and indicates the location of an impact on the bicycle if a collision occurs. For instance, a vehicle approaching from a perpendicular direction would cause a point of impact on the front of the bicycle, on the left- or right-side tangent in the direction the vehicle is approaching. The publications were analysed and coded by the first author. In the preliminary coding, the categories were continuously evaluated and modified for suitability through discussion among the authors. After establishing the final taxonomy, the literature sample was coded and analysed descriptively through frequency counts in Microsoft Excel.

5.2.2 Group interviews

We conducted two semi-structured group interviews with eight researchers working with traffic or cycling safety, automation, and human factors. The interviews took place in person in May and June 2022 at the experts' respective workplaces and had an average duration of 110 minutes. The interviews started with an introduction to the present project, followed by round table introductions. As shown in Table 5.3, the interview guide was divided into four main topics.

Table 5.3. The interview guide with a selection of questions

Topic	Question
1 Cycling safety and pleasant interactions	In an ideal world, how would we design for pleasant cycling? How do we design for safe cyclist interactions with vehicles? Which types of preventive actions, behaviours, or mechanisms do you think plays a role when cycling?
2 Automation and interaction with automated vehicles	What kind of information do cyclists need to be safe in traffic with... <ul style="list-style-type: none"> • Conventional vehicles? • Semi/partially automated vehicles (e.g., L2 vehicles, with a steward)? • Fully automated vehicles (with or without on-board passengers)?
3 Definitions of use cases and scenarios	How would you define a use case for cyclist interaction with vehicles? What is a scenario? In a scenario, which elements should be described?
4 Use case and scenario development	Where and when do cyclists interact with vehicles today? Will there be any new type of situations when interacting with partially automated vehicles? Which use cases are most relevant or important to test in cycling research? What kind of factors or elements do we need to account for? Why?

The interview guide was phrased as open-ended, enabling follow-up questions and discussions. Each question in the interview guide was displayed on a screen and repeated by the interviewer throughout the interview. See Appendix D for the complete interview guide.

At the beginning of the interviews, the interviewer encouraged the participants to speak and discuss freely and to draw and take notes. The interviewer's role was to mediate the discussions. The participants had access to paper, post-it notes, pens, and markers during the interviews. During the scenario development phase, the interviewer consecutively took notes from the discussion on post-its and placed the post-it notes on the table in front of the participants, categorising the notes into groups of locations cyclists and vehicles interact, e.g., at crossings, intersections, and straight roads. At a later stage of the scenario development phase, post-it

notes with characteristics of scenarios were added to each location group. The post-it note sorting, a technique considered helpful in organising multiple pieces of information or concepts (Faiks & Hyland, 2000), was aimed to give structure to the scenario development phase and help the participants visualise the type of situations cyclists may experience in traffic.

Prior to the interviews, participants digitally received and signed an information sheet and consent form through Adobe Sign. The participants agreed that anonymised written interview transcripts could be published in a university repository in line with open science principles. The Human Research Ethics Committee of the Delft University of Technology approved the study.

Sample and recruitment

We opted to include two institutes from two different countries to gather a range of scenarios relevant to countries with varying shares of cyclists (Buehler & Pucher, 2012; Schepers et al., 2021), cycling facilities, and cycling culture (Berge, Hagenzieker, et al., 2022): One of the group interviews was performed in English at a Dutch institute for road safety research, and the other in Norwegian at a Norwegian institute of transport research. The sample was selected by contacting relevant participants in the authors' professional networks. Both interviews had four participants, and the sample consisted of seven trained psychologists and one civil engineer. The participants had on average 15.6 years ($SD = 9.8$) of professional experience with transport-related topics.

Analysis

The methodological approach was thematic analysis, adapted from Braun and Clarke (2006). Thematic analysis provides a systematic way to organise and analyse qualitative data, allowing researchers to identify patterns or themes within a dataset (Ibrahim, 2012). The analysis was performed using ATLAS.ti 9 and consisted of a six-phase inductive and data-driven process. In Phase 1 of the analysis, audio from the interviews was transcribed clean verbatim removing filler and repetitive words. The transcripts were read several times to familiarise the analyst with the data. Regarding the language used during data collection and analysis: The researcher was proficient in both languages, mitigating potential language barriers. It is worth noting that both the researcher and participants are professionals in the field of traffic safety and automated vehicles, providing a shared context for the discussions. During Phase 2, initial coding was generated by coding text segments from the transcriptions. The codes were generated based on the text segments' semantic content, using raw text as codes. In Phase 3, codes were checked and readjusted before being sorted into thematic categories according to repetition, similarities, and differences among the codes (Ryan & Bernard, 2003). In Phase 4, we reviewed the thematic categories and grouped the codes into sub-themes. As thematic analysis is an iterative process, the codes and their allocation to their overarching theme are reassessed during the first four phases (Braun & Clarke, 2006). Phase 5 consisted of defining and naming the themes before, finally, Phase 6: Writing a full analysis report. Each theme is illustrated with a selection of representative quotations from the transcripts. The selected quotes may be excerpts from a more extended conversation and are edited for clarity, removing repetitive words and incomplete sentences. The selected quotes from the Norwegian interview were translated into English by the first author of this study. The full transcripts from the interviews and the analysis are available at 4TU.ResearchData, see section Research data.

5.2.3 Triangulation of methods

In this study, we apply a mixed methods approach by triangulating data from a systematic literature review and group interviews. Triangulation of methods is a qualitative assessment of data involving multiple data collection methods about the same phenomenon (Polit & Beck, 2013). Using multiple methods, we can compare the results from different sources to see if they align, potentially increasing the findings' validity and internal consistency (Hussein, 2009). Moreover, the triangulation of methods may provide a broader understanding and uncover meaningful insight into a phenomenon, which is particularly useful when the topic of investigation is complex and multi-faceted (Carter et al., 2014; Thurmond, 2001). To strengthen the triangulation, we evaluate the findings from the literature review and interviews in a questionnaire with the interviewed traffic safety and automation researchers.

Survey with traffic safety and automation experts

Upon completing the literature search and thematic analysis of the group interviews, a set of 20 scenarios were identified. To develop representative test scenarios applicable to assessing the interaction of cyclists and automated vehicles and the efficiency of HMIs, the scenarios must be evaluated for accident risk and relevance to current and future traffic environments. A survey was created in Qualtrics, measuring the scenarios' likelihood of an accident, frequency of occurrence today, and frequency of occurrence in the future with automated vehicles (SAE levels 3-4) on a 1–5 Likert scale ranging from “very low” to “very high”. In addition, the participants were prompted to explain their answers. A link to the survey was sent out by e-mail to the eight expert interview participants on September 5th 2022, followed by a reminder on September 16th 2022. The survey had a 100% response rate. The data from the survey was analysed descriptively in Microsoft Excel, calculating the average score of the *accident likelihood* and *frequency of occurrence today* and *frequency of occurrence in the future*. The variable *occurrence* (see Table 5.7) was calculated by subtracting the means of *frequency of occurrence in the future* from the means of *frequency of occurrence today* to assess the assumed change in frequency of occurrence per scenario. The text fields from the survey were analysed qualitatively through summarisations.

5.3 Results

The results are divided into three sections. First, we provide an overview of the systematic literature review results and the scenario characteristics identified in the study sample. Second, we outline the results from the thematic analysis of the group interviews with traffic safety and automation experts. Finally, we present the triangulation of the data sources, which includes an inventory of 20 scenarios of cyclist-vehicle interaction, relevant variables to cyclists' interaction with automated vehicles, and findings from a survey assessing the likelihood of accidents, frequency of occurrence today, and frequency of occurrence in the future for each scenario. We conclude this section by summarising the triangulation of methods and offering recommendations for future research.

5.3.1 Systematic literature review of automated vehicle-cyclist interaction

We identified 16 publications meeting the inclusion criteria: Ten journal articles, four conference proceedings, and two scientific reports. Table 5.4 outlines the characteristics of the study sample, including the number of identified scenarios, the scope of the studies, and the sources or assumptions used to develop the scenarios.

Table 5.4. The characteristics of the study sample and the sources of the identified scenarios

Reference	Scenario type	Number of scenarios	Scope	Sample	Scenario source
Bazilinskyy et al. (2023)	Illustrations	4*	Replicate the Vlakveld et al. (2020) study with an international sample, and examine the effects of blinded windows, driver presence, eye contact, and the visual complexity of the surrounding environment of cyclists.	1260 and 1086 participants	Situations at unsignalized intersections that frequently result in bicycle-car accidents (Räsänen & Summala, 1998; Schepers et al., 2011).
Boersma et al. (2018)	Real-world	1	Piloting the use of an automated shuttle bus: The legal challenges, technical aspects, infrastructure, and integration in the surroundings.	n/a	A rural bike road in Appelscha, Netherlands.
De Ceunynck et al. (2022)	Real-world	5	The types, characteristics, and frequency of interactions between automated shuttles and vulnerable road users	Video footage	Urban environments in Oslo, Norway.
Fritz et al. (2020)	Illustrations	3	Introduction of use cases and methodology to explore cyclist-vehicle interactions in a real-life setting.	n/a	The method for developing the scenarios was not described.
Hagenzieker et al. (2020)	Photo	5	Cyclists' expectations and behavioural intentions when interacting with automated vehicles.	35 participants	The photos were of real-life traffic, but the basis for choosing the traffic situations was not specified.
Hou et al. (2020)	Simulator	1	Interface concepts for cyclists interacting with automated vehicles.	18 cyclists	Based on road infrastructure in Calgary, Canada.
Kaß et al. (2020)	Simulator	3	Development of a methodological approach for determining the benefits of cyclist-oriented external human-machine interfaces.	20 cyclists	The origin of the scenarios was not described.

Lindner et al. (2022)	Simulator	1	The perceived safety of a mobile application for aiding cyclists and passengers of an automated vehicle.	16 cyclists	The origin of the scenarios was not described.
Ngwu et al. (2022)	Illustrations	6	Teenage cyclists' perceptions of infrastructure design and interfaces for interaction with automated vehicles	25 cyclists	The illustrations of the infrastructural designs originated from KOA Corporation (2015).
Núñez Velasco et al. (2021)	360 degrees video	2	The crossing intentions of cyclists based on vehicle type, gap size, speed, and right of way.	47 participants	The origin of the scenarios was not described. The videos were filmed on a rural road in the Netherlands.
Oskina et al. (2022)	Real-world	2	The safety of cyclists interacting with automated vehicles.	29 cyclists	The origin of the scenarios was not described. The data collection took part on a straight road in the Netherlands.
Parkin et al. (2022)	Real-world and simulator	2	Cyclist and pedestrian trust in automated vehicles.	33 and 37 cyclists	The authors argued that the scenarios in their study represent more complex situations than a simple crossing scenario, where the automated vehicle has to negotiate with human road users to proceed.
Pokorny et al. (2021)	Real-world	3	The behaviour of an automated shuttle bus and vulnerable road users encountering the shuttle bus.	Video footage	Urban environments in Oslo, Norway.
Stange et al. (2022)	Real-world, simulator, and online video animations	2	Automated vehicle passengers' braking behaviour and perceived risk in scenarios with a pedestrian or cyclist.	10, 28, and 118 vehicle passengers	"A space-sharing conflict that may occur between highly automated vehicles and vulnerable road users", as identified by Markkula et al. (2020) (Stange et al., 2022, p. 167).
Vlakveld et al. (2020)	Video animations	15	Cyclists' intention to yield for automated vehicles where the	1009 participants	Situations at unsignalized intersections that

				cyclist has the right of way.		frequently result in bicycle-car accidents (Räsänen & Summala, 1998; Schepers et al., 2011).
Wilbrink et al. (2018)	et	Illustrations	3	Define common terminology and a framework for describing use cases and scenarios of the interaction between automated vehicles and other road users.	n/a	The use cases and scenarios were developed in a workshop with the project partners and were anchored in previous research on pedestrians and vehicles. We did not find any studies on cyclists in the literature base of the scenarios.

Note: *Experiment 1 of the study involved 180 photos depicting 2 traffic conflict types \times 3 vehicle types \times 3 window types \times 2 visual complexity levels of the surroundings \times 5 urgency levels. We consider the two types of traffic conflicts combined with the visual complexity level of the surroundings (vehicle from left vs right and rural vs urban environments) as four distinct scenarios for the purpose of the present review. Experiment 2 used a subset of 36 of the 180 photos.

As shown in Table 5.4, only six of the publications involved descriptions of field observations or real-world scenarios of cyclists and automated vehicles (Boersma et al., 2018; De Ceunynck et al., 2022; Oskina et al., 2022; Parkin et al., 2022; Pokorny et al., 2021; Stange et al., 2022). Five publications in our study sample were simulator studies (Hou et al., 2020; Kaß et al., 2020; Lindner et al., 2022; Parkin et al., 2022; Stange et al., 2022). Additionally, one of the identified publications involved a scenario filmed in 360 degrees video (Nuñez Velasco et al., 2021), four publications described animated or still photo scenarios edited to include automated vehicles (Bazilinsky et al., 2023; Hagenzieker et al., 2020; Stange et al., 2022; Vlakveld et al., 2020), and one focus group interview study on teenage cyclists explored potential infrastructure designs, and communication interfaces through illustrations (Ngwu et al., 2022). Lastly, our study sample included two publications describing the development of automated vehicle-cyclist scenarios (Fritz et al., 2020; Wilbrink et al., 2018). In both cases, the scenarios were illustrated from the automated vehicle's point of view or the expected behavioural characteristics of the automated vehicle.

We taxonomically coded the sample from the literature review to identify the overall prevalence of scenario characteristics. Table 5.5 depicts the environmental, spatial, and temporal attributes and the road user and vehicle characteristics of the scenarios identified in the literature sample.

Table 5.5. The environmental, spatial, temporal, and road user attributes of the identified scenarios from the literature sample

Variable	Category	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Infrastructural layout	Roundabout					x											
	Straight		x	x	x		x			x	x	x					
	T-junction	x		x	x	x		x				x		x		x	x
	X-junction	x							x				x		x	x	x
	Y-junction							x									
	Shared space			x													
Cycling facilities	No bike lane		x	x	x			x	x	x	x	x	x		x		x
	Bike lane	x		x			x			x			x	x		x	
	Separated bike path	x			x	x				x						x	
	Unspecified					x											
Direction of movement	Same	x	x	x	x	x	x	x	x	x	x		x			x	x
	Perpendicular	x		x		x		x					x	x	x	x	x
	Opposite	x		x		x		x				x				x	x
Time of day	Daytime	x				x	x	x	x	x	x	x	x	x	x	x	x
	Evening												x				
	Night-time																
	Unspecified		x	x	x												
Weather condition	Direct sunlight										x	x					
	Indirect sunlight	x				x	x	x	x	x		x	x	x	x	x	
	Rain																
	Snow																
	Unspecified		x	x	x												x
Road condition	Clean roads	x	x	x		x	x	x	x	x	x	x	x	x	x	x	
	Water on road																
	Snow on road																
	Unspecified				x												x
Environment	Rural	x	x					x		x	x	x			x	x	
	Urban	x		x	x	x			x	x			x	x		x	x
Number of moving vehicles	1	x	x		x		x	x	x		x	x	x	x	x	x	x
	2				x	x							x			x	
	3												x				x
	4												x				
	Unspecified			x		x				x							
Number of other vulnerable road users than the cyclist	0	x			x	x	x	x			x	x		x	x		x
	1												x			x	
	2												x			x	
	3												x			x	
	Unspecified		x	x						x							
Right of way	Cyclist	x		x	x	x		x			x	x	x	x	x	x	

	Vehicle		x	x	x	x		x					x		x		x
	Undefined		x					x		x							x
Line of sight	Clear	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Semi-obstructed	x											x			x	
	Obstructed					x											
	Unspecified		x														
Point of impact on the bicycle	Front		x	x	x	x		x	x			x				x	x
	Front left	x		x		x		x					x	x	x	x	x
	Front right	x		x		x		x					x	x	x	x	x
	Rear		x	x	x		x			x	x		x				
	Side					x				x							x
Vehicle: Type	Passenger car	x					x	x	x	x	x	x				x	x
	Shuttle bus		x	x									x				
	Unspecified					x									x		
Vehicle: eHMI	Yes	x					x	x	x		x	x				x	x
	No	x	x	x	x	x		x	x	x			x	x	x	x	x
Vehicle: Level of automation	Low (0-1)																
	Medium (2-3)					x							x	x			
	High (4-5)					x										x	
	N/A	x					x	x	x	x	x	x				x	x
Vehicle: Attention on-board user	Attentive	x	x					x									
	Attentive, but no eye contact during interaction		x														x
	Distracted																x
	Unspecified		x				x	x	x	x	x	x	x	x	x		x

Note: 1: Bazilinsky et al. (2022), 2: Boersma et al. (2018), 3: De Ceunynck et al. (2022), 4: Fritz et al. (2020), 5: Hagenzieker et al. (2020), 6: Hou et al. (2020), 7: Kaß et al. (2020), 8: Lindner et al. (2022), 9: Ngwu et al. (2022), 10: Oskina et al. (2022), 11: Parkin et al. (2022), 12: Pokorny et al. (2021), 13: Stange et al., (2022), 14: Nuñez Velasco et al. (2021), 15: Vlakveld et al. (2020), 16: Wilbrink et al. (2018). A publication could contain more than one scenario, i.e., all relevant variables were selected per scenario within one publication.

As shown in Table 5.5, the most common scenario was a T-junction in an urban environment during daytime with indirect sunlight and no water or snow on the roads. Only three studies involved a scenario in a roundabout, a shared space, or a Y-junction, respectively. Most scenarios described one cyclist and one moving vehicle, usually a passenger car. The cyclist typically had a clear line of sight to the vehicle, and the SAE level of automation of the vehicle was rarely specified. The most prevalent impact location was on the front, and front left or front right side of the bicycle, indicating that most scenarios were passing and crossing scenarios, where the space-sharing conflict would occur when the vehicle approached from the opposite or perpendicular direction.

5.3.2 Group interviews with traffic safety and automation experts

Five themes and 16 sub-themes were identified in the thematic analysis. Table 5.6 provides an overview and a short description of the themes and sub-themes. The following sections will describe the themes illustrated with quotations from the traffic safety and human factors expert participants.

Table 5.6. An overview and description of the five themes and their sub-themes

Theme	Sub-theme	Description
1 Interaction	Behavioural strategies	Cyclists actively use speed adjustments, placement on the road, hand gestures, eye contact, and sound to communicate in traffic.
	Anticipatory behaviour	Hazard perception is important, and cyclists engage in anticipatory behavioural strategies to stay safe.
2 Safety and comfort	Cycling facilities	Infrastructure and cycling facilities are essential for safe cycling.
	Pleasant cycling	Pleasant cycling involves the absence of friction and conflicts.
	Measures	Infrastructural changes and lower vehicle speeds may affect safety and comfort.
3 Cyclist needs	Expectations	Cyclists expect to be able to predict automated vehicle behaviour and vehicle intention.
	Behavioural indicators	On-vehicle behavioural indicators might be needed.
	Trust	Trust is an important aspect for interaction with automated vehicles.
4 Assumptions about the future	Predictions	Complete segregation of automated vehicles and cyclists is unlikely. Fully automated vehicles are not likely in our lifetimes.
	Expectations	The way cyclists interact in traffic will not change significantly as long as there are still human drivers.
	Technology Changes	More connectivity among road users. Automated vehicles unexpectedly stopping and eliciting unfamiliar driving styles may cause uncertainty.
5 Scenario development	Definitions	Scenarios are prototypical descriptions of future interactions.
	Scenarios	Fourteen scenarios were identified in the interviews, see Table 5.7.
	Factors	The type of cyclist, age, gender, experience, and weather conditions may be important factors to consider.
	Recommendations	Interactive behaviour occurring at an intersection. Regarding automated vehicle behaviour, specifically: phantom braking and driving style.

Interaction

The theme of interaction pertains to the way cyclists interact with other road users in traffic today. The theme is divided into two sub-themes: behavioural strategies and anticipatory behaviour. Cyclists apply a range of strategies to communicate in traffic. In our interviews, cyclists were described as applying both implicit and explicit tactics. The explicit strategies were described as the use of sound, such as a bell and hand gestures to signal intent or direction. Among implicit strategies, speed adjustments, placement on the road, pedalling, posture, and seeking eye contact were mentioned.

The use of eye contact was discussed in both group interviews, particularly whether the term *eye contact* involves the actual eye contact between traffic participants or if it is a euphemism for communication. Movement patterns and speed changes were implicated as more important than eye contact when interpreting other road users' behaviour:

“I don't think I look at the driver to any particular extent. I just look at the movement of the car (...). You see it very clearly with (...) speed. You drive differently as a motorist when you are going to turn than when you don't have to turn”. (N4)

In one of the interviews, it was mentioned that if eye contact occurs, it is likely to be established in complex or hazardous situations. Some cyclists, for instance, wait for eye contact in chaotic environments or when navigating around heavy vehicles due to concerns about blind spots.

The interview participants explained how cyclists engage in anticipatory behaviour by exhibiting caution, maintaining distance from other users, and generally operating under the assumption that they may not be seen:

“The best is to turn on all your lights and wear a reflective vest and still think you are invisible”. (N2)

Safety and comfort

As a theme, safety and comfort investigates cyclists' perceptions and preferences related to safety and comfort while cycling, focusing on three sub-themes: cycling facilities, pleasant cycling, and measures. Cycling facilities emerged as a critical aspect for both safety and comfort. Cycling facilities should have continuity, clear markings of the right of way, sufficient width for overtaking, a smooth surface, and segregation of traffic participants:

“There [should be] a distance between parked cars and the cyclists' lane because when they open the doors”. (D3)

“I also think good separation from other road users...” (N3)

“And a comfortable surface to cycle on”. (N2)

“What we should not have – because there are a number of examples of things to make [cycling] uncomfortable, for example mixing cyclists and pedestrians... so-called combined footpaths and cycleways. We should try to get rid of those as soon as possible”. (N3)

“A horror example of [cycling facilities]: There are cycle paths that are very well facilitated, and suddenly, they end. And then suddenly you are on a road where there are only tram tracks and buses. And then you find yourself in a pedestrian zone”. (N2)

The perception of safe cycling does not necessarily imply that cyclists actually are safe:

“If you think about the cyclists who are killed by right-turning vehicles when they are going straight. They probably felt very safe. They were in the cycling lane, which they felt was theirs, and they felt safe. They didn't have to look around... They think: The truck won't drive here, so I can just go. They felt safe” (N2)

Likewise, safe cycling does not always equate to comfort. In general terms, cycling safety in the context of vehicles pertains to a reduction of interaction points between the road user groups, with segregated cycling infrastructure and signalised intersections. However, separating the terms safety and comfort may be challenging, and there are individual differences in the perception of subjective safety and comfort. While safety takes precedence, one of the discussions concluded that comfort is more than the absence of friction and conflicts:

“The two terms are very well connected, and it's actually a bit difficult to separate them. When you use the term comfortable: If you ask yourself, what does it mean to ride a bike comfortably? Is it the fact that there is an absence of friction and conflicts?” (N4)

“Pleasant cycling includes much more than safety (...). It's not just about separation [of road users]; it should also be easy to find your way. It has to be comfortable to cycle. Because if you constantly have to stop and wonder where the bicycle path continues: It may be safe enough, because there are no dangerous situations, but you can get very frustrated when you're struggling [with navigation]”. (N3)

“I agree that it is like that (...), comfort is an overarching term for safety”. (N4)

“It is perhaps a bit Maslow-like. It is primarily when you feel safe that other things become more important. But when you feel very unsafe, then you don't care if there is a bit of uneven asphalt”. (N2)

Regarding measures to increase safety and comfort, ideas such as city design to accommodate cyclists and reducing vehicle speeds were mentioned. Similarly, infrastructural changes such as adding signalised intersections or moving cycling facilities a bit further away from a complex intersection may improve safety in certain scenarios (e.g., Scenarios 4 and 6 in section 0).

Cyclists' needs

The theme of cyclists' needs explores the interviewees' deductions of the needs of cyclists in traffic with automated vehicles, divided into three sub-themes: expectations, behavioural indicators, and trust.

When questioned about the kind of information cyclists need to be safe in traffic, the interviewees agreed that cyclists' top priority is to be seen. Cyclists will expect detection by automated vehicles and will likely want to know the vehicle's intentions. The transition period from conventional vehicles to a fleet of fully automated vehicles will be long and messy, but it will not necessarily change cyclists' strategies for communicating in traffic:

“I don't think it will change the way we communicate as cyclists. (...) I will just, I guess, desperately behave normal, in an attempt to placate the computer inside the vehicle and tell it “Please can I cross don't hit me”. I guess all those things will stay the same”. (D2)

The interviewees did not fully agree on the type of information cyclists would need in the transition period. An indicator of whether the automation is active might be a desired feature:

“Automation can inform you, there is a cyclist coming, that may cross. It can also take over a part of the driving task, (...) lane-keeping or adaptive cruise control. It can inform you; it can warn you; it can warn other road users. But it can also take away, take over some parts of the driving tasks. The problem when it takes over some, (...), it could make you less attentive when you're driving”. (D3)

“But what do we need as cyclists then?” (D1)

“And cyclists... I want to know whether who is behind the wheel is driving or if he's not driving, or if he's attentive or not attentive”. (D3)

“I agree with [D3]: I would like to know, because if I see an inattentive driver, in the first one [non-automated], then I know, he's not going to stop. But in this case, maybe the vehicle itself will stop. Then I guess for safety, even if I know it's on, I will still not cross because I do not trust them. But maybe if there is external communication... or I can see them slowing down”. (D2)

“Is it important for the cyclist to know if a car is semi-automated? Because let’s take the right-turning car scenario, you would expect when it’s a driver that they’d check, sometimes they don’t. Sometimes the semi-automated or automated vehicle will detect something, and sometimes it won’t. So, does it matter for me as a cyclist? I should always be cautious”. (D4)

A similar discussion commenced in the Norwegian interview. The interviewees mentioned that eHMIs should have added value and were uncertain whether knowledge of automation mode might make a difference. Moreover, some of the Dutch interviewees questioned whether eHMIs are really necessary as cyclists will likely interpret the kinematics of the vehicle instead:

“You want to know if they see you and what their intentions are. The clearest way to communicate is by slowing down or changing your driving behaviour because lights can fail and show something that’s ...” (D2)
“What if there are multiple road users around you?” (Interviewer)
“The only thing that can’t be misinterpreted is slowing down, I guess”. (D2)
“I agree”. (D3)
“And that’s why I’m not sure about the eHMIs. I think there is value there, definitely, but the whole fool proof way is stopping”. (D2)

The interviewees discussed eHMIs providing verification of detection and the possible confusion when multiple road users are involved:

“Would it not be dangerous to include a light, showing you are detected? Because then you would also assume that it works”. (D2)
“But if it does detect you...” (D4)
“Then it will brake, I guess. But if the light is off then it will always...” (D2)
“At the same time: what if it’s detecting something further way?” (D4)
*“It has to detect **you**, and not someone else”. (D3)*

Moreover, an eHMI must be designed to be simple and intuitive to use:

“I think if that the signal has to be... it isn’t enough that the car’s sensors have detected you. It has to be: The car’s sensors have detected you, and something is going to happen”. (N2)
“Therefore, one must look for changes in speed and...” (N3)
“Yes, but I think [the eHMI] must be on a very primitive level in a way... I have read an article from a study where they tested very advanced messages. There were only 3-4 different messages, but it was so complicated that it was”... (N2)
“If you see green and yellow, two flashes - it means I’ve seen you, but I’m going to drive” (N4)
“[eHMIs have to be] at the level of brake lights: They light up red when you brake... at that level, I think... if they could create automated vehicles that they give off signals that on a completely elementary level are intuitively understandable without [the user] having to think and interpret and have background knowledge”. (N2)

For cyclists, the placement of an eHMI in terms of a light or display might pose a challenge because cyclists share the road parallelly with vehicles:

“There would be a lot of screaming vehicles, yeah. Or lights and sounds. And it’s of course not only crossing, because you can be overtaken by a car on a small road, and there is no way to check if a light is on or you will have to bike like this [turns around to illustrate how cyclists would have to turn to see the vehicle approaching from behind], and it would make these things worse”. (D2)

Knowledge about automated vehicle capabilities and experience with vehicles in traffic will also affect the type of information cyclists need. Automated vehicles programmed to be uniform may be essential when cyclists are interpreting and predicting automated vehicle behaviour:

“You’re crossing, and you see that the car is slowing down, then you would cross. There are two scenarios for me: Both times, the car wants to stop, but for one instance, it stops very slowly, so I can see from far ahead that this car is stopping. But sometimes they wait until the last second, they already know that they want to stop, but then they hit on the brakes. And meanwhile, I’m just waiting there, not knowing whether they want to stop or not. I think having automated cars on the road would make it always uniform; you will always notice because they always decelerate at the same rate. When it is fully automated, it is very accurate, but still, as a bicyclist, I want to have it slow down early and slowly because I can see that. Maybe not necessary, but I do want it. I will not trust it when it moves fast and it abruptly brakes”. (D4)

Likewise, trust in automation and experience with automated vehicles are important factors affecting how cyclists will react and interact with automated vehicles:

“I think there are many who would doubt the sensors for a long time... that there is enough redundancy in a way... that if that sensor is dirty, [the automated vehicles] have some other systems that pick it up anyway”. (N1)

“There will be a group of people who will just trust”. (D4)

“Some will, but I won’t”. (D3)

“But if you grow up with automated vehicles and all you have known your whole life is that they will brake if something is in front of them. Never encountered a “normal” vehicle”. (D2)

“That’s true”. (D4)

“But I guess we’re now talking about four lifetimes [from now]”. (D2)

Assumptions about the future

This theme pertains predictions and expectations about the future of automated vehicles and cyclist interaction. The theme is divided into four sub-categories: predictions, expectations, technology, and changes.

The interviewed experts were hesitant to predict the widespread introduction of fully automated vehicles: They were cautious about foreseeing full automation in our lifetimes, citing manufacturer liability as a significant hurdle:

“It’s not so much the technique... It’s a matter of liability” (D3)

“Yeah, I think so, too” (D1)

“How so? Could you explain the liability?” (Interviewer)

“Because then the manufacturer of the car has to guarantee that it will never go wrong and that... no manufacturer, of course, will ever do that”. (D3)

“But I think... I believe that we will, in many years, reach a point where all vehicles are automated and can communicate with each other, the other road users, and the infrastructure. And I think, even if a car manufacturer doesn’t say a 100% “we will avoid all accidents”, already by having that system, the number of accidents will have reduced significantly. I think that’s something to strive for because maybe we can never eliminate it, but if it’s much, much less...” (D4)

“But it will never happen”. (D1)

“I don’t think I will be alive, but I do think it’ll happen. Because I do agree that liability is a huge issue, but it’s also a bureaucratic issue. I think there is no impossibility there. I think all of the aspects of automated vehicles, fully automated vehicles, are solvable”. (D3)

Both interview groups discussed how increasing degrees of automation might depend on the context and type of transport: Vehicles driving on highways or other roads with little to no interaction with vulnerable road users will likely offer full automation mode before vehicles in urban areas, and public transport will likely become fully automated before privately owned vehicles. There is also potential in automated freight transport at night when traffic is lower than during peak hours.

Regarding expectations, it is likely that we will see an increasing amount of connectivity among road users in the coming years. However, as long as there are human drivers on the road, the way cyclists interact with vehicles will likely not change significantly.

“I don’t think it will change much, because if there are still normal cars on the road; unless it’s completely clear what vehicle is fully automated and what is not, I think people will assume that it’s still not safe to jump in front of a car and expect it to stop”. (D4)

When the interview participants were prompted to think of new situations that may occur with automated vehicles, they mentioned the issue of phantom braking:

“They will stop for you when you least expect it because you are so close that you are caught by the sensors. (...). If it turns out that there will only be self-driving cars, then I think that people will start to change their behaviour (...)because then you will learn that they stop a lot”. (N3)

“There are those sudden stops. For quite a while, [the vehicles] will behave differently from normal cars and block the road”. (N4)

“There will be more abrupt stopping. (...). A cyclist hitting a vehicle from behind is not an unusual accident, really. And the risk might be higher if there are more unpredictable, sudden stops among the cars”. (N3)

With increasing degrees of automation, the driving style of the vehicle may become increasingly important to cyclists. The driving style of automated vehicles may have to be regulated to become uniform across manufacturers.

“(...) I think, having automated cars on the road would make it always uniform, you will always notice because they always decelerate at the same rate. (...)” (D4)

“But you do not know — and the thing is, maybe such a car can be hard braking in the very last moment. When it is fully automated, it is very accurate, but still, as a bicyclist, I want to have it slow down, early, and slowly because I can see that. Maybe not necessary, but I do want it. I will not trust it when it moves fast and abruptly brakes”. (D3)

“Is it going to stop? You still have these different brands: Apple cars will stop immediately; Toyota cars will stop from 30 meters” (D1)

“Maybe there will be regulations for that”. (D3)

Scenario development

The scenario development phase of the interviews started with a brief discussion on how to define scenarios and use cases. In general, there was some disagreement and confusion about the difference between scenarios and use cases. The terminology differs between research fields and may be a matter of semantics.

“I would say use cases are intersection, and a scenario would be different interactions of a cyclist crossing an intersection turning right, turning left. Automated vehicles coming from the left, or right, or straight ahead”. (D2)

“Scenario is more the description of what could happen and what has happened”. (D1)

“Or a description of what the situation is, and then to see what would happen. We don’t know what happens, but we know the elements of the situation”. (D4)

“I think it’s a rather semantic discussion... and technical field they speak about use cases and the rest of us speak about scenarios”. (D3)

“I think use cases is a group of scenarios. I think it’s useful to group all intersections”. (D2)

Using the definition of Wilbrink et al. (2018), we settled on the common understanding of a scenario as “a description of the sequences of actions and events performed by different actors over a certain amount of time” (p. 13): A cyclist storyboard.

We encouraged the participants to think of any situation where cyclists interact with vehicles and factors present in the environment. Through the thematic analysis, we identified 14 situations describing the interaction between cyclists and vehicles. Table 5.7 provides an overview of the scenarios and a description of each scenario.

Table 5.7. Overview of the identified scenarios from the thematic analysis

#	Scenario	Description
1	Discontinued bike lane	The cyclist is cycling on a bike lane in congested traffic. At the upcoming intersection, the bike lane is discontinued. The cyclist continues straight through the intersection, merging with the vehicle on the cyclist’s left side.
2	Dooring	The cyclist is cycling on a straight road with on a bike lane. Vehicles are parked next to the bike lane. A vehicle door may open from the right side, or the vehicle might pull out in front of the cyclist.
3	Negotiation	The cyclist is approaching a vehicle in the opposite direction on a narrow road. The road is one lane wide with limited width to pass on each side. The cyclist and vehicle have to negotiate passing each other.
4	Phantom braking	The cyclist is cycling behind a vehicle. The vehicle abruptly and unexpectedly stops.
5	The bi-directional bike track	A vehicle is turning left in a T-junction with a bi-directional bike path parallel to the driving direction of the vehicle. Cyclists are cycling on the bike path in both directions.
6	The bicycle crossing	The cyclist intends to cross a road with vehicles approaching from both directions. The vehicles have the right of way.
7	The bus stop	The cyclist is cycling on a bike lane on a straight road. Up ahead, a bus stops at a bus stop. The bike lane is discontinued right before the bus stop or continues behind the bus stop.
8	The driveway	The cyclist is cycling on a straight road or a sidewalk. A vehicle exits from a driveway from the right of the cyclist.
9	The kerbside takeover	The cyclist is cycling in congested traffic on a road without bicycle infrastructure. At an intersection, the cyclist is positioned on the right side of a vehicle. The cyclist intends to continue straight. It is unclear to the cyclist whether the vehicle is continuing straight or turning right.

10	The left-turning cyclist	The cyclist is cycling straight in congested traffic with vehicles in both directions. At an intersection, the cyclist intends to turn left, crossing the carriageway.
11	The parked vehicle	The cyclist is cycling on a bike lane on a straight road. Up ahead, a vehicle is parked, blocking the bike lane.
12	The right-turning vehicle	The cyclist is going straight at an intersection. The vehicle is positioned on the left side of the cyclist and performs a right turn.
13	The roundabout	A separated bike path runs parallel to the road and crosses the leg of a roundabout. A vehicle performs a right turn and exits the roundabout, intending to cross the bike path in front of a cyclist. The cyclist is cycling straight on the bike path.
14	Fixed track following	The cyclist is cycling between the tram tracks on a road. A tram or a vehicle approach from behind at a higher speed, indicating intent to pass or for the cyclist to get out of the way.

At the end of the interviews, participants were prompted to provide recommendations for scenarios and factors of the environments to focus on in future research. The participants indicated that cyclist factors such as age, gender, experience, and cycling style might be important. Weather and lighting conditions were also mentioned, particularly rainy weather and night-time conditions. Regarding the type of scenario for assessing safety, interactive behaviour occurring at an intersection (e.g., vehicle turning manoeuvres or cyclists crossing the road) was recommended. Focusing on automated vehicle behaviour specifically, phantom braking and the vehicle's driving style were indicated as essential variables to consider in future research.

5.3.3 Triangulation of methods

Scenario collection

We identified 20 scenarios from the triangulation of the literature reviews and the group interviews. The scenarios are grouped into four scenario groups according to the direction of movement at the point of the space-sharing conflict between the cyclist and a vehicle: Crossing, passing, overtaking, and merging scenarios. Figure 5.2 illustrates the scenario groups and the directions of movement of the involved parties.

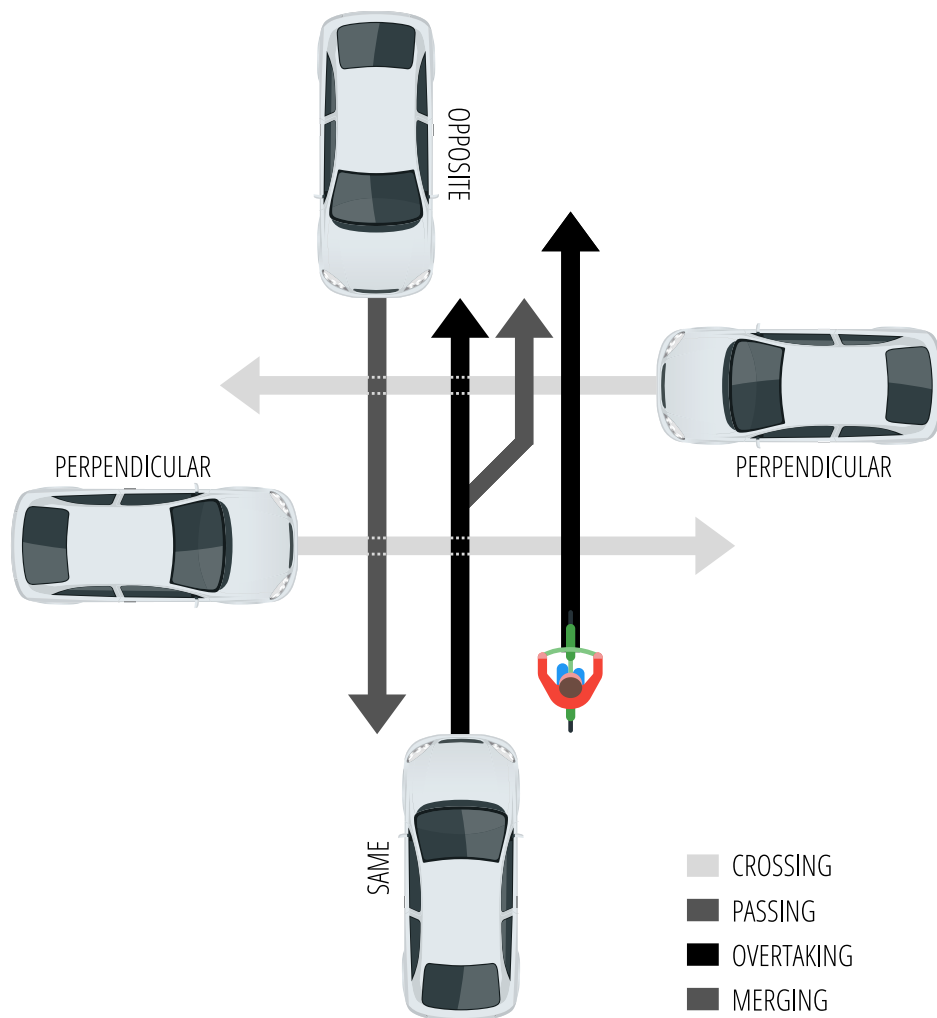


Figure 5.2 Illustration of the four scenario groups and the directions of movement

Note: The dotted lines indicate that the vehicle can change direction. If more than one vehicle is involved in a scenario, the scenario can belong to more than one group.

Scenario group 1: Crossing scenarios

Figure 5.3 shows an overview of the six scenarios grouped as crossing scenarios. In crossing scenarios, the precursor to the interaction between the cyclist and the opposing road user is typically defined by the involved parties moving towards an intersection or crossing.

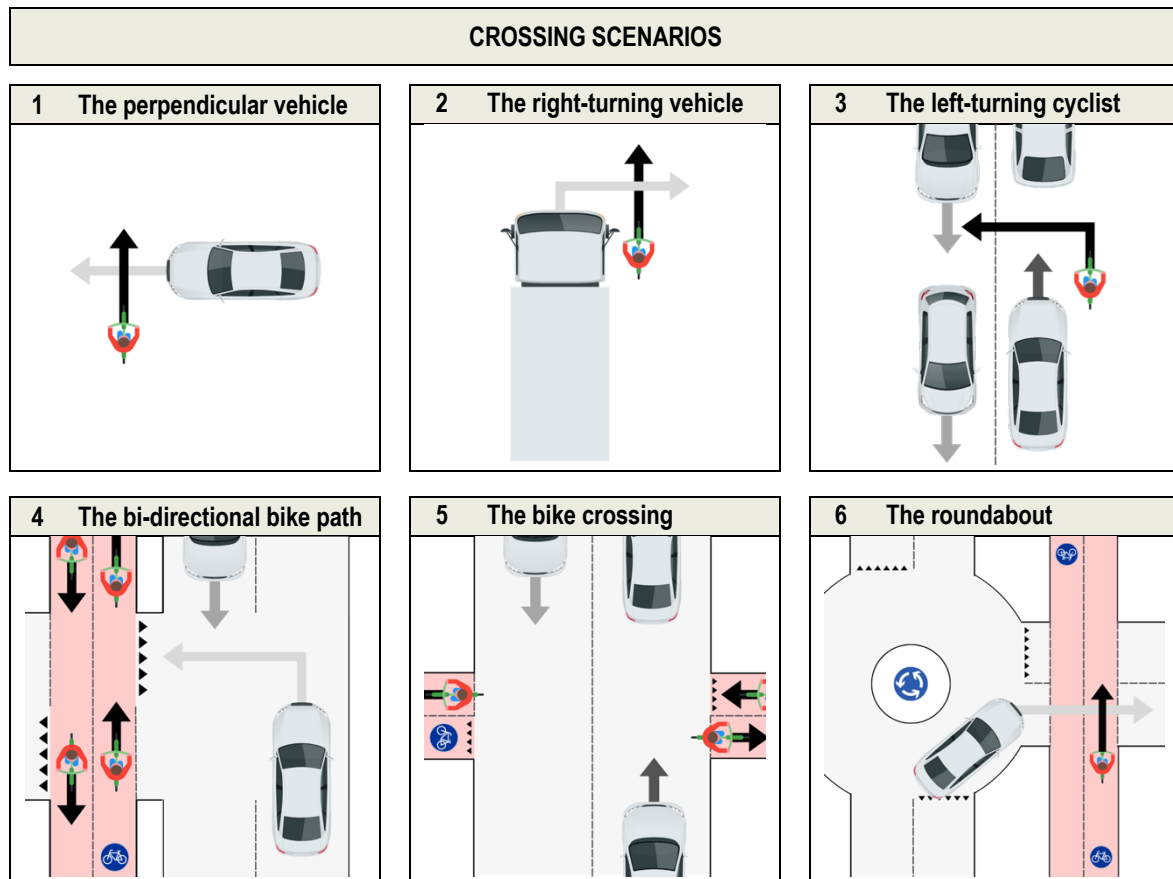


Figure 5.3 Illustrations of the six crossing scenarios

Note: The infrastructural layouts may vary regarding the number of legs, lanes, and other environmental details (e.g., barriers, traffic signs, colours). In Scenario 1, the vehicle may approach perpendicularly from the left or right. Scenarios 1, 2, and 3 are illustrated without infrastructure, as more than one type of infrastructure was identified as relevant to these scenarios. The underlying infrastructure most relevant to these scenarios are X- and T- junctions and shared spaces. Scenario 2 is illustrated with a heavy vehicle as our interview data indicated that vehicle size might be a risk factor in this type of scenario.

As seen in Figure 5.3, the point of interaction occurs when the cyclist's and vehicle's trajectories cross at the intersection. The underlying infrastructural layout of crossing scenarios is intersections (X- and T-junctions), roundabouts, or shared spaces. From the literature review and group interviews, we identified four variables that typically are present and vary in crossing scenarios: cyclist facilities, the type of environment (urban vs. rural), the number of vehicles, and the vehicle trajectory relative to the cyclist (e.g., the vehicle approaching from the left or right direction).

Scenario group 2: Passing scenarios

Illustrations of the four passing scenarios can be seen in Figure 5.4. In passing scenarios, the cyclist and the opposing road user are typically on a straight road or a shared space. The interactive part of the scenario occurs when the cyclist and the oncoming vehicle have to negotiate how to pass each other.

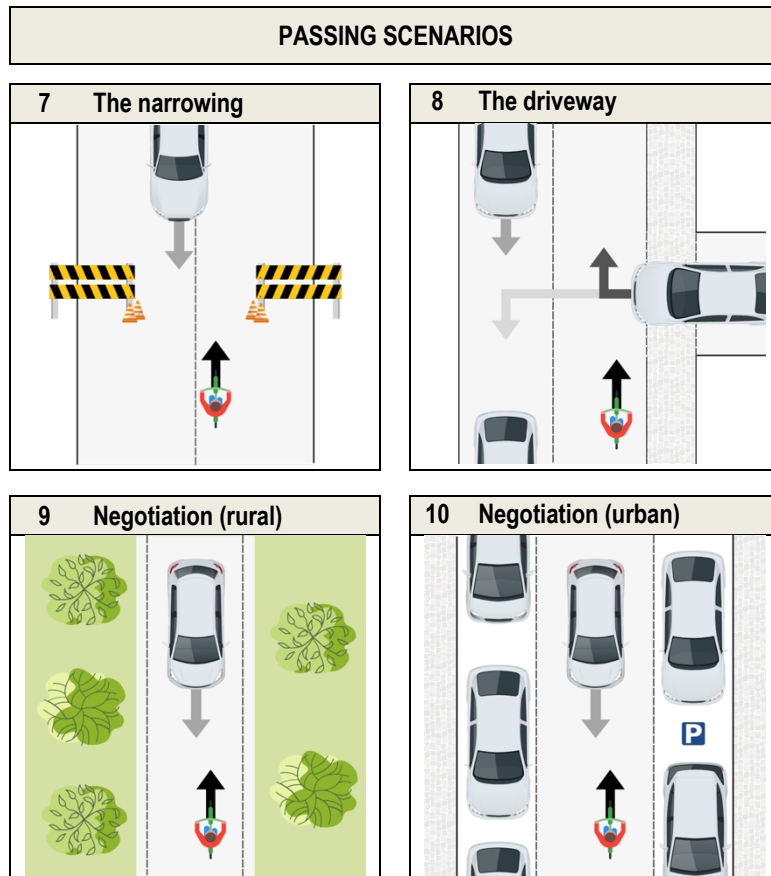


Figure 5.4. Illustrations of the four passing scenarios

Note: The infrastructural layouts may vary in lanes, vegetation, and other environmental details (e.g., barriers, traffic signs, colours). As indicated by the different shaded arrows of direction, Scenario 8 can be interpreted as a passing, crossing, and merging scenario. We have chosen to group it as a passing scenario, prioritising the cyclist's direction of movement: In this scenario, the point of conflict may occur when the cyclist intends to pass the two vehicles. If the right-side vehicle blocks the cyclist's path, the cyclist might swerve onto the lane of the oncoming vehicle, creating a passing scenario.

The directions of movement of the cyclist and the opponent vehicle are typically opposite to each other. However, in a driveway, exit or shared space with no road markings indicating traffic direction, the vehicle may approach from an angled or perpendicular direction (e.g., Scenario 8 in Figure 5.4). From the literature review and group interviews, we identified four variables that typically may be present and vary in passing scenarios: cyclist facilities, the type of environment (urban vs. rural), obstacles or barriers, and driveways or exits.

Scenario group 3: Overtaking scenarios

In overtaking scenarios, the cyclist is either overtaken by a vehicle or must perform a takeover of a vehicle, typically on a straight road where the cyclist's lane is discontinued or blocked (see Figure 5.5).

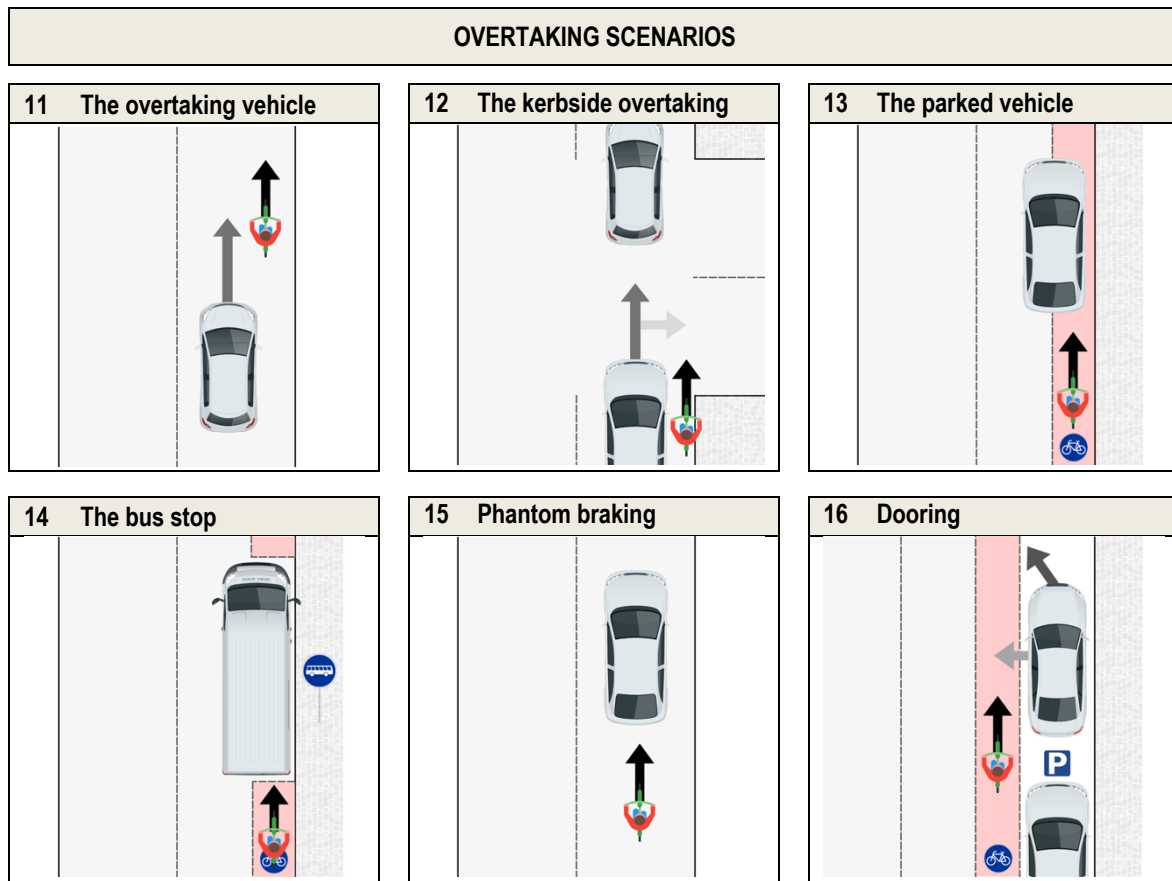


Figure 5.5. Illustrations of the six overtaking scenarios

Note: The infrastructural layouts may vary in terms of legs, lanes, vegetation, and other environmental details (e.g., barriers, traffic signs, colours).

The points of interaction occur before, during, and after the takeover. As seen in Figure 5.5, most of our identified overtaking scenarios were on a straight road. However, overtaking may be executed in intersections (e.g., Scenario 12) and shared spaces. Both cyclists and vehicles are moving in the same direction. We identified three variables typically found and vary within overtaking scenarios: cycling facilities, obstacles, and the number of vehicles involved in the interaction.

Scenario group 4: Merging scenarios

In merging scenarios, the cyclist and the vehicle intend to occupy the same road space moving in the same direction. The interaction occurs when the road users negotiate the right of way, typically on a straight road or at an intersection. Figure 5.6 shows the four identified merging scenarios. Merging scenarios characteristically occur if the cycling infrastructure is discontinued at an intersection (e.g., Scenario 19) or the bike lane is blocked by an obstacle (e.g., Scenario 17). The number of vehicles may add extra complexity to the interaction.

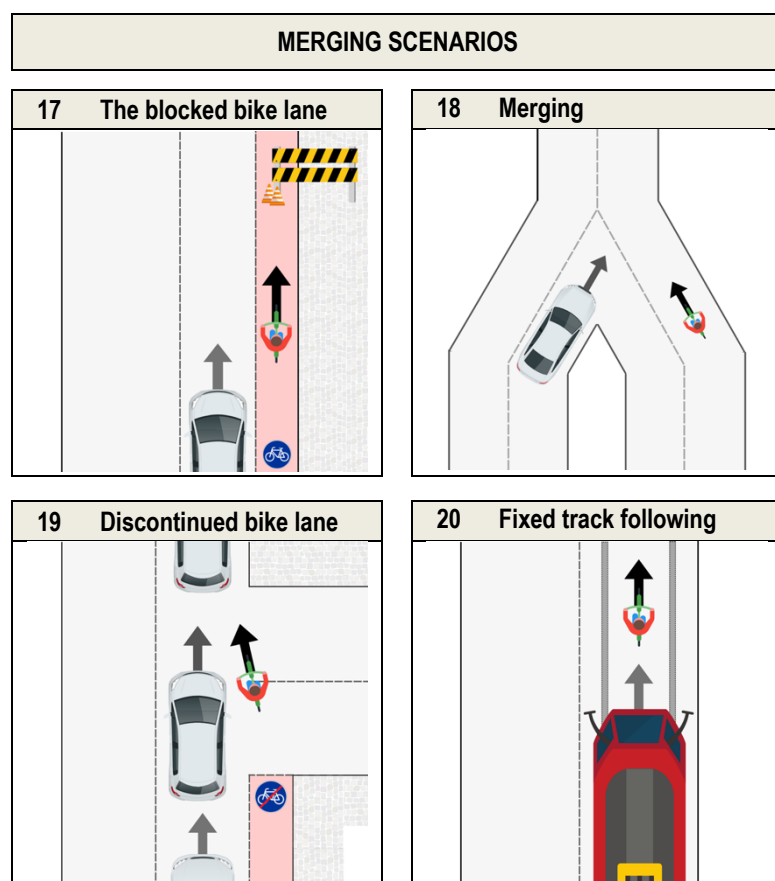


Figure 5.6. Illustrations of the four merging scenarios

Note: The infrastructural layouts may vary in terms of legs, lanes, vegetation, and other environmental details (e.g., barriers, traffic signs, colours).

Identified scenario challenges

The literature review and interview data analysis indicated that variables related to each scenario are particularly relevant to control for in research. Table 5.8 shows the variables identified as potential challenges in the 20 scenarios.

Table 5.8. Potential scenario challenges

Variable	Assessment	Scenario
Right of way and negotiation	Uncertainty or challenges in yielding and negotiating space between cyclists and vehicles. Negotiation can be particularly challenging for automated vehicles in ambiguous situations.	1, 2, 3, 8, 7, 9, 10, 17, 18, and 19
Line of sight	Limited or obstructed visibility between the cyclist and the vehicle due to physical obstructions, blind spots, or poorly designed infrastructure misleading the road users to assume they have a clear line of sight.	6, 8, 12, 13, 14, 15, 17, 18, and 19
Cognitive load	Complex traffic situations or erratic vehicle behaviour may lead to a higher mental workload, causing errors or poor decision-making.	3, 4, 5, 6, 12, 13, and 15
Infrastructure and environmental factors	Discontinued cycling infrastructure or longitudinal crossing of tram tracks, especially during rain or wet surface conditions.	6, 17, 19, and 20

Speed and stability	At lower speeds, the stability of cyclists may become an issue, potentially causing the cyclist to swerve or lose balance.	7, 9, and 10
Automated vehicle behaviour	Issues unique to automated vehicles, such as phantom braking – unexpected or explained braking of the vehicle, or misunderstanding road markings or obstacles, potentially leading to erratic vehicle behaviour.	7, 9, 10, 12, 13, 15, and 20
Dooring	The risk of a cyclist being hit by a vehicle door opening	13 and 16

Survey results

The results from the descriptive analysis of the survey with the interviewed traffic safety and automation experts are seen in Table 5.9, Scenario 2. *The right-turning vehicle* had the highest accident likelihood (4.38), followed by Scenarios 4. *The bi-directional bike path* (3.75), 6. *The roundabout* (3.75), 16. *Dooring* (3.75), 12. *The kerbside takeover* (3.50) and 3. *The left-turning cyclist* (3.38). The scenario rated with the lowest accident likelihood was 1. *The perpendicular vehicle* (1.88). With this scenario, the respondents noted that the illustration did not indicate any regulations and provided limited information: Changes in visibility and vehicle speed may affect the accident likelihood with vehicles approaching from perpendicular directions.

Table 5.9. The results from the descriptive analysis of the survey with the interviewed experts

#	Scenario	Accident likelihood	Occurrence	<i>n</i>
Crossing scenarios				
1	The perpendicular vehicle	1.88	-0.25	8
2	The right-turning vehicle	4.38	-0.64	7
3	The left-turning cyclist	3.38	-0.38	8
4	The bi-directional bike path	3.75	-0.71	7
5	The bike path crossing	2.63	0.00	7
6	The roundabout	3.75	-0.86	7
Passing scenarios				
7	The narrowing	2.13	0.00	7
8	The driveway	3.25	-0.43	7
9	Negotiation (rural)	2.25	-0.43	7
10	Negotiation (urban)	2.88	-0.57	7
Overtaking scenarios				
11	The takeover	2.63	-0.57	7
12	The kerbside takeover	3.50	-0.43	7
13	The parked vehicle	2.88	-0.14	7
14	The bus stop	3.25	-0.57	7
15	Phantom braking	2.88	+0.63	8
16	Dooring	3.75	-0.14	7
Merging scenarios				
17	The blocked bike lane	2.75	-0.29	7
18	Merging	2.63	-0.14	7
19	Discontinued bike lane	2.75	+0.29	7
20	Fixed track following	3.00	-0.33	6

Note: All variables were measured on a 5-point Likert scale. The variable ‘occurrence’ represents the difference between the average score of a scenario occurring today and the occurrence in the future with SAE level 3-4 vehicles and was calculated by subtracting the means of ‘frequency of occurrence in the future’ from the means of ‘frequency of occurrence today’ per scenario.

As shown in Table 5.9, the scenarios rated with the highest negative difference from today to the future with automated vehicles were 6. *The roundabout* (-0.86), 4. *The bi-directional bike path* (-0.71), and 2. *The right-turning vehicle* (-0.64). For Scenarios 4 and 6, the lower chances of occurrence were generally explained by automated vehicle sensors assumed to compensate for a human driver's limited capacity to detect other road users in complex traffic environments, for example, environments with bi-directional bike paths or high-traffic volume. Automated vehicles are also assumed to comply with right-of-way regulations, possibly lowering the risk of accidents in situations where the cyclist has the right of way.

Although the average sum scores for Scenario 2. *The right-turning vehicle* indicates that the scenario will occur less frequently in the future with automated vehicles SAE level 3 and 4 (-0.64), see Table 5.9, the qualitative assessments of text fields from the survey offer a more nuanced explanation: Although vehicle sensors will likely reduce the risk of an accident by detecting the cyclist that may otherwise be in the blind spot of the driver, observation studies of automated shuttle buses (e.g., De Ceunynck et al., 2022; Pokorny et al., 2021) show that the vehicle struggle with detecting cyclists during right-turning manoeuvres. During a transition period with increasing numbers of automated vehicles that yield to cyclists during right-turning manoeuvres, cyclists may also become complacent by generalising automated vehicle behaviour (i.e., sensors detecting the cyclist's presence and yielding) to human drivers, potentially increasing the risk of an accident.

The results indicate that the scenario depicted in 15. *Phantom braking* is assumed to increase in occurrence in the future (+0.63, see Table 5.9). The behavioural component of phantom braking is not limited to Scenario 15 and may occur in any situation with an automated vehicle. With increased shares of automated vehicles in traffic, we can expect to see an increase in phantom braking among the vehicles interacting with human road users, particularly vulnerable road users. The dynamic and organic aspects of human road user behaviour are challenging to imitate. It is assumed that vehicle programming will err on the side of caution and brake in ambiguous situations. Phantom braking may increase the risk of rear-end collisions or startle cyclists to potentially lose balance if a vehicle unexpectedly and abruptly stops suddenly during a turning manoeuvre or at an intersection.

In the survey text-fields, automated vehicle behaviour was also described as relatively rigid, especially automated vehicles operating on a pre-programmed path (e.g., the automated shuttle buses described in Boersma et al. (2018); De Ceunynck et al. (2022); Pokorny et al. (2021)), In Scenario 19. *Discontinued bike lane*, the cyclist has to merge with traffic while exiting an intersection due to a discontinued bike lane. Suppose an automated vehicle strictly abides by traffic regulations or its pre-programmed path. In that case, the vehicle may not position itself further left in the lane and provide the additional right-side space necessary for the cyclist to merge. Automated vehicles failing to give space to the cyclist has been observed in video observation studies (e.g., De Ceunynck et al., 2022; Pokorny et al., 2021), reinforcing the notion that an automated vehicle may struggle with similar situations as Scenario 19 in the future.

5.3.4 Triangulation: Conclusion

The literature review of research on automated vehicles and cyclists revealed that the most common scenario was one cyclist and one passenger vehicle approaching from the opposite or perpendicular direction before intersecting in a T-junction in an urban environment during daytime. The recommendations from the group interview align with the results from the analysis of the scenarios in the literature review: The most relevant scenario for safety

assessments would be at an intersection, with vehicles turning or cyclists crossing the road. Moreover, the interviewees suggested it could be worthwhile to explore the effects of different types of weather and lighting conditions on cyclist behaviour and cyclist factors such as age, gender, and cyclist type (experience and cycling style). Regarding automated vehicle behaviour, the thematic analysis indicated that scenarios assessing automated vehicle behaviour should account for the effects of the vehicle's driving style and phantom braking incidents.

Lastly, we would like to emphasise that the choice of scenarios depends on the objective of the research. For safety assessments, choosing a scenario rated with a high accident likelihood is likely the most appropriate approach, e.g., Scenario 2. The right-turning vehicle. If the study objective is to investigate the effects of communication solutions for vulnerable road users, such as eHMIs, choosing a passing or merging scenario that is expected to increase in occurrence in the future could increase the validity of the findings, e.g., Scenario 19. Discontinued bike lane. Passing and merging scenarios are particularly relevant because they target negotiation – human behaviour heavily influenced by social and cultural norms – a behaviour that automated vehicle technology struggles to imitate.

5.4 Discussion

The aim of this study was to triangulate data from previous research on interactions between cyclists and automated vehicles with group interviews and a questionnaire to create realistic test scenarios of cyclists' interaction with automated vehicles and to provide recommendations for defining automated vehicle behaviour in future research. In the following sections, we discuss the findings from the triangulation, starting with the suggested scenarios and critical factors to account for in future research. Subsequently, we discuss the implications of automated vehicles' phantom braking, the role of implicit and explicit communication of automated vehicles through driving styles and the use of eHMIs, before reflecting on the importance of incorporating anticipatory behaviour into the automated vehicle decision-making process.

5.4.1 Scenario recommendations

The results from the survey indicated that Scenario 2, *the right-turning vehicle* had the highest likelihood of an accident. This is in line with previous research: Right-turning vehicles crossing a cyclist's path at an intersection is a common accident, likely due to drivers' inadequate scanning, visual search strategies, and "looked-but-failed-to-see" errors (Brown et al., 2021; Poudel & Singleton, 2021; Räsänen & Summala, 1998; Summala et al., 1996). As automation increases, sensors may compensate for drivers' misplaced expectations and human errors, and it is likely that the frequency of right-turning vehicle accidents will decrease in the future. As reported in the survey results, automated vehicle sensors and programming that compensate for drivers' human errors may result in complacent cyclists. In traffic with varying degrees of automation, this complacency may cause cyclists to pay less attention in right-turning vehicle situations, mistakenly assuming the vehicle will stop. Video observations of automated shuttles showed that right-turning shuttles failed to yield to cyclists going straight in 38% of the observed interactions (De Ceunynck et al., 2022), indicating that right-turning vehicle scenarios will likely continue to be relevant for some time. Although the failure to yield to cyclists in the De Ceunynck et al. (2022) study may be manufacturer-specific and not applicable to automated vehicles in general, the right-turning vehicle scenario may still be the most appropriate scenario for safety assessments in the forthcoming years of varying degrees of automation.

Scenarios 3. *The left-turning cyclist*, 4. *The bi-directional bike path*, 6. *The roundabout*, and 12. *The kerbside takeover* were also scored with a higher-than-average accident likelihood in the expert survey. We assume that these scenarios involve high complexity, including cyclists approaching in both directions and multiple road users. Higher complexity will likely cause higher mental demands on the human road user (Campbell, 1988; Stinchcombe & Gagnon, 2010). The results from the survey also predicted that these four scenarios might decrease in occurrence, suggesting that automation is expected to offload parts of the mental demands on the driver in the future. Due to the scenarios' high accident likelihood ratings paired with the literature review showing that most research is performed on one vehicle and one cyclist participant, investigating the effect of automation in the complex Scenarios 3, 4, 6, and 12 with several road users may be important during the transition period while automated vehicle technology is in development.

Scenario 16. *Dooring* was rated to have a higher-than-average accident likelihood. Dooring is more likely caused by a human road user opening the door rather than automation. However, this scenario offers the possibility to investigate the effects of vehicle and cyclist sensors or warning systems on the safety of cyclists in dooring situations. For instance, Von Sawitzky et al. (2021) found that an augmented notification system increased cyclists' lateral distance to a potential dooring, allowing the cyclists to safely pass the parked vehicle without braking.

Scenarios 1, 2, and 3 are illustrated without underlying infrastructure. These three crossing scenarios were described as occurring across different types of infrastructure. Moreover, none of our scenarios was illustrated with shared space infrastructure, although shared spaces were identified in the literature review. However, the behaviour of the traffic participants identified in the shared space scenarios applied to other scenarios in the collection. Inherent to shared spaces, this type of infrastructure often lacks lane markings and may involve unpredictable behaviour of vulnerable road users, such as cyclists overtaking on both sides of the vehicle in De Ceunynck et al. (2022). While the scenario collection did not specifically consider shared spaces as a component of infrastructure, it is important to note that the underlying infrastructure, such as the type of intersection (e.g., T-, Y, and X-junctions), roundabouts, and shared spaces, can often be utilised interchangeably. Ultimately, it is the behaviour of the parties involved that likely holds the most significance. Nevertheless, it is crucial to acknowledge that modifications to infrastructure and environmental factors in a given scenario may impact the findings of the study. Due to the likelihood of high numbers of vulnerable road user interactions and potential complications with non-standard lane markings, automated vehicles might find shared spaces particularly challenging. This should be explored in future research.

Line of sight was identified as an important factor for all four scenario groups: crossing, passing, overtaking, and merging scenarios. In particular, we identified blind spots caused by the size of the vehicle or positioning of the cyclists, and obstacles blocking the field of view, as critical factors. Moreover, the analysis of previous literature showed that the cyclist and the vehicle had a clear line of sight in most of the scenarios identified in previous studies on cyclists and automated vehicles. Although vehicle sensors will likely aid cyclists positioned in the blind spot of the driver to a greater extent in the future, the lack of variations in line of sight in the literature indicates that the effect of occlusion should be explored in future studies.

5.4.2 Automated vehicle behaviour and characteristics

To effectively investigate the interaction between automated vehicles and cyclists, a number of factors must be considered, including technological capabilities and limitations, user behaviour

and expectations, the effect of HMIs, and the complexity of interactions between human road users and automation. One of the objectives of this study was to identify the typical behavioural characteristics of automated vehicles and the novel situations that may occur in traffic with increasing degrees of automation.

Phantom braking

Phantom braking, a phenomenon where an automated vehicle unexpectedly and abruptly applies the brakes, is a behavioural characteristic of automated vehicles that may lead to novel situations. The triangulation showed that the behavioural component of phantom braking is not limited to Scenario 15. *Phantom* braking may occur in any situation with an automated vehicle.

Although academic research on phantom braking is scarce, phantom braking has been observed among automated vehicles in previous studies (De Ceunynck et al., 2022; Moscoso et al., 2021; Nordhoff et al., 2023). Car manufacturers inform their buyers of automated systems that phantom braking may occur, but the circumstances and causes are unclear (Moscoso et al., 2021). It is likely that the origin of phantom braking pertains to sensor technology and the algorithms applied to interpret the environment. For instance, current sensor technology and the limitations of the sensors in terms of range, resolution, and accuracy may cause the vehicle to brake due to the system generating false detections and incorrect interpretations of the objects in the environment. The algorithms used to analyse and make decisions from the sensor data could be a factor as well. Algorithm complexity might introduce errors and inconsistencies in the system's decision-making process. Similarly, the vehicle's programming might be too conservative, causing the vehicle to seemingly brake unexpectedly because a cyclist came within the vehicle's sensors' safety threshold, as observed in De Ceunynck et al. (2022).

Sudden and unpredictable changes in the automated vehicle's speed and trajectory caused by phantom braking can be particularly hazardous for vulnerable road users like cyclists, who have higher speeds than pedestrians and venture into traffic largely unprotected compared to human drivers. Furthermore, as our interviewees pointed out, phantom braking may result in rear-end collisions. Cyclists are also at risk of abruptly braking as a consequence, which may result in their propulsion over the handlebars. The results from Moscoso et al. (2021) indicated that phantom braking can potentially put other road users at risk by causing chain collisions. Unexpected braking may result in a chain reaction of braking and evasive manoeuvres and affect traffic flow, with the potential of congestion and subsequent accidents.

The results from the survey suggest that Scenario 15. *Phantom braking* will increase in the future with automated vehicles. As phantom braking may occur in all scenarios with automated vehicles, it is crucial for the developers of these systems to address and mitigate its potential. In research, it is imperative to consider and account for phantom braking in future studies to preserve the safety of vulnerable road users such as cyclists and to ensure the safe and reliable operation of automated vehicles.

5.4.3 The role of implicit and explicit communication

Our findings suggest that implicit communication through differences in driving style is a determinant of automated vehicle behaviour. The driving style of a vehicle is a term used to describe how a vehicle operates on the road, typically the speed, acceleration, braking, and turning manoeuvres. The thematic analysis indicated that automated vehicles' driving styles

might affect vulnerable road users such as cyclists. For instance, braking early in front of a vulnerable road user intending to cross the road may signal that the vehicle is giving the right of way, while harsh braking may be interpreted as the opposite. Our interviews indicated that driving style should likely be uniform across car manufacturers to increase predictability for other traffic participants.

The driving styles of automated vehicles have been addressed in research, focusing on the vehicles' drivers and passengers (Ekman et al., 2019; Lee et al., 2021; Oliveira et al., 2019; Ossig et al., 2021; Peng et al., 2022). We suggest that the driving style of automated vehicles is explored and accounted for in future research, particularly research on vulnerable road users such as cyclists. Our passing and merging scenarios are particularly relevant for investigating the effect of driving style as they may involve more negotiation and ambiguity than the other types of scenarios.

Another focus area for future research on cyclist-automated vehicle interaction is the role of implicit versus explicit communication and automated vehicle eHMIs. In line with the results from the present study, Lee et al. (2020) suggested that pedestrians use vehicle-based motion cues such as yielding rather than explicit communication from drivers. For instance, our thematic analysis indicated that movement patterns and speed changes are cyclists' most important interpretation cues and that eye contact between cyclists and drivers is sought in complex or dangerous situations. Similarly, Bazilinskyy et al. (2023) found that eye contact with the driver stimulated cyclists to continue pedalling. However, no visual contact with the driver caused cyclists to brake unless there was an eHMI signalling that the cyclists could go.

On-vehicle interfaces, such as eHMIs, can improve vulnerable road user interaction with automated vehicles (De Winter & Dodou, 2022). Still, most eHMIs are designed for and tested on pedestrians (Dey, Habibovic, Löcken, et al., 2020). The video observations of cyclists in traffic with an automated shuttle bus showed that cyclists overtake vehicles on both the right and left-hand sides (De Ceunynck et al., 2022). This overtaking behaviour implies a need for eHMIs to be visible from more than one side of the vehicle. An eHMI should ideally be positioned all around the vehicle or be omnidirectional to accommodate the movement patterns of cyclists. Future studies could focus on the role of eye contact for cyclists and the implications of cyclist gaze behaviour and movement patterns on eHMI design and placement. Moreover, the experts interviewed in our study identified several challenges with implementing eHMIs, such as signalling to multiple road users and determining the type and timing of the information displayed, all of which should be explored in future research.

5.4.4 Proactive and anticipatory behaviour

The safety of automated vehicles is relatively well-studied in academia, with researchers noting the need for these vehicles to navigate the social complexities of interacting with vulnerable road users (Rasouli et al., 2018). However, existing safety research primarily focuses on preventing accidents based on past data, which may not account for the nuances of vulnerable road user behaviour. As such, the decision-making of automated vehicles may be based on incorrect expectations of vulnerable road user behaviour derived from accident avoidance. The results from our interviews uncovered a range of implicit and explicit strategies that cyclists utilise when interacting with vehicles, such as adjustments in speed, posture, and placement on the road, and using sound and hand gestures to signal intent or direction. The interview participants also explained that cyclists engage in a range of anticipatory behaviour to remain safe in traffic, namely exhibiting caution, scanning the environment for potential hazards, and

keeping their distance, all of which human drivers can anticipate based on training and experience. With a reactive focus on safety, these characteristics may not be accurately replicated in the decision-making process of automated vehicles, resulting in novel, high-risk situations instead.

We argue that it is imperative to explore whether automated vehicle programming should incorporate positive, anticipatory behaviours by taking proactive measures to avoid potential hazards rather than reacting to them when they occur. For instance, an automated vehicle programmed to recognise the body language of a cyclist scanning the environment for potential hazards could slow down or increase its distance from the cyclist. The ultimate goal of large-scale deployment of automated vehicles should not be to merely avoid accidents but also to provide a safe and comfortable environment for all road users. Automated vehicles possessing knowledge of the anticipatory strategies employed by vulnerable road users, such as cyclists, could help create a safer and more harmonious transport system for all road users. As anticipatory behaviour has been largely neglected in academic literature, we recommend that future research approaches automated vehicle-vulnerable road user interactions with a holistic perspective by comprehensively examining anticipatory behaviours elicited by drivers and vulnerable road users as well as accident and near-miss data.

5.4.5 Limitations

This study has provided a collection of scenarios for testing cyclist interaction with automated vehicles, recommendations for scenario selection based on the type of study and highlighted the importance of including the automated vehicle behavioural components of phantom braking and driving style in future research. However, some limitations of the methodology applied in this study should be acknowledged. We applied a qualitative approach by triangulating data in this chapter. The qualitative approach was beneficial given the exploratory and emergent nature of the field. Still, incorporating quantitative data, such as contributory factors to cyclist accidents with vehicles, could uncover other relevant aspects of the scenarios. Risk assessments of contributory factors of cyclist accidents might identify factors of the road users and the environment, e.g., the type of infrastructural layout, or characteristics of the road users and other objects present in the environment, that are particularly important to include in the cyclist scenarios utilised in future research.

Although thematic saturation can be achieved from small sample sizes in qualitative research (Fugard & Potts, 2015; Guest et al., 2006), the thematic analysis applied in our study could have benefited from a more diverse range of perspectives. Incorporating insights from experts in universities and industry could have strengthened our analysis on automated vehicles. It should also be acknowledged that other perspectives, such as those from everyday cyclists or groups traditionally underrepresented in transport research, were not included in this study. Although our focus was on academic and professional perspectives due to the emergent nature of high-level automated vehicle technology, we recognise that further research involving a broader spectrum of viewpoints could result in more nuance and comprehensiveness of the scenarios.

Each group interview had participants with expertise in human factors and automation. However, the survey data was collected on an individual basis. Assessing the scenarios' accident likelihoods and frequency based on the limited information in the online survey was reported as challenging for some participants. The triangulation of data from multiple sources may have counteracted the low sample size and improved the reliability of our results.

Nonetheless, the survey's results should be interpreted as probable inferences rather than conclusive evidence.

Another limitation of our study pertains to the categorisation and individual treatment of the scenarios included in the collection. While we recognise that some scenarios in our collection appear to be closely related or variations of each other, e.g., scenarios 1 and 5, scenarios 8 and 9, or scenarios 13 and 14, we chose to include them separately to examine the impact of incremental complexities. For instance, the distinct infrastructural elements or number of road users in each scenario could influence the likelihood and frequency of accidents. Therefore, we consider these as unique scenarios that warrant individual attention, even though they might be regarded as subsets of more general scenarios.

5.5 Conclusion

This exploratory study resulted in 20 prototypical scenarios of cyclist-automated vehicle interaction, clustered into four groups according to the direction of movement at the point of conflict between the cyclist and a vehicle: crossing, passing, overtaking, and merging scenarios. The survey results indicated that the *right-turning vehicle* and *dooring* scenarios and scenarios with increased complexity have the highest accident likelihood. Although these scenarios are expected to occur less frequently in the future, they remain relevant for safety assessment testing of cyclist-automated vehicle interaction. Passing and merging scenarios target negotiation – human behaviour that is heavily influenced by social and cultural norms. These scenarios are especially useful in research focusing on communication solutions such as eHMIs. Lastly, the scenario of *phantom braking* was expected to increase in occurrence. Behavioural characteristics of automated vehicles, phantom braking, and implicit communication cues through differences in driving style may be particularly important to define and account for in future research. We also recommend that future research consider the anticipatory behaviour of human road users and design eHMIs to accommodate cyclists.

Chapter 6

Understanding cyclists' perception of driverless vehicles through eye-tracking and interviews

As automated vehicles become increasingly popular, the question arises as to how cyclists will interact with such vehicles. This study investigated (1) whether cyclists spontaneously notice if a vehicle is driverless, (2) how well they perform a driver-detection task when explicitly instructed, and (3) how they carry out tasks. Using a Wizard-of-Oz method, 37 participants cycled a designated route and encountered an automated vehicle multiple times in two experimental sessions. In Session 1, participants cycled the route uninstructed, while in Session 2, they were instructed to verbally report whether they detected the presence or absence of a driver. Additionally, we recorded participants' gaze behaviour with eye-tracking and their responses in post-session interviews. The interviews revealed that 30% of the cyclists spontaneously mentioned the absence of a driver (Session 1), and when instructed (Session 2), they detected the absence and presence of the driver with 93% accuracy. The eye-tracking data showed that cyclists looked more frequently and longer at the vehicle in Session 2 compared to Session 1. Additionally, participants exhibited intermittent sampling of the vehicle, and they looked in front of the vehicle when it was far away and towards the windshield region when it was closer. The post-session interviews also indicated that participants were curious but felt safe, and reported a need to receive information about the automated vehicle's driving state. In conclusion, cyclists can detect the absence of a driver in the automated vehicle, and this detection may influence their perceptions of safety. Further research is needed to explore these findings in real-world traffic conditions.

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6.1 Introduction

Automated vehicles are undergoing continuous development in terms of technology and capability (Liu et al., 2023; Parekh et al., 2022). The first commercial applications of robo-taxis are now available to the public (Public Utilities Commission, 2022; West, 2022), and advanced Level-2 automated vehicles are driving on the roads (Nordhoff et al., 2023). Despite these technological strides, automated vehicles grapple with imperfections in urban environments, where they may encounter pedestrians, cyclists, and other vulnerable road users (VRUs) (Matin & Dia, 2023; Sánchez et al., 2022). In particular, the interaction between automated vehicles and cyclists requires more research due to the growing concerns over cycling safety (e.g., European Commission, 2021; SWOV, 2023).

A challenge in the development of automated vehicle technology is the issue of social communication. Both cyclists and drivers are known to engage in such communication, including eye contact, nodding, and hand gestures (Al-Taie et al., 2023; Färber, 2016; Li et al., 2023; Stanciu et al., 2018). However, in an automated vehicle, the driver is potentially inattentive or absent, leading to a potential breakdown in the communication process. This interaction void has been argued to be an obstacle to automated vehicle-VRU interaction (Rasouli & Tsotsos, 2020; Strömberg et al., 2018) and is cited as a reason for developing external human-machine interfaces (eHMI) mounted on the exterior of the automated vehicle (Faas et al., 2020; Forke et al., 2021; Hensch et al., 2020; Rouchitsas & Alm, 2019; Wilbrink et al., 2021).

At the same time, a counter-narrative within the academic literature argues that the importance of social signals in traffic is grossly overestimated (Lee et al., 2021; Moore et al., 2019). As shown in various studies (e.g., Pekkanen et al., 2022; Tian et al., 2023; Wang et al., 2010), crossing decisions of VRUs depend on implicit variables such as relative distance and speed. The automated vehicles that have been developed so far do not incorporate eHMIs, barring a small number of exceptions (drive.ai, 2018; Mercedes-Benz, 2023). This raises the question of whether it is imperative to develop eHMIs or sensors that can detect the social signals of VRUs.

Consistent with this counter-narrative, a study using photographs found that VRUs often cannot detect the presence of a driver, particularly under conditions of darkness and windshield glare (AlAdawy et al., 2019). These findings are supported by observational studies where pedestrians interacted with automated vehicles in Wizard-of-Oz setups intended to create the illusion that the vehicle is driving automatically (Cefkin et al., 2019; Chen et al., 2020; Habibovic et al., 2018; Hensch et al., 2020; Moore et al., 2019; Rothenbücher et al., 2016; Sirkin et al., 2016). These studies showed that the absence of a driver behind the steering wheel was not noticed in 10–20% of the encounters. However, the existing Wizard-of-Oz studies aim to create a believable interaction with the automated vehicle through conspicuous signals, and, as noted by Moore et al. (2019): “without the props, it is likely few would have noticed the absence of a driver”. Features of the automated vehicle, such as eHMIs, often go unnoticed as well, depending on the salience of the eHMI signal (Cefkin et al., 2019; Chen et al., 2020; Habibovic et al., 2018; Hensch et al., 2020). Instead, pedestrians interacting with driverless vehicles appear

to look longer out of curiosity (Li et al., 2020), sometimes accompanied by a certain playfulness (Currano et al., 2018).

Hensch et al. (2020) pointed out that not noticing a driver is not the same as seeing that the driver's seat is empty. They found that 79% of the participants correctly indicated no driver in the vehicle. However, when there was a driver in the vehicle, only 52% of the participants recognised this, presumably due to windshield glare. In other words, it remained unclear whether the VRU could see the absence of a driver or whether they were unable to see anything at all. Therefore, the methodology of this type of Wizard-of-Oz research merits improvement, by considering not only the possibility for misses (i.e., VRU fails to detect the presence of a driver) but also false positives (i.e., VRU reports the presence of a driver while there is no driver).

All Wizard-of-Oz studies cited above were conducted with pedestrians; there appears to be no research among cyclists, a category of VRUs who are likely to have more difficulty detecting drivers than pedestrians due to their higher speed, and, as found in earlier eye-tracking research (Pashkevich et al., 2022; Trefzger et al., 2021), their tendency to look at the road ahead, as they have to stabilise and navigate their bicycles. It is conceivable that cyclists, when faced with a visually challenging task like detecting a driver in an automated vehicle, will exhibit a coping strategy (also referred to as 'behavioural adaptation'), such as cycling more slowly.

The literature reveals a knowledge gap regarding whether VRUs, particularly cyclists, can detect the presence of a driver in the driver's seat. With the advent of automated vehicles, cyclists will find themselves more often confronted with the task of estimating whether the automated vehicle is under manual or automatic operation, by gauging the presence of a driver. In light of this, the current article aims to address the following two research questions:

1. Do cyclists notice the absence of a human driver when they pass an approaching automated vehicle?
2. When explicitly asked to do so, how accurately can cyclists determine whether or not there is a human driver behind the steering wheel?

We also examined *how* cyclists performed these tasks:

3. How do cyclists perform a driver detection task, in terms of eye movements and cycling speed adjustments?
4. How do cyclists experience their interactions with automated vehicles, particularly regarding the need for additional vehicle information and distinguishing between automated vehicles and conventional vehicles?

Answering these research questions is important for determining whether modifications are needed in the design of automated vehicles, for example regarding eHMIs that explicitly indicate whether the vehicle is being driven manually or automatically, or to assess whether cycling safety might be compromised when they try to make such an estimation.

A field experiment involving human participants was conducted to answer the research questions. In Session 1, participants repeatedly cycled past an approaching vehicle without receiving specific information. In Session 2, the participants were informed that the vehicle could drive automatically, and they were explicitly instructed to verbally report whether someone was behind the wheel. In our study, we did not use a real automated vehicle but instead used a hidden human driver. We used a variety of measurement methods, including verbal

utterances during cycling, post-session semi-structured interviews, mobile eye-tracking, and determination of cycling speed.

6.2 Method

6.2.1 Participants

The sample consisted of 37 participants (23 males and 14 females), ranging from 22 to 67 years of age ($M = 31.9$, $SD = 11.0$). Regarding participants' highest educational degree completed, 16 (43%) had completed a bachelor's degree, 20 (54%) a master's degree, one held a degree from a Higher Technical School (a former institution in The Netherlands that provided vocational education in engineering). The participants reported cycling on average 4.75 hours a week ($SD = 3.36$), and the majority reported "commuting or utilitarian" as their primary motivation for cycling (73%). Assessing the participants' vision, one participant reported 'moderate difficulty' to the question 'Do you have any difficulties (e.g., blurred vision) seeing or detecting objects while being on the road?', while 7 reported 'a little difficulty'; the remaining 29 (78%) reported 'no difficulty at all'.

Participants were recruited using convenience sampling through flyers distributed on the TU Delft campus and via social media, as well as invitations through our personal and professional networks. The study was approved by the university's Human Research Ethical Committee (approval number 2300). All participants provided written informed consent.

6.2.2 Experimental design

The experiment was of a within-subjects design consisting of two sessions with different instructions for the participants and two driver states. In each session, the participants cycled the same route four times, encountering a vehicle once per round.

In the literature, various Wizard-of-Oz methods have been used to investigate pedestrians' responses to automated vehicles. These include a tinted windshield (Bindschädel et al., 2023; Chen et al., 2020), a dummy steering wheel (Habibovic et al., 2018), a mirror film (Liu & Hirayama, 2023; Liu et al., 2021), or the car being controlled from the passenger seat (Rodríguez Palmeiro et al., 2018). However, the most common option is that of a seat suit (Faas & Baumann, 2021; Fuest, Michalowski, et al., 2018; Hensch et al., 2020; Joisten et al., 2020; Large et al., 2023; Li et al., 2020; Liang et al., 2016; Loew et al., 2022; Rothenbücher et al., 2016; Taima & Daimon, 2023; Wang et al., 2021). In our study, the vehicle was operated by a concealed driver in a costume (see Figure 6.1) in half of the encounters, emulating an automated vehicle.



Figure 6.1. Seat costume used in the experiment.

In Session 1, participants were neither led to believe nor informed that the vehicle could be operated without a driver. In Session 2, participants were informed about the dual state of the vehicle, either human-driven or driven in automated mode. For Session 2, the participants were also instructed to verbally state either 'Yes, driver' or 'No, driver' as soon as they could determine the presence or absence of a driver.

In two out of the four encounters in each session, the vehicle had no visible driver. The presence of the driver in each session followed one of four predefined sequences: No-Yes-Yes-No, Yes-No-No-Yes, Yes-Yes-No-No, or No-No-Yes-Yes. The sequence differed among participants but was consistent for the same participant across Session 1 and 2. This pattern was used to facilitate the role transition of the driver (i.e., experimenter).

6.2.3 Procedure

Data collection occurred over three weekends in November and December 2022. Collecting data during the weekend allowed the closing of the test area with fences to minimise the interference of other cyclists and pedestrians and to ensure the safety of our participants. In addition, we had guards placed at potential entry points of the test area, preventing interference from outside road users.

Upon arrival, the participants received an information sheet and signed an informed consent form. They were equipped with Tobii 3 eye-tracking glasses, calibrated using a bullseye card

held by an experimenter at a distance of about 0.8 m from the participant. The calibration was conducted before each of the two sessions. In sunny conditions, participants wore infrared-blocking tinted protective lenses (Tobii, 2022) attached to the eye-tracking glasses, and wore a baseball cap (Evans et al., 2012; Simpson et al., 2018) to minimise interference by sunlight.

Session 1

The participants received the instruction to cycle a 530-metre route around TU Delft in the Netherlands. They were told to cycle like they usually would. The participants used their own bikes during the experiment, except for two participants who used the bicycle of an experimenter. All participants used a conventional, non-electric bike. While cycling, the participants interacted with a grey 2018 Toyota Yaris. With its headlights on, it approached from the participant's left-hand side at an angle of approximately 160° (Figure 6.2).

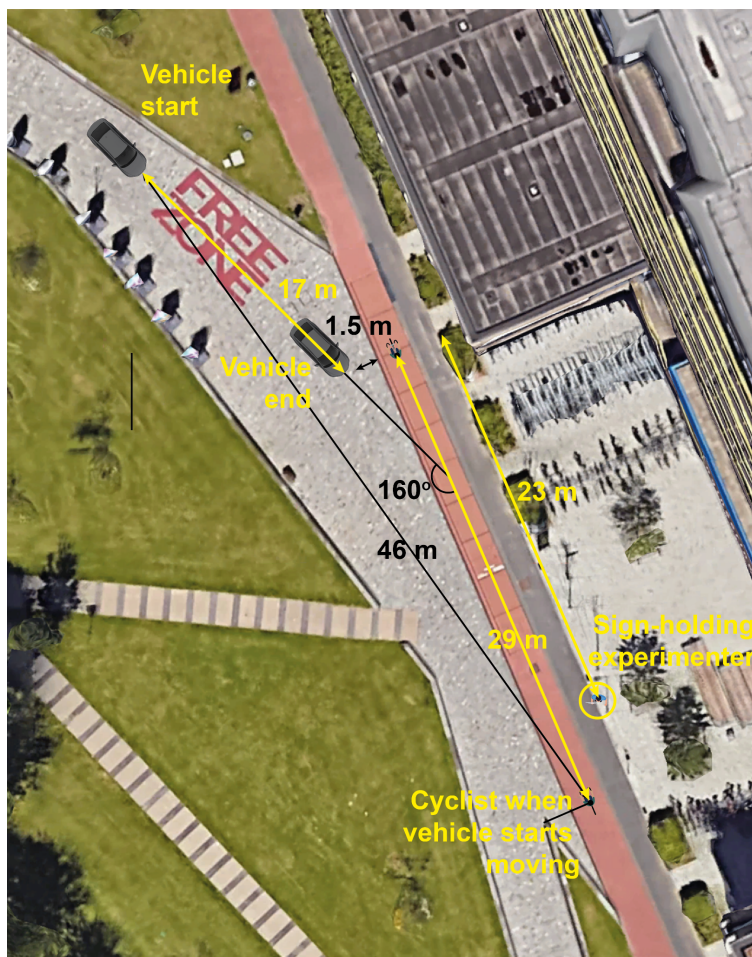


Figure 6.2. Top-down view of the interaction scenario.

Note: The sign-holding experimenter was present in Session 2 only.

The driver proceeded straight ahead with a speed of about 10 km/h and stopped with the vehicle's left front edge approximately 1.5 metres from the edge of the bike path (see Figures 6.2 and 6.3). The speed and distance from the bike path were chosen based on pilot tests to create ambiguity about the traffic interaction. While driving in 'no driver' mode, the concealed driver placed their hands at the lower part of the steering wheel. In 'human-driven mode', the driver placed their hands at the top of the steering wheel and looked straight towards the cycling

participant. In Session 1, the participants cycled the route four times consecutively before briefly being interviewed about their experience.

Session 2

At the end of the interview after Session 1, the participants were informed that the vehicle they were interacting with was driven either by a human or was in an automated mode, as a driverless vehicle.

The second session involved a repeat of the route for four additional rounds but with additional tasks. During each of the four rounds, the participants had to read two letters on a sign held by an experimenter on the right-hand side of the cycling path (Figure 6.3). We alternated between signs with the two-letter combinations of “HN”, “NH”, and “OD”. The participants passed the vehicle after cycling a further 23 metres (an average of 5.4 s, depending on cycling speed). They indicated whether they could detect a driver in the vehicle by uttering "Yes driver" or "No driver" at the earliest possible moment they could discern the driver's presence or absence. The microphone of the eye-tracker recorded their utterances.

We included the secondary task of reading letters before passing the vehicle to increase visual attention demands (see Figure 6.3). In this way, we prevented the possibility of cyclists prioritising the driver-detection task in an unrealistic manner, such as by focusing their attention solely on the vehicle. Additionally, performance on the letter-reading task served as a way to obtain a control measurement of the participant's level of perception. Our analysis of the audio showed that the 34 participants performed the letter-reading task with very high accuracy, with 134 correct answers, 0 incorrect answers, and 2 trials in which a participant did not mention the letters at all.

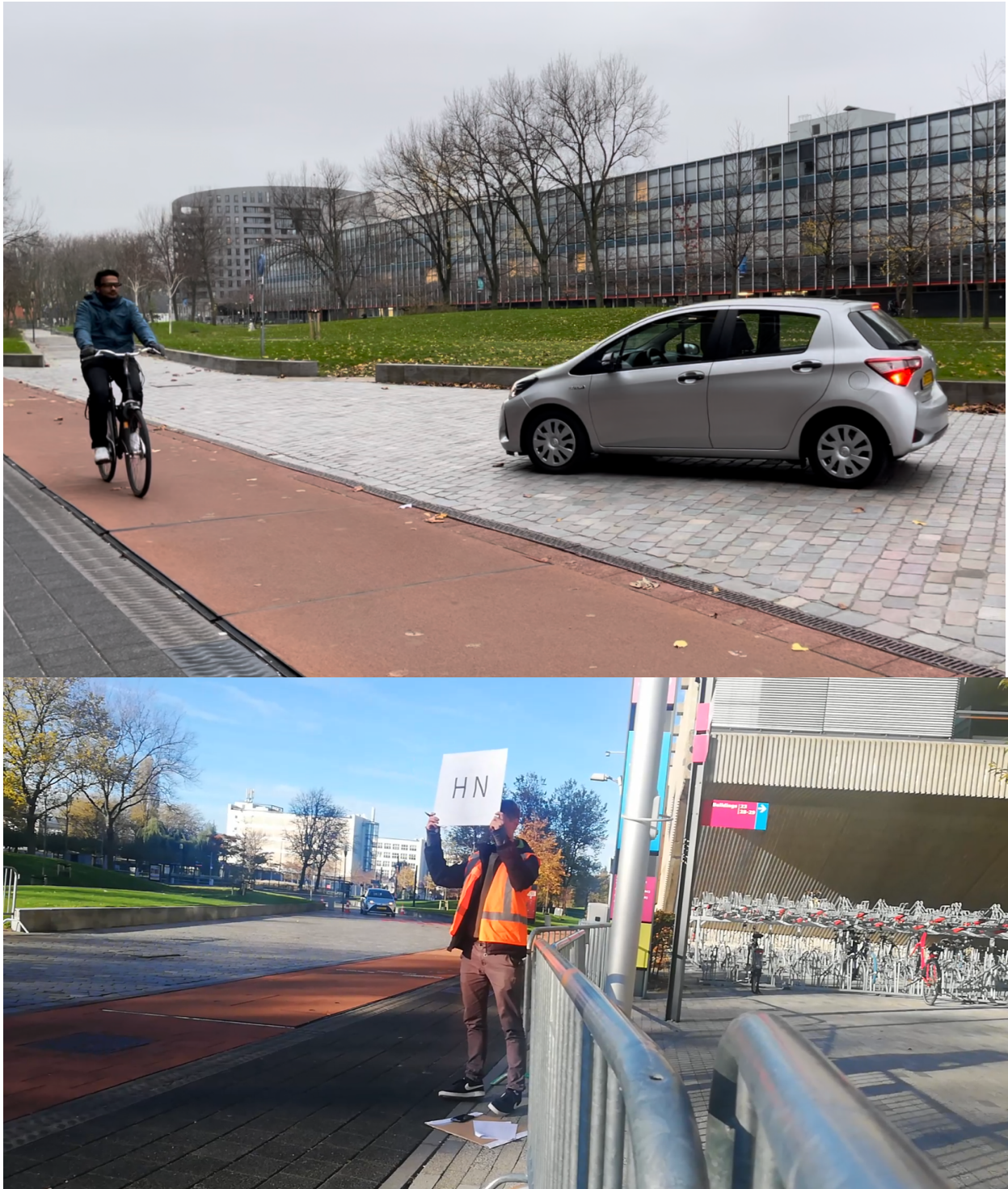


Figure 6.3. Participant interacting with the experimental vehicle on the predetermined route (top) and experimenter holding the sign for the letter-reading task (bottom).

After Session 2, the participants were interviewed a second time. At the end of the experiment, participants completed a questionnaire regarding their demographics and cycling habits. Finally, participants received a debriefing on how the vehicle was controlled. For participating, they received a voucher of 10€ and a baseball cap.

6.2.4 Eye-tracking data analysis

Pre-processing of eye-tracking data

The eye-tracking data were processed according to Onkhar et al. (2023). Firstly, the x and y gaze-point data were filtered with a moving median filter with 0.3-s time interval. The median filter ensures that high-frequency jitter is removed and that short-term gaps, for example, caused by blinking, are filled in. The remaining gaps in the data were filled with a linear interpolation. The eye-tracking data was stored at a frequency of 100 Hz, while the scene camera stored frames at 25 Hz. A gaze x and y point was calculated per video frame by averaging the four available values for each frame.

Automatic identification of the vehicle in the scene camera

In the analysis of mobile eye-tracking data, the question arises of how these data should be analysed. One option involves manual annotation of whether the gaze point falls within an area of interest (AOI), either per fixation (Gruden et al., 2021; Vos et al., 2023) or frame-by-frame (Vansteenkiste et al., 2015). Aside from the fact that this method is subjective (Pfeiffer & Renner, 2014; Vos et al., 2023), it is also time-consuming (Meißner et al., 2019). Furthermore, cycling encompasses considerable head movement and variability in the bicycle's roll angle (Kováčsová et al., 2016). Therefore, a cyclist's field of vision is constantly in motion, and the definition of a 'fixation' (i.e., the eye focusing on a single point for a certain duration) may not be applicable (Vansteenkiste et al., 2015).

In light of these considerations, the decision was made to identify AOIs automatically, using a computer-vision method named YOLO (Redmon et al., 2016). YOLO accepts an image as input and outputs bounding boxes and associated object classes.

We used YOLOv4 (Bochkovskiy et al., 2020), pretrained on the COCO dataset (Lin et al., 2014; from sbairagy-MW (2021)). The COCO dataset comprises 80 object classes. However, we only used the 'car' class for our study. Each frame recorded by the eye-tracker scene camera was submitted to the YOLO algorithm, from which we extracted the bounding box surrounding the vehicle.

Calculation of viewing angle

We calculated, per video frame, the viewing angle between the gaze point and the bounding box surrounding the vehicle. The viewing angle describes the minimum angle the cyclist's eyes would have to rotate to look at the vehicle. The formula for viewing angle uses calibrated values of the eye-tracker concerning the number of pixels of the camera (1920×1080) and its focal length (Onkhar et al., 2023)⁵.

Figure 6.4 illustrates the concept for a video frame, in which the participant would need to rotate their eyes by 33° to look at the bounding box. If the gaze point fell within the bounding box, the viewing angle was defined as 0°. It was assumed that the participant was 'looking at the vehicle' if the angular distance was less than 4°, based on Onkhar et al. (2021).

⁵ Note that we could also determine this distance in pixels. However, the use of an angle provides more generalisable and human-centric information than pixels, which depend on the camera resolution and camera field of view.

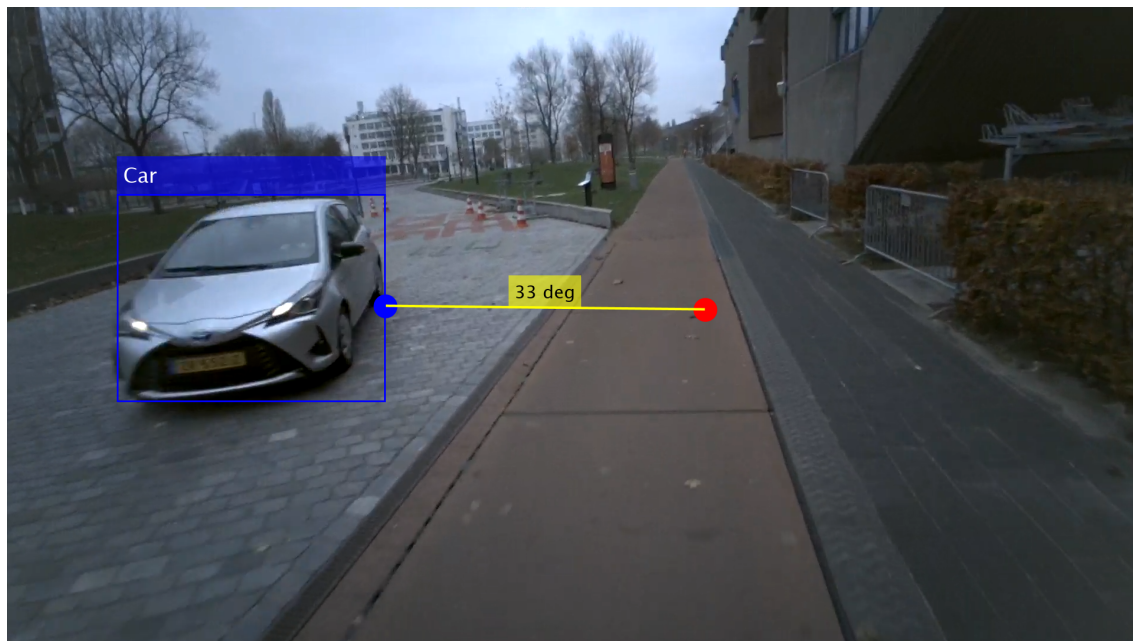


Figure 6.4. A still frame from the video recorded by the eye-tracking glasses, with an overlay of gaze point and bounding box of the interacting vehicle.

Note: The red circle indicates the participant's gaze point, and the blue box surrounds the vehicle.

Figure 6.5 illustrates the angular distance over a trial, i.e., a single interaction with the vehicle. The x -axis represents the elapsed time, where $t = 0$ s is the moment at which no portion of the vehicle was in view of the scene camera anymore. The y -axis shows the angular distance, with a value below four degrees being considered as the cyclist looking at the vehicle.

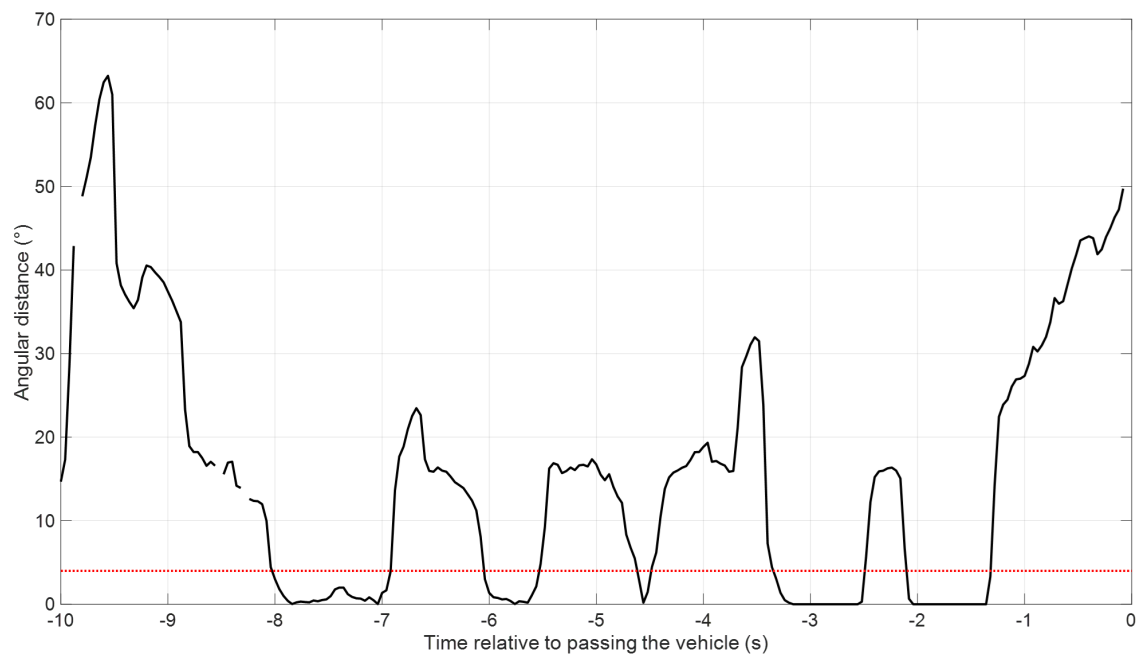


Figure 6.5. Angular distance between gaze point and vehicle for a single cyclist-automated vehicle encounter.

Note: The horizontal line is depicted at an angle of 4°.

Determining Bicycle Speed

Cycling speed was determined manually: All videos were annotated to determine the elapsed time when passing nine landmarks surrounding the interaction with the vehicle. These landmarks were salient features, such as maintenance holes on the cycling path and walkway entries located on the left side of the cycling path. In total, there were four landmarks prior to the automated vehicle and five landmarks after it. The distance between consecutive landmarks varied between 13.70 and 36.64 metres, and the total distance between the first and last landmarks was 182.6 metres.

The mean speed between two subsequent landmarks was estimated as the distance between the two landmarks as measured in Google Maps divided by the time the participant took to cycle between them, where elapsed time was estimated from the corresponding number of frames in the video divided by the frame rate (see Kováčsová et al. (2019), for a similar approach).

Dependent Measures

We extracted the following dependent variables per trial:

- *Looking-at-vehicle*. Whether the participant was looking at the vehicle in the 10-s interval preceding the interaction (see Figure 6.5).
- *Looking-at-vehicle-percentage*. How long the participant looked at the vehicle, defined as the percentage of time, determined over the 10-s interval.
- *Maximum speed*: The maximum speed from the eight distance intervals over which the cycling speed has been calculated.
- *Relative minimum speed*: The minimum speed from the eight distance intervals over which the cycling speed has been calculated, divided by the aforementioned maximum speed. This ratio indicates how much the participants had slowed down.

For Session 2, we additionally determined the following measure:

- *Driver detection accuracy*. Whether the participant correctly reported whether there was a driver in the vehicle. We manually extracted whether participants said “Yes, driver” or “No driver” from the eye-tracker’s audio recordings. These utterances were compared with the ground truth, namely whether a human was behind the wheel in the respective trial. This analysis could yield 1 of 4 possibilities per trial: a true positive, a true negative, a false positive, or a false negative.

6.2.5 Interview analysis

The interview guide of the semi-structured interviews for Session 1 and Session 2 are shown in Tables 6.1 and 6.2.

Table 6.1. Guide for the interview after Session 1.

#	Question
	<i>While cycling, you encountered a vehicle ...</i>
Q1	How did you interact with this vehicle?
Q2	What did you look at? <i>[Probe for looking at certain areas of the car (e.g., windshield, hood, wheels), motion cues, searching for eye contact etc].</i>
Q3	Did anything stand out? If so, what? <i>[Probe for whether they noticed anything different between the vehicles].</i>
Q4	Did you interact differently with this vehicle as opposed to vehicles in daily life? How? Why?

Note: The text segments in brackets indicate prompts or cues not always conveyed to the participants.

Table 6.2. Guide for the interview after Session 2.

#	Question
	<i>While cycling, there was no driver in half of the times you encountered the vehicle ...</i>
Q5	To what extent did the interactions affect your <i>[cycling]</i> behaviour? From 1 (not at all) to 5 (very much).
Q6	How was your <i>[cycling]</i> behaviour affected?
Q7	Did you feel safe? Please elaborate on your answer.
Q8	Would you like to be able to distinguish the vehicle from a “normal vehicle”? <i>[e.g., a sign or marking that indicates automation].</i>
Q9	Would you like additional communication from the vehicle? <i>[e.g., extra lights or a display]</i> Please elaborate on your answer. <i>[Probe for the preferred modality of communication: visual, auditory, haptic, connectivity, vehicle, infrastructure, bike, cyclist].</i>
Q10	To what extent do you think the experiment setup was realistic? From 1 (not realistic) to 5 (very realistic).
Q11	Is there anything else you would like to add?

Note: The text segments in brackets indicate prompts or cues not always conveyed to the participants.

We recorded the interview audio with an Olympus VP-20 voice recorder. The average interview duration following Session 1 and Session 2 was 3 and 8 minutes, respectively. The audio was transcribed clean verbatim by Amberscript (2023, May 1) and checked manually to correct the interviewer and interviewee identification.

The interview data was analysed with OpenAI’s ChatGPT, using a prompting method presented by Tabone and De Winter (2023). Each question per participant has been summarised using the ChatGPT API (model: gpt-4-06013). In this manner, we created 407 summaries (37 participants x 11 questions). An example prompt is provided in Table 6.3.

Table 6.3. Prompt for summarising a participant's transcript, with regard to one question (Q5).

This is a transcript of an interview done with a participant who had cycled four rounds and interacted with a Wizard-of-Oz automated vehicle in each round. Before this session, the participant was told to look for and verbally indicate whether a driver was present.

Speaker 1 is the interviewer; Speaker 2 is the participant.

This is the transcript:

...

...

Based on this interview, what did the participant say about the extent to which the interactions affected their cycling behaviour? ; do not report numbers; only explanations

As a validation check of the ChatGPT output, the interview data from the first 15 participants of Session 1 were analysed manually by one of the authors, creating brief summaries of each interview question (Q1–Q4) per participant. Another author compared these summaries with the transcripts and ChatGPT summaries. Compared to manual analysis, the summaries generated by ChatGPT contained more repetitive statements per participant across Q1–Q4, but captured details slightly better. We did not find any hallucinations in the ChatGPT output; see Supplementary Data for the comparison of ChatGPT and manual summaries.

The 37 ChatGPT summaries per question were subsequently summarised again for each question, creating meta-summaries. A prompt through which we achieved this, in this case for Q5, is displayed in Table 6.4. The meta-summaries are described in the results section, accompanied by illustrative quotes from the transcripts. The complete ChatGPT meta-summaries are provided in Appendix E.

Table 6.4. Prompt for summarising the summaries of all 37 participants, with regard to one question (Q5).

Please summarise the above summaries into a meta-summary, capturing the views of all 37 participants, in four sentences. The output should capture the essence in an interesting and specific manner, in UK English.

Participant No. 1: ...

Participant No. 2: ...

While ChatGPT is linguistically proficient, its numerical counting accuracy is debatable (Wang et al., 2023). To investigate the number of participants who reported noticing the absence of a driver during the interviews after Session 1, we manually analysed the transcripts. One researcher counted the number of participants who mentioned that a driver was absent, who did not mention a driver was absent (but did mention the word 'driver'), and who did not mention the notion of a driver at all in the transcripts.

6.3 Results

6.3.1 Driver presence/absence recognition (Session 1)

Following Session 1, the participants were interviewed. Out of the 37 participants, 11 correctly mentioned that (in some trials) the vehicle was devoid of a driver (Table 6.5). An additional 19 participants mentioned the notion of a driver but did *not* point out that there was no driver in

the vehicle in some trials. The remaining 7 participants did not mention the notion of a driver in the interview.

Table 6.5. The number and percentage of participants recognising driver presence or absence during the interview after Session 1

Driver presence/absence recognition	Number of participants	%
Mentioned that a driver was absent	11	30%
Did not mention that a driver was absent	19	51%
Did not mention the notion of a driver	7	19%

Note: $n = 37$.

6.3.2 Accuracy of detection of driver presence and absence (Session 2)

The confusion matrix of the driver detection task in Session 2 shows mostly accurate detections of the driver's presence or absence, with 63 true positives and 64 true negatives (Table 6.6). Conversely, incidences of false negatives (misses) and false positives were small (5 and 4, respectively). A total of 6 participants were responsible for the 9 mistakes.

Table 6.6. Confusion matrix depicting participants' detection of driver presence/absence, self-reported during Session 2 (total number of trials: 136)

		Ground truth	
		Driver present	Driver absent
Participant	"Yes, driver"	63	4
	"No driver"	5	64

6.3.3 Looking at the vehicle (Sessions 1 & 2)

Of the 37 participants, no eye-tracking data was available in Session 2 for three participants due to a software error. In addition, for one participant, the eye-tracking data from the first of four trials of Session 1 was not used because the vehicle did not drive due to experimenter error.

Figure 6.6 depicts the percentage of participants looking at the vehicle as a function of time during the interaction. Note that a time of 0 seconds corresponds to the vehicle completely disappearing from the eye-tracker scene camera view. It can be seen that participants looked substantially more at the vehicle in Session 2 than in Session 1. These findings are supported by quantifying the percentage of participants that looked at the vehicle at least once during a trial, i.e., the looking-at-vehicle measure. Averaged over the 4 trials per session, this was 87.8% of the trials in Session 1 and 94.9% in Session 2. According to a Wilcoxon signed-rank, this difference was not statistically significant, $p = 0.375$ ($n = 34$). Note that the percentages are high, but still conservative, as eye-tracking data are imperfect. It is possible that a participant was looking at the vehicle, but the eye-tracker did not capture this as being within 4° of the bounding box.

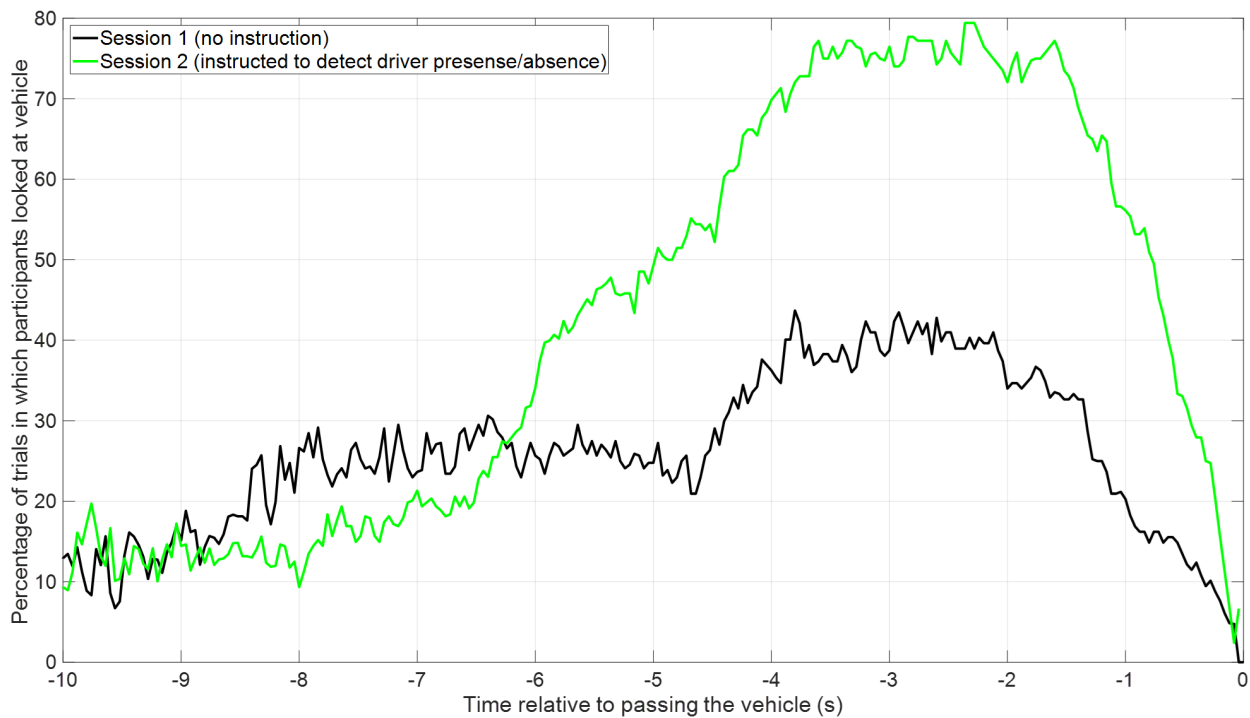


Figure 6.6. Percentage of trials in which participants looked at the vehicle, defined for each video frame across a 10-s window preceding the encounter.

The percentage of time spent looking at the vehicle over the 10-s window was 27.4% ($SD = 18.7\%$) in Session 1 versus 44.5% ($SD = 19.4\%$) in Session 2. This difference was statistically significant according to a paired-samples t -test, $t(33) = 4.06$, $p < 0.001$.

6.3.4 Gaze distribution

The next question addressed is *how* the cyclists divided their attention while approaching the vehicle. To this end, all gaze data were partitioned into groups based on the distance between the cyclist and the vehicle, in 5-metre increments. The distance was estimated from the bounding box height in pixels. Only plausible bounding boxes were retained, with a width/height ratio between 1.00 and 1.90. Heatmaps were created from this partitioned data.

The heatmaps, depicted in Figures 6.7 and 6.8, show the average size of the bounding box in a green outline in consecutive order. The smaller the bounding box, the further away the vehicle is. The heatmaps were created by counting the number of gaze points in a grid of 20×20 pixels.

In Session 1 (Figure 6.7), a bimodal distribution in the viewing direction can be observed for all distances. That is, the cyclists frequently looked towards the vehicle but also frequently to the right of the vehicle, i.e., toward the bike path being ridden. The closer the cyclist approached the vehicle, the greater the horizontal distance between the two-point clouds. This can be explained by the fact that the vehicle and the bike path show an increasing angular separation as the vehicle gets closer. Another interesting phenomenon in Session 1 is that at far distances (Distance > 15 m), the cyclists did not look directly at the vehicle but lower than the vehicle. When the vehicle was closer, the cyclist looked at the vehicle, i.e., within the bounding box.

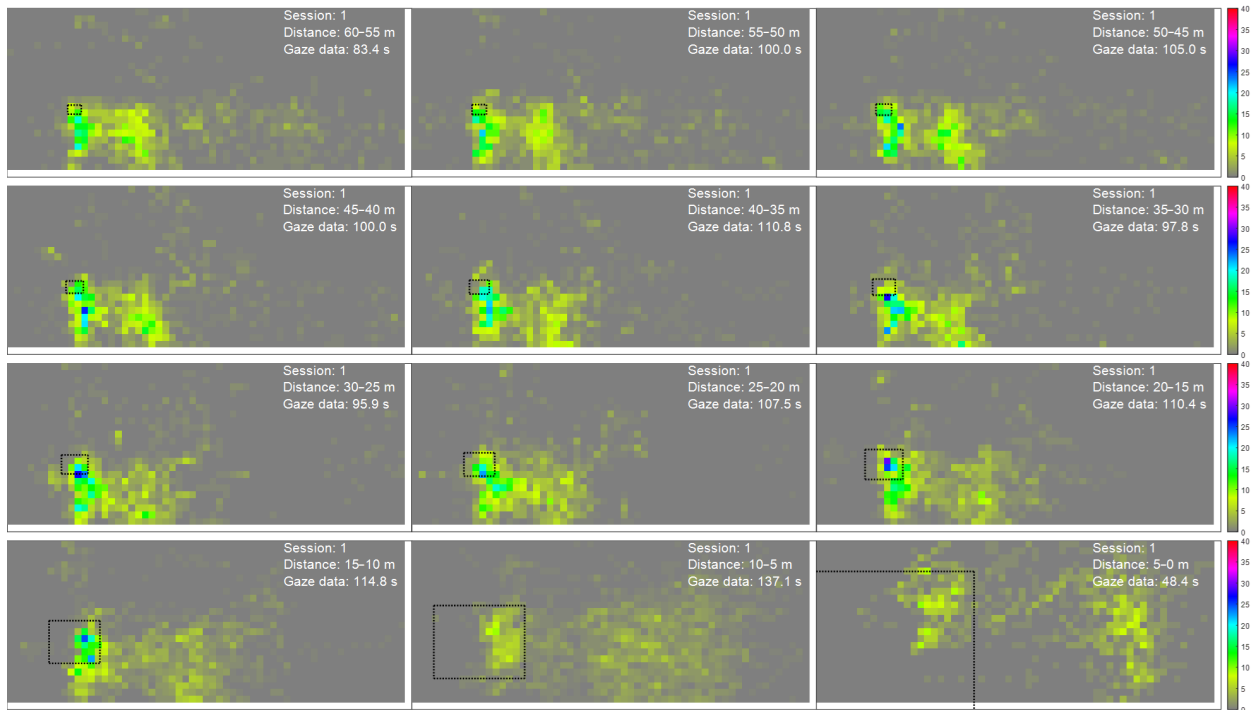


Figure 6.7. Heatmaps of gaze distribution relative to the bounding box surrounding the vehicle, for different distances to the vehicle, for Session 1.

Note: The heatmaps consist of 20×20-pixel cells and are 1200 pixels wide and 500 pixels high. The sum of the depicted values equals 1000. The mean dimensions of the bounding boxes are presented by the dotted black rectangle.

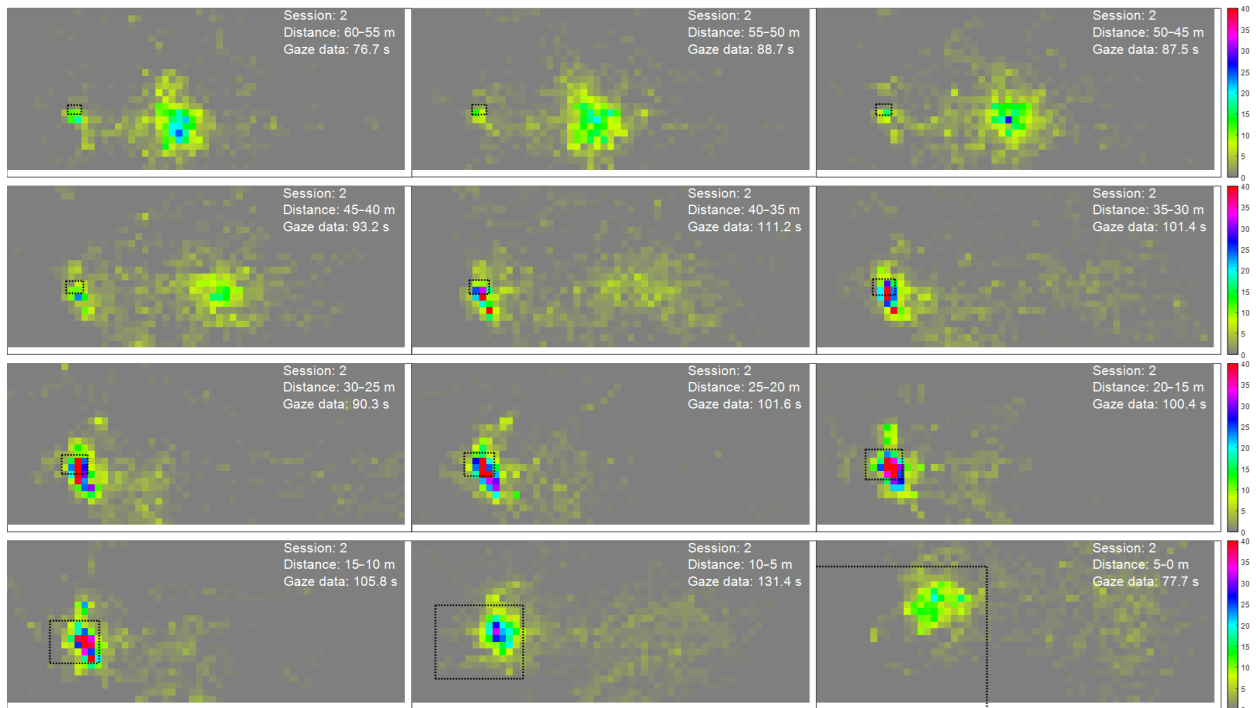


Figure 6.8. Heatmaps of gaze distribution relative to the bounding box surrounding the vehicle, for different distances to the vehicle, for Session 2.

Note: The heatmaps consist of 20×20-pixel cells and are 1200 pixels wide and 500 pixels high. The sum of the depicted values equals 1000. The mean dimensions of the bounding boxes are presented by the dotted black rectangle.

The viewing distribution in Session 2 is substantially different from Session 1 (see Figures 6.7 and 6.8). It can be seen that the bimodal distribution at a far distance to the vehicle (Distance > 40 m) is more pronounced compared to Session 1, which can be explained by the fact that participants had the secondary task of reading letters on the sign held by the person positioned on the right-hand side of the cycling path. Shortly after (Distance < 40 m), participants focused their attention to a great extent on the vehicle itself. When the vehicle was very close (e.g., Distance < 9 m), the difference with Session 1 is clearly noticeable: In Session 2, the gaze was concentrated around the location of the driver (top right corner of the bounding box). In contrast, in Session 1, it was much less directed into the bounding box and less clustered (yet still on the right-hand side of the vehicle, from the cyclist's perspective).

6.3.5 Cycling speed (Sessions 1 and 2)

The maximum speed at which participants cycled was not significantly different in Session 1 (M : 18.1 km/h, SD : 3.3 km/h) versus Session 2 (M : 18.1 km/h, SD : 3.0 km/h), $t(33) = 0.53$, $p = 0.598$. Figure 6.9 (left) illustrates that the speed correlated strongly between Session 1 and 2.

The relative minimum speed was significantly lower in Session 2 (M : 0.837, $SD = 0.052$) than in Session 1 (M : 0.864, $SD = 0.044$), $t(33) = 3.67$, $p < 0.001$. This could indicate that some participants in Session 2 slowed down in an attempt to better identify if there was someone behind the wheel. These effects are shown in Figure 6.9 (right).

There also appeared to be a learning effect where the relative minimum speed in the first trial of a session was consistently low (Session 1: 0.822, 0.877, 0.871, 0.883; Session 2: 0.781, 0.850, 0.855, 0.863 km/h, for Trials 1, 2, 3, and 4, respectively).

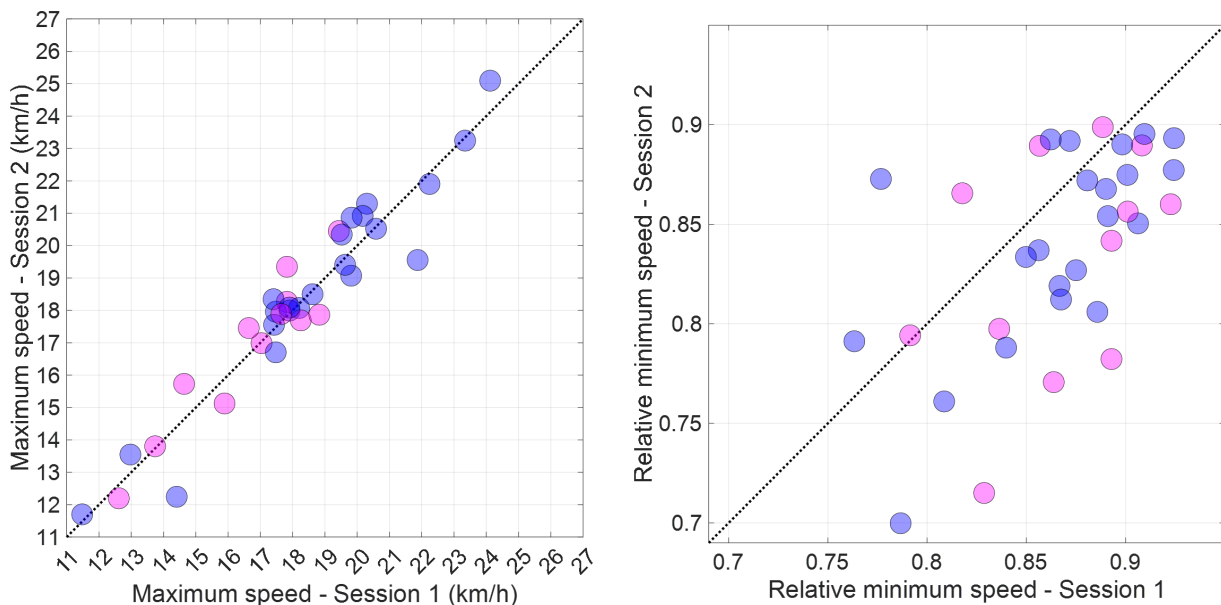


Figure 6.9. Left: Maximum speed (average of 4 trials) in Session 2 versus Session 1; Right: Relative minimum speed (average of 4 trials) in Session 2 versus Session 1.

Note: Each marker represents a participant (blue: male, magenta: female).

6.3.6 Interview data

Session 1

Table E1 in Appendix E provides the full ChatGPT meta-summaries of the interviews after Session 1. In short, the interviews revealed that participants interacted with the vehicle by observing its speed and adjusted their cycling speed accordingly (Q1). Participants frequently focused on the front of the vehicle and tried to identify the driver. They often observed the vehicle's speed and direction but rarely mentioned looking for specific cues or making eye contact (Q2):

"I started looking and sort of, you know, calculating whether it would be a hazard for me or not. Judging by its speed and how far into the cycling area it was". (P39)

While some participants noticed variations in vehicle speed and driver presence, and a few spotted unusual vehicle movement, many did not observe differences between the four trials (Q3). Participants interacted somewhat differently with the vehicle than normal due to its slower speed and the controlled experimental environment, and they generally felt safe due to its predictable behaviour (Q4). Some participants reported confusion, but also increased caution and curiosity in response to the driverless condition (Q4).

"First two times: no driver in there. I was like, what is happening here? I was pretty confused about it, but how did I interact with it? It was going that slow, so I didn't feel like we were going to collide with each other". (P11)

"I tend to stare at the vehicle longer when there's no driver in it because ... it's a little bit strange. The first time I was a little bit shocked and then, a little bit curious about how this car works (...)" (P15)

"At first, I didn't notice, but when I just passed it and I saw, "Oh, there is no [driver]". So, I just turn my head back [to] see. (...) Just out of curiosity". (P16)

Session 2

Tables E2–E4 in Appendix E contain the ChatGPT meta-summaries of the interviews for Session 2. These summaries revealed that the interactions with the automated vehicle often increased caution in cyclists, with driver absence influencing some participants' behaviour, similar to the participants noticing the vehicle sometimes was driverless in Session 1. Participants also said they trusted or treated automation technology like any other vehicle (Q5). Many felt safer with a driver than without, but the trust in the automated vehicle increased over time (Q6). While the task of identifying the driver affected their eye movements and cycling speed, most still felt safe due to the vehicle's slow speed and the controlled setting (Q6, Q7).

"I saw that the speed was very moderate. So even if I didn't see the driver, I thought, okay, this vehicle for sure won't hit me. (...) looking at the speed, I estimated that [it] would have not hit me". (P9)

"It's not on the street, it's on campus. So, in this kind of situation, I feel safer. And I know I'm participating in the experiment". (P24)

The majority of participants expressed a preference for being able to differentiate automated vehicles from traditional vehicles:

"(...) I think in more busy traffic it would be nice to know how unpredictable a person can be or a road user can be. So yeah, I think it would be nice to know whether there is a driver driving or not". (P36)

“I would want to know whether a car is currently being driven by some sort of robotic system. I mean, anything could go wrong. I'd rather be able to know that if I'm going to look inside the car, probably I'm going to find people distracted. So, I shouldn't shock myself because that's happening; I would know. I would make the distinction that that car is [automated]”. (P39)

However, a minority of participants did not need such distinctions as long as the automated vehicle was reliable (Q8). Visual communication methods such as lights, signs, or displays were the most favoured, but some also mentioned auditory communication, especially in complicated or high-speed scenarios (Q9). A few participants also suggested haptic feedback or connectivity, although these methods were considered secondary to visual signals.

“I think a [visual] sign would do for me. And of course, you can also imagine that you wear a wearable, and it interacts with the car and it communicates through haptic communication”. (P6)

Most participants preferred the vehicle to be the source of communication. A minority felt that additional communication was unnecessary or expressed concerns about information overload (Q9).

“In traffic, there's already a lot going on. (...) it can also be kind of information overload”. (P25)

Some participants suggested that the experiment needed more elements like road users and obstacles. Also, certain elements in the experiment, such as the experimenter holding the letters and the presence of pedestrians at a specific corner, were questioned by some participants. Furthermore, some participants suggested varying the vehicle's position, speed, and direction, indicating that the existing conditions might have felt too predictable (Q11).

6.4 Discussion

While some research suggests that road users rely on social cues from drivers (Färber, 2016; Li et al., 2023; Stanciu et al., 2018), other studies indicate that VRUs rarely pick up on such social cues (Lee et al., 2021; Moore et al., 2019). The objective of the current experimental study was to determine whether cyclists notice if a vehicle is driverless, and whether they can detect if there is, or is not, a driver in the driver's seat. Additionally, we examined *how* cyclists performed these tasks, using post-session interviews, eye-tracking, and speed measurements.

Our experiment with 37 cyclists found the following: (1) in a post-session interview, 30% (11 out of 37) of the cyclists spontaneously noted that the vehicle had no driver, and (2) when asked to do so, the cyclists could detect whether someone was behind the wheel with 93% accuracy. In previous 'ghost driver' studies in which VRUs reported 'no driver', it was impossible to ascertain whether this was because the VRU did not notice the driver due to inattention or windshield glare or because they could actually discern there was no driver. In our study, we accounted for this issue by measuring false negatives (misses) and false positives, discovering an even distribution between the two, which indicates minimal response bias.

Apart from investigating cyclists' ability to recognise the presence or absence of a driver, we used eye-tracking to examine how cyclists performed this task. The results showed that the cyclists' attention was bimodally distributed, with cyclists looking either at the path ahead or the vehicle. These findings differ from pedestrian gaze behaviour (De Winter et al., 2021) but are consistent with previous research on gaze behaviour among cyclists (Pashkevich et al., 2022; Trefzger et al., 2021): Cycling is a steering task that requires intermittent attention. Our

results resonate with classic research on car driving (Godthelp, 1988; Senders et al., 1967), in which occlusion techniques were used to examine how drivers steer their vehicle while their vision was intermittently occluded.

When the vehicle was far away (> 15 m), our participants tended to look at the area in front of the vehicle. As the vehicle got closer, the cyclists looked predominantly at the vehicle itself, particularly the windshield. We could not retrieve similar findings in the literature, except for Dey et al. (2019), who investigated the gaze behaviour of pedestrians as a vehicle approached them. A potential reason for the cyclists' focus in front of the vehicle could be that they were trying to anticipate its future position. Other forms of anticipatory viewing have been observed among VRUs. For example, studies among pedestrians (De Winter et al., 2021) and motorcyclists (Aupetit et al., 2015; Papakostopoulos et al., 2020) have found that they do not necessarily focus on the nearest vehicle but rather on vehicles further away, paying attention to distinct features such as turned wheels, to predict the path of these vehicles better.

This study also found that cyclists mainly looked at the right side of the vehicle. One possible explanation is that the driver was positioned on this side of the vehicle. An alternative explanation is that this strategy of looking requires smaller eye movements. According to a visual attention model by Wickens (2008), people's gaze behaviour is partly determined by 'effort', and humans are not inclined to make larger eye and head movements than needed. Future research, for example, on cars with the steering wheel on the left versus the right, should provide further clarification.

In our study, we observed behavioural adaptation: participants in Session 2 slowed down, regardless of the driver's presence. Reducing cycling speed affords the cyclist additional time to detect the driver, and may enhance the quality of perception, since it reduces optical flow and vibrations. Additionally, speed reduction improves safety and enables cyclists to focus on the vehicle instead of primarily on the bicycle path. However, slower cycling speeds can reduce the bicycle's stability, implying that cycling too slowly can also be unsafe (Schwab & Meijaard, 2013; Sharp, 2008). Previous research into cyclist-automated vehicle interaction has used video clips (Thellman et al., 2023; Vlakveld et al., 2020) and still photographs (Bazilinskyy et al., 2023; Ngwu et al., 2022), or asked participants to imagine themselves interacting with an automated vehicle (Sahaï et al., 2022), approaches which neglect the adaptive nature of cycling. In our study, the individual differences in cycling speed were highly replicable from Session 1 to Session 2 and showed significant gender differences. These findings align with those for vehicle driving (De Winter & Happee, 2012; Groeger, 2001), with the physical strength of cycling as additional explanatory power for gender differences in cycling speed (Kováčsová et al., 2016).

The post-session interviews revealed a novelty effect, with participants demonstrating curiosity and alertness in their encounters with the driverless vehicle, a pattern also observed in pedestrian-automated vehicle interaction (Li et al., 2020). However, some participants expressed confidence in the automated vehicle's safe and reliable behaviour. Previous research suggests that the absence of a driver lowers perceived safety, but this effect diminishes when the vehicle has an eHMI (Bazilinskyy, Sakuma, et al., 2021; Faas & Baumann, 2021). Other research showed that perceived safety depends on the presumed reliability of the automated vehicle. For example, online research by Rodríguez Palmeiro et al. (2018) found that cyclists felt more certain that the automated vehicle had detected them and would be inclined to proceed when they were informed that the automated vehicle's sensors were reliable. Similarly, research among pedestrians found that a vehicle that was crawling forward slowly (not unlike our study)

was interpreted as poor human driving by some pedestrians but as advanced automation by others (Bazilinskyy, Sakuma, et al., 2021). Onkhar et al. (2022) found that a driver's eye contact influenced pedestrian crossing intentions but only when vehicle motion were ambiguous. Similarly, (Al-Taie et al., 2023) showed that cyclists use gestures and on-vehicle signals in less regulated situations. In summary, from past research, it appears that responses of VRUs to driverless vehicles are context-sensitive and dependent on their beliefs about the reliability of the automated vehicle (see also Parkin et al., 2023; Thellman et al., 2023). Longer-term studies where participants encounter both traditional and driverless automated vehicles are required to make conclusive statements about how the lack of a driver behind the wheel influences cycling experience and behaviour.

Our research may have implications for the development of eHMIs that inform road users about an automated vehicle's actions (e.g., Bindshädel et al., 2023; Colley et al., 2021; Forke et al., 2021), its awareness of them (e.g., Block et al., 2023; Eisele & Petzoldt, 2022; Epke et al., 2021), or its automated driving mode (e.g., Daimon et al., 2021; Joisten et al., 2020). Results from the interviews following Session 2 indicated that most participants would like to receive such information, especially through visual eHMIs on the automated vehicle. However, eHMI developers should consider that cyclists apply intermittent visual sampling, which implies that eHMIs should be readable in a single glance. Participants were more sceptical about solutions requiring connectivity, such as bike-mounted devices. Hence, the present findings provide a sobering perspective on the many on-bike warning systems described in the literature (Berge et al., 2023).

At the same time, automated vehicle developers should be responsible for enhancing the detection of cyclists and other VRUs (Berge, Hagenzieker, et al., 2022). Automated vehicles still struggle to predict road-user behaviour (Rahmati et al., 2020; Song et al., 2022), and as a result, they often drive conservatively or brake unnecessarily (Aittoniemi, 2022; Yang et al., 2023). Sometimes referred to as 'phantom braking' (Berge et al., 2024; Linja et al., 2022; Moscoso et al., 2021; National Highway Traffic Safety Administration, 2022), this phenomenon may explain why automated vehicles are frequently rear-ended (Kutela et al., 2022; Ma et al., 2022; Petrović et al., 2020). Cyclists can also trigger such braking events in automated shuttles by overtaking them (De Ceunynck et al., 2022; Pelikan, 2021; Pokorný et al., 2021). Moreover, studies indicate that test drivers frequently take over control out of safety necessity (Boggs et al., 2020; Houseal et al., 2022) or embarrassment (Lindgren et al., 2021; Nordhoff & De Winter, 2023). Therefore, advancements in sensor technology and artificial intelligence (AI) are important for enhancing automated vehicle perception capabilities and increasing overall safety.

6.4.1 Limitations

One limitation of this research is that despite its real-world setting, it was still staged. In the interviews, participants questioned the vehicle's presence in a campus area restricted to vehicles. Berge et al. (2024) highlighted 20 key scenarios for future cyclist-automated vehicle interaction studies. Our research corresponds with the 'perpendicular vehicle' scenario. Further research should explore scenarios like right-turning vehicles, left turns, parked vehicle situations, and scenarios requiring negotiation.

Another limitation of the experiment was that it involved varying lighting conditions because it was conducted across three full days in November and December. While weaker sun intensity typical of these months reduce problems with infrared radiation affecting the eye-tracker (Tobii,

2020; Vos et al., 2023), the low sun angle could increase glare, possibly impairing driver visibility.

The participants were primarily recruited from a technical university, which limits the representativeness of our findings. Additionally, although all participants reported engaging in weekly cycling, the cycling behaviour of several international participants diverged from typical Dutch cycling behaviour: they displayed cautiousness, characterised by their avoidance of the vehicle and a slow cycling pace.

It is unknown how many participants believed the vehicle was driving automatically. Previous Wizard-of-Oz research showed believability percentages ranging from 97 to 100% (Faas & Baumann, 2021; Habibovic et al., 2018; Joisten et al., 2020), but also 60% to 88% (Currano et al., 2018; Faas & Baumann, 2019; Hensch et al., 2020; Large et al., 2023; Li et al., 2020; Moore et al., 2019; Rothenbücher et al., 2016), and 40% (Rodríguez Palmeiro et al., 2018). These percentages appear to be context-dependent, for example, whether a modern-looking vehicle was used. In our study, our impression was that the participants generally believed that the vehicle was driving automatically, as noted in participant responses during the debriefing.

A final limitation involves our use of ChatGPT for generating interview summaries. Similar approaches have been previously used, with seemingly valid results (Patel & Lam, 2023; Tabone & De Winter, 2023). However, ChatGPT's usage of terms such as "some participants" or "many participants" is somewhat ambiguous. Therefore, it is recommended that a summary produced by ChatGPT should be used as a supplement to quotations and the manual extraction of counts, as we have done in our study.

6.5 Conclusion

While cyclists often did not spontaneously mention the absence of a driver in a post-cycling interview, they were highly capable of detecting the presence/absence of a driver when specifically instructed to do so. Cyclists slowed down when trying to detect the presence of a driver. Furthermore, they focused either on the path ahead or towards the vehicle itself, indicating that cycling is a task that requires intermittent attention. When the vehicle was still far away, cyclists looked in front of the vehicle rather than at the vehicle itself. Finally, participants reported increased caution and curiosity when encountering a driverless vehicle but also expressed trust in the automated vehicle's safe behaviour. They wanted clear communication from automated vehicles, such as visual signals or signs, to differentiate automated vehicles from traditional vehicles. Participants preferred the automated vehicle as the source of communication rather than relying on external devices or infrastructure.

Future research on cyclist-automated vehicle interaction should be conducted in more diverse traffic scenarios. Furthermore, it would be beneficial to investigate the perceptions and behaviours of a more diverse sample of cyclists. Finally, we recommend further exploring the use of computer vision for analysing eye-tracking data and large language models for analysing interview data; these approaches may offer promising opportunities for future research.

Chapter 7

Phantom braking in automated vehicles: A theoretical outline and cycling simulator demonstration

The emerging use of automated driving systems introduces novel situations that may affect the safety of vulnerable road users such as cyclists. In this chapter, we explain and conceptualise the phenomenon of phantom braking – sudden and unexpected deceleration – in automated vehicles. We apply signal detection theory to interpret phantom braking as a by-product of automated decision-making, with the vehicle favouring the avoidance of accidents at the cost of potentially causing rear-end accidents. To illustrate phantom braking and its effects on cyclists, we used a newly developed cycling simulator. An exploratory measurement, conducted with a single cyclist participant revealed a possible complacency effect of the cyclist, with the cyclist's decision-making mirroring the automated vehicle's decision-making. The findings provide a testament to using cycling simulators for further exploration of the effects of phantom braking on cyclists.

This chapter is based on Berge, S. H., De Winter, J. Feng., Y., & Hagenzieker, M. (2024). Phantom braking in automated vehicles: A theoretical outline and cycling simulator demonstration. In *Proceedings of the 15th International Conference on Applied Human Factors and Ergonomics (AHFE 2024)*. <http://doi.org/10.54941/ahfe1005212>

7.1 Introduction

Automated vehicles (AVs) have the potential to transform the dynamics of urban traffic. The impact of these changes on the safety of vulnerable road users is a topic of great concern (Matin & Dia, 2023). The absence of a human driver will likely affect how vulnerable road users interact and communicate with vehicles. Moreover, the increasing use of automated driving systems introduces novel situations and unpredictable vehicle behaviour. Among these behaviours is the phenomenon of phantom braking (Berge et al., 2024). Phantom braking in AVs refers to the sudden, unexpected deceleration typically caused by the vehicle's sensors or algorithms misinterpreting the traffic situation (Linja et al., 2022; Moscoso et al., 2021; National Highway Traffic Safety Administration, 2022).

While phantom braking is a technological issue, it poses safety implications for vulnerable road users such as cyclists. Cyclists trailing an automated vehicle risk rear-ending the vehicle or potential propulsion over the handlebars in the event of abrupt braking. Although human drivers may be at greater collision risk due to their higher speeds, cyclists have less protection than drivers. To ensure cyclists are safe in traffic with automated vehicles, understanding the occurrence and frequency of phantom braking and its impact on cyclists is vital. The present chapter aims to explain and demonstrate the concept of phantom braking and measure a cyclist's response to such events.

Signal detection theory (Abdi, 2007; Green & Swets, 1966) provides a framework that can be used to understand the process behind phantom braking in automated vehicles. This theory describes how automated vehicle sensors distinguish meaningful data ("signals"), such as the presence of a pedestrian at a zebra crossing, from irrelevant sensor input ("noise"). The decision threshold of the sensor system determines whether the automated vehicle will respond to a given sensory input. Setting a lower threshold may increase the detection of actual hazards but also the chance of false positives, leading to phantom braking. For instance, an automated vehicle with an appropriate decision threshold would decelerate and stop to let a pedestrian cross a zebra crossing, but not stop when unneeded. In contrast, an automated vehicle with a lower threshold may also brake and stop due to irrelevant sensor input, such as a leaf or plastic bag blowing across the road.

Automated vehicles are typically programmed with a sensitive threshold to minimise the risk of overlooking real threats. Such overly sensitive thresholds are seen in studies on automated shuttle busses: De Ceunynck et al. (2022) reported that cyclists' overtaking manoeuvres often led to phantom braking, and in Boersma et al. (2018), high grass on the side of the road had to be cut to stop triggering the shuttle's emergency braking. Unexpected automated driving system behaviour, such as phantom braking, is also reported among drivers of privately owned vehicles (Nordhoff et al., 2023) and robo-taxis (Pitts, 2023). According to Petrović et al. (2020), automated vehicles are often rear-ended compared to manual-driven vehicles, yet they exhibit a very low incidence of pedestrian collisions. In that sense, phantom braking can be seen as a by-product of an imperfect sensor system and may persist until technological improvements in sensors and algorithms are realised.

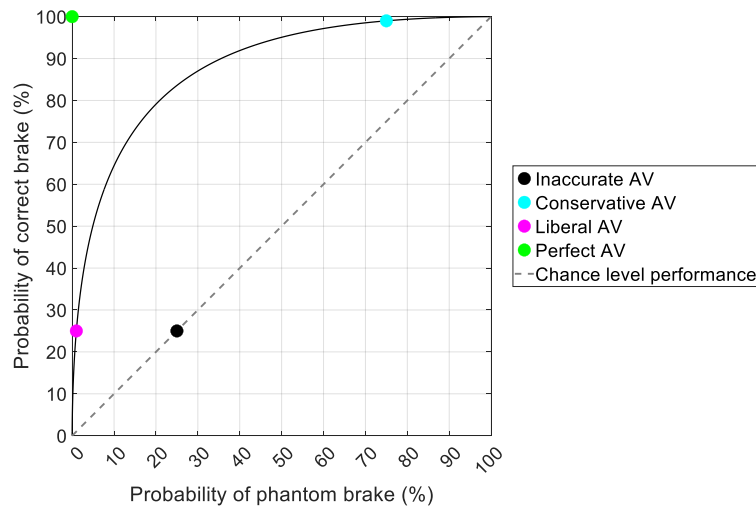


Figure 7.1. Hypothetical ROC curve for four types of AV sensors: perfect AV (fail-to-brake [FBR]: 0%, phantom brake rate [PBR]: 0%), inaccurate AV ($d' = 0.00$; FBR: 75%; PBR: 25%), and accurate AV ($d' = 1.65$) with two different criterion levels, resulting in conservative (FBR: 1%, PBR: 75%) vs. liberal AV behaviour (FBR: 75%, PBR: 1%).

Note: In this figure, we assume normally distributed signal + noise and noise distributions with equal standard deviations. d' , an index of sensor discriminability, is calculated as $Z(\text{correct brake rate}) - Z(\text{phantom brake rate})$, where Z is the inverse of the normal cumulative distribution function.

Figure 7.1 shows a hypothetical receiver operating characteristic (ROC) curve explaining the performance of automated vehicle braking systems. The x -axis signifies the probability of phantom braking events, and the y -axis depicts the probability of correct braking events. The curve depicts the trade-off faced by automated vehicle systems: the sensitivity to real hazards that require a braking action versus the tendency for phantom braking, i.e., unwarranted braking events in the absence of actual hazards.

The curve of Figure 7.1 is plotted with data points representing four automated vehicle systems, each illustrating different sensitivity thresholds. The ‘Inaccurate AV’ represents a vehicle with poor sensor capabilities, performing at chance level, characterised by frequent phantom braking and low rates of correct braking. Conversely, the ‘Conservative AV’ indicates a vehicle system with better capabilities but a low decision threshold, leading to a high correct and phantom braking rate. It is plausible that automated vehicle manufacturers opt for this conservative approach. The ‘Liberal AV’, with a high decision threshold, brakes less often, reducing phantom braking but increasing the risk of missing genuine hazards. Lastly, the ‘Perfect AV’ is a hypothetical system with ideal sensors that perfectly discriminate true from false braking cues, ensuring 100% correct braking without phantom instances.

In traffic, one must understand the automated vehicle’s responses to the environment and how a human road user – the cyclist – interprets and reacts to both the automated vehicle and their surroundings. Figure 7.2 illustrates this concept, building on signal detection theory and the model of parallel human and automation alerting system adapted from Wickens et al. (2023).

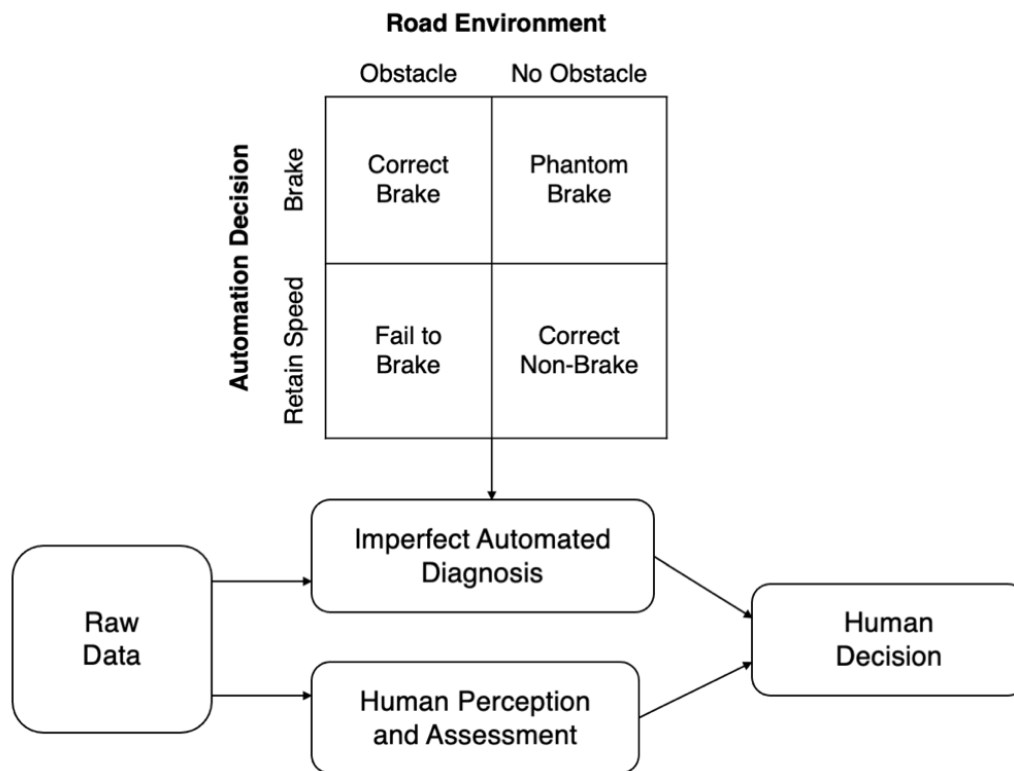


Figure 7.2. Conceptual model of phantom braking (adapted from Wickens et al., 2023, p. 30).

Note: Depending on the level of trust in the AV, the human decision-maker may assign more weight to the visual cues from the AV (i.e., mirroring the imperfect automated diagnosis) or to the surrounding environment (i.e., human perception and assessment based on raw data).

In Figure 7.2, environmental visual information, termed ‘Raw Data’, is fed into two parallel decision-making processes: the automated vehicle’s ‘Imperfect Automated Diagnosis’ and the cyclist’s ‘Human Perception and Assessment’. The automated vehicle and the cyclist can decide whether to respond based on their respective decision thresholds. Suppose the automated vehicle frequently triggers phantom braking or fails to detect real obstacles (fail to brake, e.g., retains speed when a pedestrian indicates intent to cross the road). This can diminish the cyclist’s trust in the reliability of the automated vehicle. Consequently, the cyclist may become more inclined to ignore the brake lights and instead rely on their own assessments of the situation, potentially leading to overtaking the vehicle or braking independently of the automated vehicle’s actions. Thus, the cyclist’s response is shaped by automated vehicle behaviour, which depends on its sensor capabilities and criterion level, and the cyclist’s own capability and decision thresholds.

Having conceptualised and introduced the theoretical rationale behind phantom braking, the present study seeks to illustrate further the effects of phantom braking on cyclist behaviour in a simulated environment. Bicycle simulators have been increasingly employed in research on cyclist behaviour and have the advantage of enabling researchers to conduct measurements in controllable and safe conditions (Sporrel et al., 2023). Using a single-participant approach in a virtual reality (VR) bicycle simulator, this proof-of-concept study aims to set the stage for broader empirical research on automated vehicle-cyclist interaction. Our work also highlights the need to prioritise cyclist experiences and cyclist and pedestrian safety in the deployment of automated vehicle technologies.

7.2 Method

7.2.1 Cycling simulator

In this study, we illustrate a cyclist's responses to phantom braking using a newly developed VR cycling simulator at the Faculty of Civil Engineering and Geosciences at Delft University of Technology. The study was approved by the university's Human Research Ethics Committee (ID #3327). The bicycle simulator consists of a bicycle mounted on a Tacx Flow Smart wheel-on trainer and a VR headset (HTC VIVE Pro Eye). It offers resistance through an electromagnetic resistance unit on the rear wheel. The simulator features no bicycle tilt or pitch and only allows forward motion without steering, see Figure 7.3.



Figure 7.3. The virtual reality cycling simulator

7.2.2 Experiment design

The automated vehicle's braking behaviour was categorised into four types: true and false positives, and true and false negatives. See Table 7.1 for a description of the respective behavioural variables.

Table 7.1. The programmed automated vehicle braking behaviour

Variable	Definition
Correct brake	The AV correctly stops for a pedestrian at a zebra crossing
Phantom brake	The AV stops without a pedestrian present at a zebra crossing
Fail to brake	The AV fails to stop when a pedestrian is present at a zebra crossing
Correct non-brake	The AV correctly continues driving through a zebra crossing without a pedestrian present

We designed four experimental conditions, each consisting of 16 pedestrian crossings, with the likelihood of each event type based on the probabilities shown in Figure 7.1. At 8 of the 16 pedestrian crossings, there was a pedestrian standing still at approximately 1.5 m from the side of the road; at the other 8 pedestrian crossings, there was no pedestrian present. A single cyclist, identified as author S.B., rode the simulator in each of the four conditions:

- *Inaccurate AV*: This AV failed to brake for a pedestrian in 6 out of 8 cases and incorrectly stopped without a pedestrian present (phantom brake) in 2 out of 8 cases.
- *Conservative AV*: This AV displayed high caution, with correct braking in front of a pedestrian at the crossing (8 out of 8 cases) and a high degree of phantom braking: 6 out of 8 cases with no pedestrian present.
- *Liberal AV*: The liberal AV behaved in the opposite way of the conservative AV. It retained its speed (correct non-brake) in 8 out of the 8 cases with no pedestrian present at the crossing but had only 2 cases of correct braking (i.e., braking with a pedestrian present). The liberal AV had no phantom braking.
- *Perfect AV*: This AV exhibited perfect detection capability, stopping 8 of the 8 times a pedestrian was present at the crossing (correct brake). The perfect AV also retained speed at 8 out of 8 cases with no pedestrian present at the crossing (correct non-brake).

The order of the 16 events was randomised for each trial. The AV maintained a predetermined distance from the cyclist, meaning that the cyclist could not alter this distance by cycling slower or faster. The fixed distance was released upon nearing a pedestrian zebra crossing and re-established before the next pedestrian zebra crossing. The speed of the AV showed fluctuations with respect to the cyclist's speed, as a result of which the centre-to-centre distance between the AV and the cyclist varied between 14 and 21 metres. The concept of the lead vehicle maintaining an automatic set distance from the trailing road user was based on earlier research that used a similar experimental design among car drivers (De Winter et al., 2023).

Figure 7.4 provides a screenshot of the experimenter's terminal. It shows the participant's view of the VR headset and the experimental progress. In this frame, the AV has just come to a full stop while a pedestrian is present. This event represents a correct brake since the AV stopped for a pedestrian.



Figure 7.4. Screenshot of the terminal of the experimenter

7.2.3 Data collection and analysis

The data from the four conditions was collected in an Unreal Game Engine 4 research module (Feng et al., 2022). The speed of the virtual bicycle was slightly affected by the pedalling frequency of the cyclist. This variation in speed indicates the high accuracy of the speed measurement but is not directly relevant to our purposes. Therefore, we filtered the speed signal of the bicycle and that of the AV. We did this with a forward-reverse moving median filter, applied over a time interval of 90 samples, corresponding to 1 second. Subsequent analysis involved calculating the cyclist's brake reaction times (BRTs). These were calculated by subtracting the moment the AV initiated deceleration from the moment the cyclist began decelerating. The speed filtering result is illustrated in Figure 7.5.

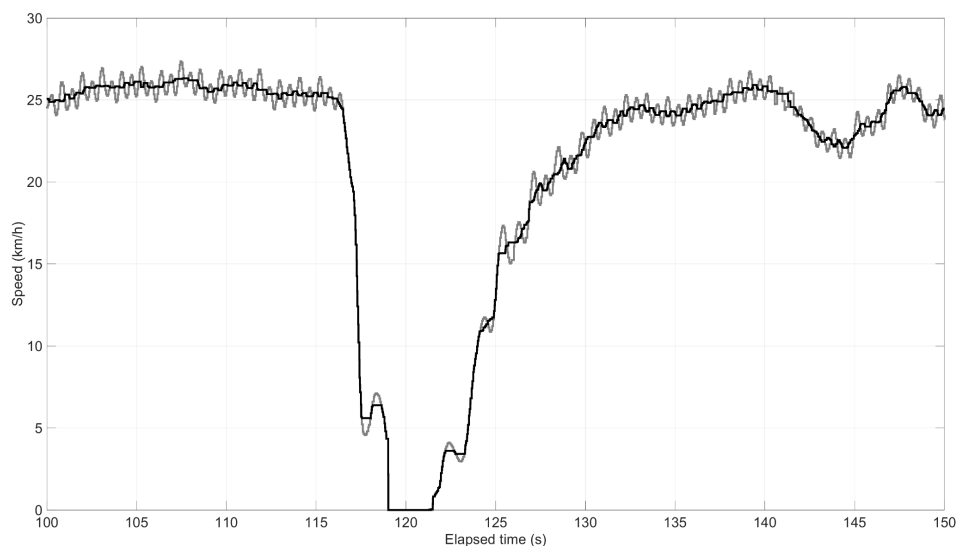


Figure 7.5. Filtering of the bicycle speed signal.

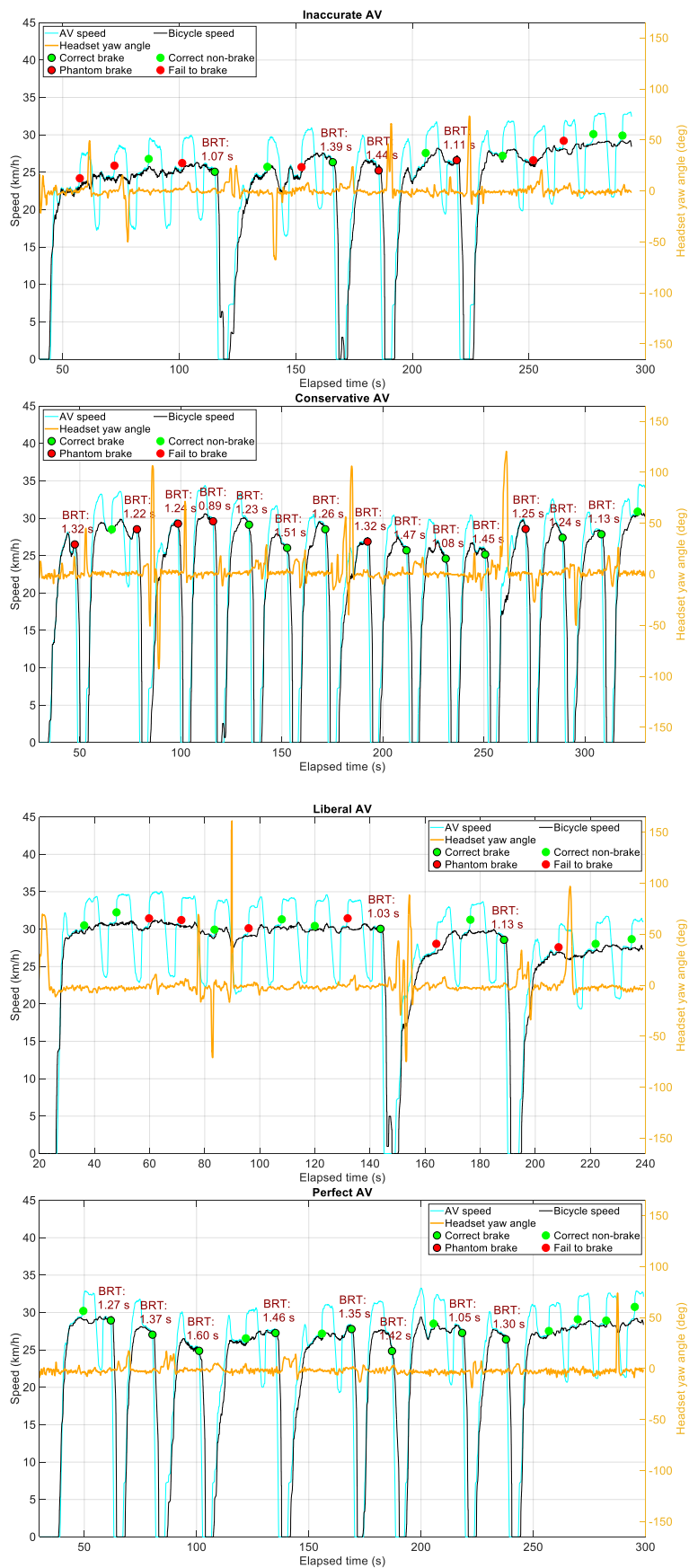


Figure 7.6. Speed of the cyclist and the automated vehicle (AV) in the four conditions.

7.3 Results

The speeds of the cyclist participant and AV are illustrated in Figure 7.6. In all cases where the AV decelerated – whether due to the correct identification of pedestrians (correct brake) or unnecessary phantom braking – the cyclist also braked to a stop. The corresponding brake reaction times (BRTs) varied between 1.0 and 1.6 seconds. This demonstrates that the cyclist responded quite consistently to the AV's implicit and explicit deceleration signals, such as the looming cues of the approaching AV during braking and the brake light signals.

Interestingly, the cyclist did not brake, as shown by the near-constant cycling speeds, when the AV failed to brake for the pedestrian. In other words, if a pedestrian was present at the crosswalk and the AV continued, the cyclist also maintained their speed. The data from Figure 7.6 also shows that both the cyclist and the AV, which was programmed to maintain a constant distance from the bicycle, generally travelled at a high speed, nearly 30 km/h. This speed was partly due to the adjustable resistance motor but could also reflect the experience of riding an electric bike, where such speeds are more easily achievable.

Finally, from the recorded head movements, it was observed that the cyclist primarily looked straight ahead, in the direction of the AV, with occasional intermittent glances to the left or right sides. Especially at a standstill or low speed, the cyclist tended to look at the pedestrian, as indicated by the positive yaw-angle value.

7.4 Discussion

In this study, we introduced and demonstrated the concept of phantom braking in AVs in a VR bicycle simulator. While the results are not generally applicable due to the single-participant design, they lay the groundwork for additional empirical research on phantom braking and its implications for cyclists.

Our research highlights the issue of phantom braking and interprets it through signal detection theory. We argue that phantom braking results from imperfect sensor systems and the inherent trade-off between avoiding accidents and unnecessary braking (phantom braking). Previous research shows that AV manufacturers likely prefer a conservative approach for safety and liability purposes (Berge et al., 2024; Boersma et al., 2018; De Ceunynck et al., 2022; Nordhoff et al., 2023). This erring on the side of caution inadvertently increases the frequency of phantom braking.

Furthermore, by applying the model of Wickens et al. (2023) (see Figure 7.2), we clarified that a following cyclist's responses depend on the braking behaviour of the leading AV, as well as cues in the environment, such as a pedestrian at a crosswalk. However, in our demonstration, we observed that the cyclist mimicked the AV behaviour, effectively disregarding the rights of the pedestrian. This reliance on automation behaviour, termed *complacency* (e.g., Bahner et al., 2008) or *automation bias* (e.g., Parasuraman and Manzey, 2010), forms an interesting phenomenon to be explored in future research. Our data revealed the risk that cyclists may depend too much on the lead AV reactions without considering 'raw data' in the environment, such as the pedestrian. This leader-and-follower phenomenon could also have real-life implications for cyclist safety, as complacency might cause cyclists to pay less attention to the road and environment, potentially increasing their chances of rear-end accidents due to abrupt

braking, or the cyclist swerving, losing balance, and falling due to unanticipated braking events of the vehicle.

The cyclist disregarding their legal obligation to yield to the pedestrian could be attributed to the participant's idiosyncratic interpretation of the task. Another explanation is that cyclists may be inclined to overlook or ignore traffic regulations due to their agility and relatively small size compared to cars, as suggested by Berge, Hagenzieker, et al. (2022). Furthermore, in our virtual environment, the pedestrian remained stationary at the crossing, regardless of the cyclist stopping, which might have influenced the cyclist's decision to continue pedalling. Gathering more data would provide more clarity on these behaviours.

Finally, this study offers a new perspective on using VR bicycle simulators. Previous studies (e.g., Lee et al., 2017) faced challenges in simulating realistic cycling experiences, especially in steering and balancing, due to the complex dynamics of a bicycle and the role of peripheral vision in inducing a sense of motion, which can lead to imbalance and simulator sickness. By deploying a fixed bicycle simulator on a straight road and focusing on stop-and-go decisions, we found a pragmatic method to test the decision-making of cyclists in a controlled environment. To address the rising issues of simulator sickness or safety, a large TV screen may be considered instead of a VR headset, which would sacrifice the ability to track head movements natively.

7.5 Conclusion

This study using a novel VR bicycle simulator is an initial step in understanding phantom braking in AVs and its impact on cyclists. Our single-participant findings indicate the need for AV systems that balance safety with real-world functionality. The data also provides validation for using bicycle simulators to further explore the effects of phantom braking by an AV. Future studies should include a larger sample to study phantom braking and its effects on cyclists regarding behavioural changes such as complacency and the risk of rear-end accidents.

Chapter 8

Discussion and conclusion

As our exploration of cycling in the age of automation draws to a close, it is time to reflect on and synthesise the findings of the studies presented in this dissertation. Anchored in the overarching objective of enhancing the interaction between cyclists and automated vehicles, this body of work has outlined the mechanisms of communication in traffic and assessed technological solutions and design strategies that may provide cyclists with safer traffic environments in the future.

In this dissertation, a cyclist-centric perspective is adopted, exploring the factors that shape the interaction between cyclists and automated vehicles and their implications for cyclist safety from a cyclist's point of view. The preceding chapters have laid the groundwork by exploring cyclists' interaction with vehicles today and their expectations and requirements of the automated vehicles of tomorrow. Core to our discussion has been understanding how cyclists interact in traffic, focusing on implicit and explicit communication, and the current trends within human factors research suggesting HMIs as essential tools to fill the social void that may occur between cyclists and automated vehicles.

The following sections present and discuss the knowledge acquired throughout this doctorate research endeavour, offering recommendations and guidelines for interface development, future research, and policy-making.

8.1 Synthesis of findings

The insights gathered throughout this dissertation have been synthesised into four interrelated research topics: cyclist-automated vehicle interactions, scenarios and behavioural challenges, ethical considerations, and HMI solutions. Each topic and its corresponding research questions have been investigated to uncover the technological, psychological, and ethical factors potentially impacting the safety of cyclists as they coexist with automated driving systems on urban roads. Figure 8.1 shows how the synthesis of findings is structured, with the four research topics, their respective research questions (*RQs*), and the relevant chapters.

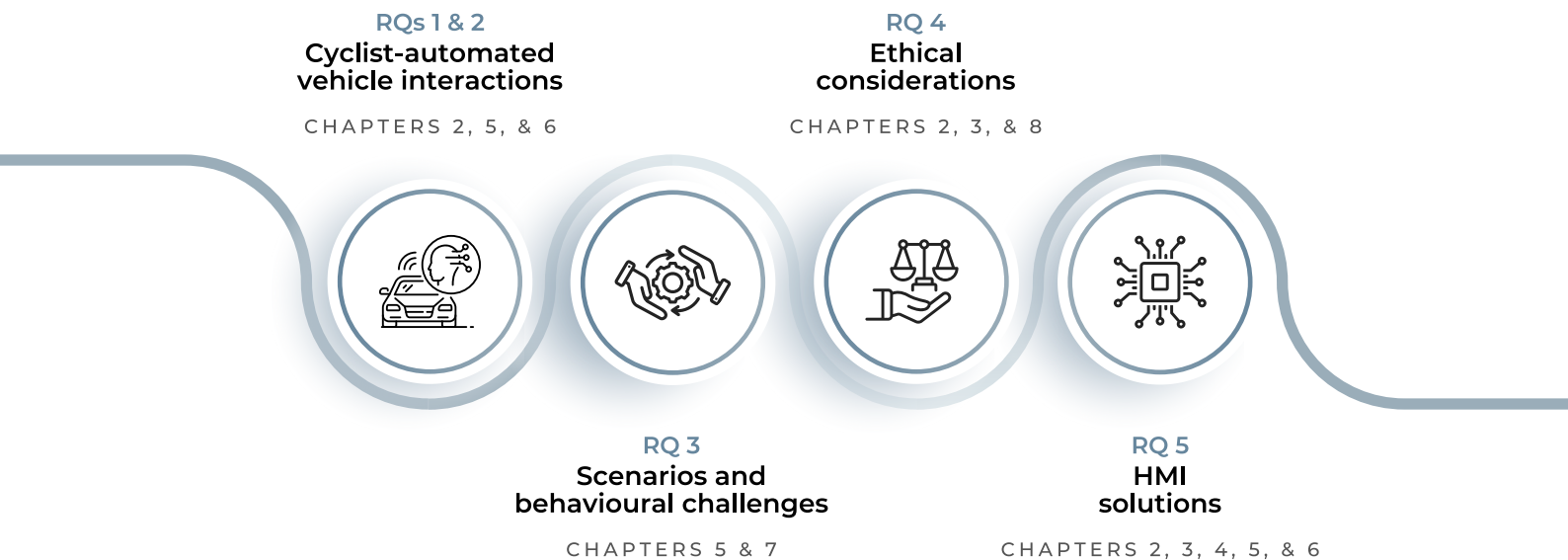


Figure 8.1. Overview of synthesis of findings.

Note: RQ1: How do cyclists' interactions with human drivers inform their requirements and expectations of future interactions with automated vehicles? RQ2: What is the role of implicit versus explicit communication in cyclist-automated vehicle interactions? RQ3: What are common scenarios and automated vehicle behaviours likely to influence future interactions with cyclists? RQ4: What ethical and practical considerations should inform design and policy to accommodate cyclists in future automated traffic? RQ5: What key features do cyclists want in HMIs, and how should these HMIs be designed to accommodate the characteristics of cyclists?

8.1.1 Cyclist-automated vehicle interactions

This section is framed around two essential research questions guiding our exploration of bridging the gap between cyclists and automated vehicles through HMI solutions. The initiation into this endeavour begins with understanding how cyclists currently interact with human-driven vehicles, setting a baseline for expectations in future traffic environments with automated vehicles. Investigating the current communication patterns of cyclists and drivers provides foundational insights necessary for effective HMI designs that safeguard and improve communication between cyclists and automated vehicles.

RQ1: How do cyclists' interactions with human drivers shape their requirements and expectations of future interactions with automated vehicles?

The exploration of *RQ1* seeks to uncover how existing interactions influence cyclists' expectations for future encounters with automated vehicles. Understanding how cyclists interact with drivers today is essential for developing HMIs that can accommodate cyclists'

expectations and ensure cyclists' needs are met in their future coexistence with automated vehicles. Aiming to capture direct insights into cyclists' perspectives and experiences in traffic, *RQ1* was explored qualitatively through in-depth interviews with cyclists and traffic safety experts in Norway and the Netherlands.

RQ2: What is the role of implicit versus explicit communication in cyclist-automated vehicle interactions?

Similar to the topics investigated in the first research question, the studies illuminating *RQ2* address the social void that may occur with automated vehicles. To design safe and efficient HMI solutions for cyclists, we must understand the extent to which cyclists use information concerning implicit communication cues, such as vehicle movement and placement on the road, and whether they rely on explicit communication signals, such as eye contact and hand gestures, from human drivers. The extent to which cyclists rely on explicit communication has implications for substituting or adding to these cues through support solutions like HMIs. Investigating *RQ2* involved combining data from qualitative studies with a field experiment using eye-tracking to discern cyclists' interactions with vehicles in a real-life environment. This included exploring cyclists' ability to detect the absence of a driver and their accuracy in identifying the presence of a driver when prompted. The two following sections summarise and discuss the insights gathered from exploring *RQ1* and *RQ2*, starting with the key findings from each research question.

Cyclists' interactions with human drivers, their requirements, and expectations of future interactions

Key findings

- Cyclists expect improved detection capabilities and explicit communication from automated vehicles.
- Cyclists prefer separated cycling infrastructure.
- Automated vehicles must adapt to cyclists' social dynamics, culture, and anticipatory safety behaviours.
- Future automated vehicle technology should align with cyclists' needs for predictability and safety.

The interview studies in **Chapters 2 and 5** uncovered that cyclists employ a range of proactive strategies to interact in traffic with human drivers. Cyclists use a combination of eye contact, head movements, hand gestures, and motion cues such as speed and placement on the road to interact with other road users. Eye contact was reported as particularly important in ambiguous situations such as crossings or intersections or when road users deviate from traffic norms.

Chapter 2 showed how cycling culture might affect cyclists' interactions in traffic: In Norway, although slowly changing to become more inclusive, the cycling culture was portrayed as aggressive and anarchic, where cyclists were stereotypically described as a nuisance to drivers. Contrarily, cycling in the Netherlands was described as a natural part of Dutch culture, with an extensive network of cycling infrastructure and priority for cyclists. The drivers were also depicted as patient and considerate, likely because they have regular experience with cycling themselves. The differences in culture and experiences may have implications for automated vehicle programming, considering that vehicles must understand a country's informal rules and customs to anticipate human behaviour and blend into traffic.

Regardless of automation, the interview data portrayed a clear preference for more cycling infrastructure and separation of bicycles and vehicles, particularly among the Norwegian interviewees. Complete separation is preferred, but bicycle lanes were deemed an acceptable solution. With increasing degrees of vehicle automation, the preference for separated infrastructure become more prominent. Although our interview sample in **Chapter 2** included informants with expertise in automated vehicle and human factors, the general sample was inexperienced and naïve in their approach to automated vehicle capabilities at the time of the interviews. Cyclists' expectations and attitudes towards automated vehicles, including their preferences for separated infrastructure, might change as they get more real-life experience with automated driving systems.

In the future of fully automated vehicles, our interview participants of **Chapter 2** expect the vehicles to respond faster and make fewer mistakes while displaying a level of rationality and predictability superior to human drivers. Automated driving systems rely on algorithms typically prioritising safety, but these systems may still inadvertently reflect the biases and imperfections of their human programmers. One interviewee pointed out that unlike humans, who are naturally inclined to avoid harm to themselves and others, automated systems operate without such intrinsic safeguards. This disparity may add to the complexity of traffic interaction and lead to novel vehicle behaviour and unpredictability in traffic.

Although the cycling culture differs from country to country, cyclists' interaction strategies show similarities across the interview studies in **Chapters 2 and 5**. In **Chapter 5**, the experts elaborated on cyclists' anticipatory and behavioural strategies to stay safe in traffic. These strategies include exhibiting caution, ensuring a buffer zone from surrounding traffic, and consistently cycling with the mindset that they are invisible to other road users. Taken together, our research implies that visibility is paramount for cyclists in traffic today and in future traffic with automated vehicles. In the future, cyclists expect to be reliably detected by automated vehicles and prefer to receive confirmation of detection. A preference was found among study participants for indicators of vehicle intention (**Chapters 2 and 4**) and information about the current state of automated driving, e.g., whether a human driver is operating the vehicle or if automation is driving on its own (**Chapter 6**).

In conclusion, past interactions between cyclists and human drivers form the basis of their future expectations of automated vehicle technology. Cyclists anticipate improved detection capabilities and explicit communication from automated vehicles, reflecting their likely underlying need for safe and informed interactions. Paired with the preference for separated cycling infrastructure, this expectation points towards an imperative for automated vehicles to adapt to the social dynamics and anticipatory safety behaviours of cyclists. The interview studies outlined in this dissertation suggest an envisioned future where automated vehicle technology is seamlessly integrated with cyclists' demands for predictability, safety, and the right to shared road use without added vulnerability.

The role of implicit versus explicit communication in cyclist-automated vehicle interactions

Key findings

- In today's traffic, cyclists report using a mix of explicit and implicit communication cues to interact with vehicles.
- Cyclists rely on implicit communication to gauge intent and trajectory, particularly when the vehicle is at a distance.
- Cyclists can detect the presence or absence of a driver behind the steering wheel, but the task demands additional attention.
- The necessity of HMIs substituting vehicles' explicit communication is likely dependent on the traffic situation.

One of the challenges with the upcoming wave of automation is that vulnerable road users may have fewer ways to communicate with vehicles than today. With automated driving systems, the person seated in the driver's seat might be a passenger with limited or no vehicle control. The role of implicit versus explicit communication in cyclist-automated vehicle interactions has implications for the necessity of substituting or adding communication to the interaction, due to the potential confusion or workload increase a cyclist may experience when encountering an automated vehicle. In turn, the extent to which cyclists use implicit versus explicit communication helps guide the design of HMI solutions for cyclists in traffic with automated vehicles.

In our interview studies (**Chapters 2 and 5**), cyclists did report using explicit communication cues in today's traffic, such as eye contact, posture, head movements, and hand gestures. Without a driver, human-to-human communication will be lacking or become more complex if a potentially distracted passenger occupies the driver's seat.

Whether cyclists truly use the amount of explicit communication cues they report is debatable, particularly the extent of eye contact with human drivers. Instead, our data suggests that cyclists often infer the intentions of other road users through implicit movement patterns and speed changes. This was prevalent in both interview studies (**Chapters 2 and 5**). Our findings from the field study in **Chapter 6** further strengthen this notion: Two-thirds of the cyclist participants did not notice that the experiment vehicle had no driver during parts of Session 1. In Session 2, the cyclists were instructed to identify whether a driver was present in the vehicle, and they could do so with 93% accuracy. However, they cycled slower than during Session 1, suggesting that the task of detecting a driver adds mental demand. The findings from this study indicate that cyclists may not actively search for a driver and instead depend on the vehicle's motion cues to gauge its intent and trajectory.

Analysis of the cyclists' gaze behaviour also suggests implicit communication is key: The cyclists tended to look back and forth between the bike path and the pavement in front of the vehicle, the wheels, bumper, and the lower parts of the vehicle when it was 60 to 20 metres away. At closer ranges, the cyclists looked slightly more on the hood and windshield on the driver's side of the vehicle (see Figure 8.2). In the interview data from **Chapter 6**, some participants described how they calculated whether the vehicle would be a hazard to them based on its speed and position relative to the cycling path. Combining the detection rate and gaze behaviour with the interview findings, the overall data indicates implicit communication is more useful than explicit communication in interactions between cyclists and drivers, particularly at a distance.

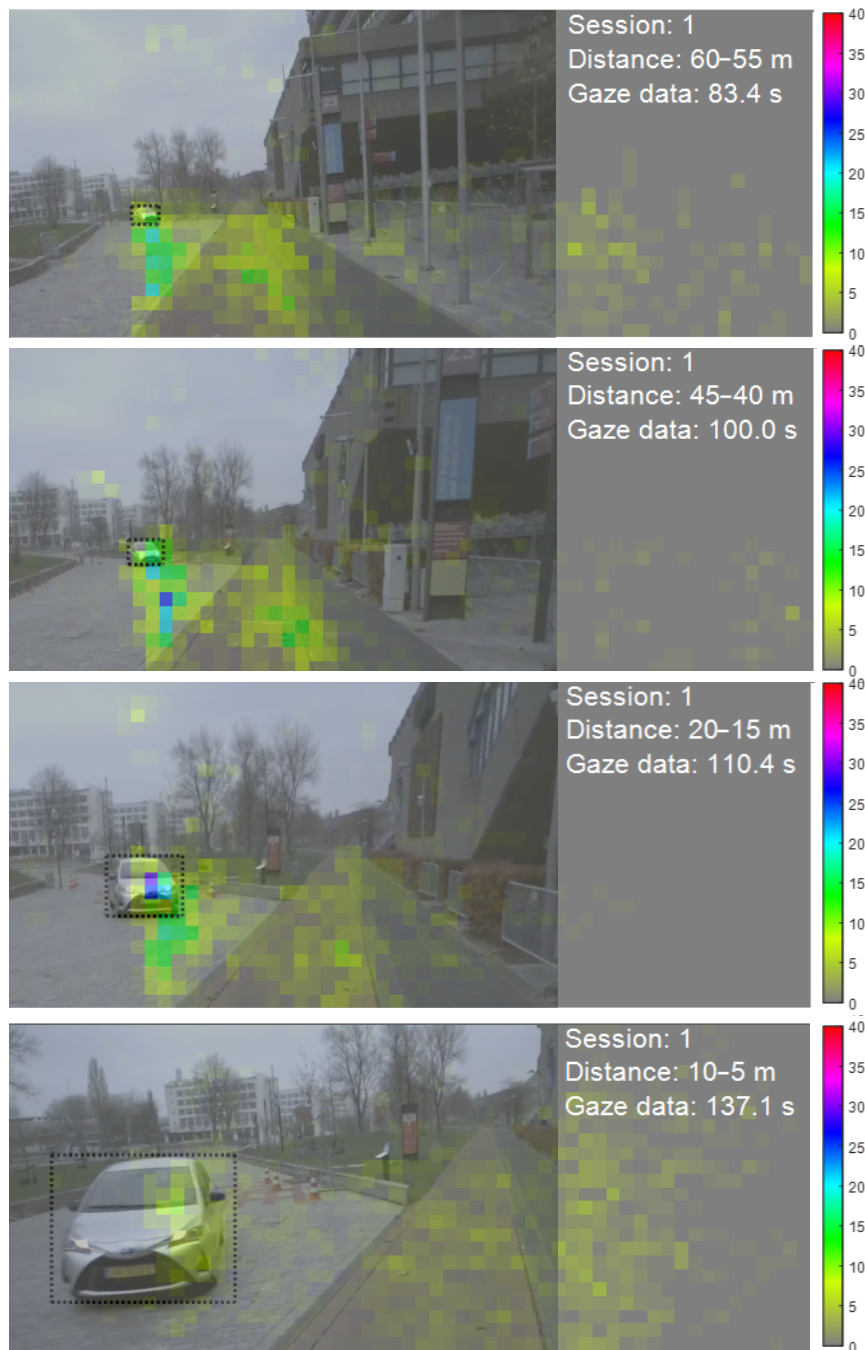


Figure 8.2. Still photos overlaid on selected heatmaps of cyclists' ($n = 36$) gaze behaviour during Session 1 of the field study in *Chapter 6*.

Note: The still photo overlays are taken from the eye-tracking videos of a single participant and are intended as a visual aid only. See Figure 6.7 of Chapter 6 for the original heatmaps.

It is essential to note that the observations in *Chapter 6* are likely specific to the experimental scenario. In our study, the cyclists were cycling on a bike path with a vehicle approaching from the left – a scenario where cyclists, especially in a bike-friendly culture with clear right-of-way regulations such as the Netherlands, may not be inclined to scrutinise every approaching vehicle or its potential driver. Findings from a naturalistic eye-tracking study imply that cyclists tend to look in the direction of the driver's seat in ambiguous situations usually requiring negotiation, such as uncontrolled intersections, lane merging, overtaking, parking, and bottlenecks (Al-Taie

et al., 2023). Although gaze fixation on the areas of the vehicle where the driver is usually seated does not equate to eye contact, this does point towards cyclists searching for the driver, presumably to observe whether the driver is attentive or has noticed the cyclist, as a communication strategy in situations requiring negotiation.

The extent of explicit communication between cyclists and drivers in today's traffic has implications for the necessity of substituting this type of communication through HMIs. Based on the studies outlined in this dissertation, it is challenging to conclude on the necessity of HMIs. Other researchers have pointed out that vulnerable road users *want* additional interfaces in traffic with automated vehicles, primarily because the HMIs can complement implicit communication, indicate whether the automated driving systems are active, and add clarity to the interaction between road users (De Winter & Dodou, 2022). Our data indicates similar notions. The necessity of HMIs to substitute explicit communication is likely dependent on the traffic situation but is desired by most cyclists nonetheless.

To conclude on *RQ2*, the role of implicit and explicit communication could change in cyclist-automated vehicle interaction, transitioning towards implicit signalling due to the diminished role of human drivers in automated vehicles: There may no longer be a driver for cyclists to communicate with explicitly. Our field study showed that cyclists can detect both the absence and presence of a human driver, although it was revealed that the task requires additional attention. Cyclists rely on vehicle behaviour and movement patterns as indicators of intent, particularly when the vehicle is at a distance. Still, taking other previous research into consideration, it is recognised that HMIs have the potential to supplement cyclists' interaction with vehicles. HMI solutions should be designed based on cyclists' characteristics and behaviour, though further research is needed to understand these dynamics fully.

8.1.2 Scenarios and behavioural challenges

The topic of scenarios and behavioural challenges focuses on delineating scenarios and automated vehicle behaviours that influence cyclists' safety and communication in traffic with automated vehicles. The idea is that by identifying and describing common cyclist-automated vehicle scenarios, we may better understand the challenges cyclists encounter in dynamic traffic situations with automated vehicles and how changes in vehicle behaviour affect cyclist safety. Representative scenarios are also necessary for guiding future research and performing realistic safety assessments. In that context, the following research question was derived:

RQ3: What are common scenarios and automated vehicle behaviours likely to influence future interactions with cyclists?

The approach to this research question was mixed methods by triangulation of data. The findings from a systematic literature review, group interviews with traffic safety and automation experts, and a questionnaire to evaluate the scenarios identified in the literature and interviews were triangulated to create a collection of scenarios and behavioural challenges. Later, we further explored one of the vehicle behaviours – phantom braking – in a cycling simulator study.

The section addressing *RQ3* is split into two: one provides scenario recommendations, and the other presents and discusses automated vehicle behaviour relevant to future research.

Scenario recommendations

Key findings

- Twenty scenarios were identified and categorised into crossing, passing, overtaking, and merging scenarios.
- The scenarios with high accident likelihood, such as *the right-turning vehicle* and *dooring*, are suitable for safety assessments.
- Negotiation-intensive scenarios, such as the *discontinued bike lane* and passing scenarios, are useful for researching HMI solutions.

The data triangulation in **Chapter 5** resulted in 20 prototypical scenarios of cyclist-automated vehicle behaviours that can be applied in future research. These scenarios are grouped into four categories according to the direction of movement at the point of conflict between the cyclist and vehicle: crossing, passing, overtaking, and merging scenarios. The most common cyclist-automated vehicle interaction scenario studied in previous research consisted of one cyclist and one passenger vehicle approaching from the opposite or perpendicular direction before intersecting in a T-junction in an urban environment during the daytime.

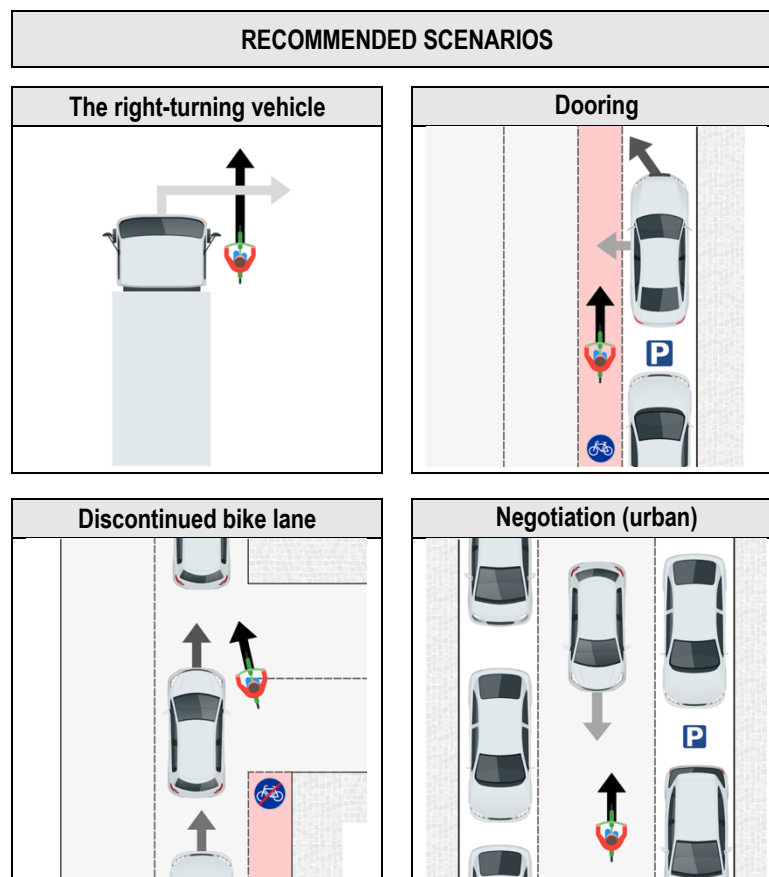


Figure 8.3. Recommended scenarios to focus on in future research.

Note: The infrastructural layouts may vary regarding the number of legs, lanes, and other environmental details (e.g., barriers, traffic signs, colours). The right-turning vehicle scenario is illustrated with a heavy vehicle, as our interview data indicated that vehicle size might be a risk factor in this type of scenario. The scenario is also shown without infrastructure, as more than one type of infrastructure was identified as relevant to this scenario, e.g., X- and T- junctions and shared spaces. See Chapter 5 for the complete scenario collection.

The choice of scenario depends on the objective of the research: Opting for a scenario rated with a high likelihood of accidents, such as *the right-turning vehicle* and *dooring* scenarios (see

Figure 8.3), and scenarios with increased complexity, was indicated as the most appropriate choice for safety assessments. On the other hand, research on communication solutions such as HMIs should prioritise passing or merging scenarios, e.g., the *discontinued bike lane* (see Figure 8.3). These scenarios are ambiguous and rich in negotiation demands, where the interpretive burden is typically high, usually requiring clear and explicit communication to resolve. By focusing on passing and merging scenarios, it is possible to assess the utility value and impact of HMIs substituting explicit communication cues more accurately.

Automated vehicle behaviour

Key findings

- Phantom braking – unexpected deceleration or stopping in automated vehicles – is a novel vehicle behaviour that can potentially affect cyclists' safety and complacency in traffic.
- Driving styles across automated vehicles should be uniform to promote predictability.

A core part of *RQ3* explored automated vehicle behaviours critical in cyclist-automated vehicle interaction. Our analysis in Chapter 5 revealed how the occurrence of phantom braking and differences in implicit communication through driving styles are likely to affect cyclists in traffic with vehicles of varying degrees of automation.

The triangulation in **Chapter 5** showed that, with the introduction of automated vehicles, phantom braking, defined as unexpected deceleration or stopping in automated vehicles, is anticipated to increase in occurrence with the introduction of automated vehicles. In a later study in **Chapter 7**, we presented a theoretical outline of phantom braking. Phantom braking can be explained as a by-product of an imperfect sensor system, where the vehicle favours avoiding accidents at the cost of potentially causing rear-end accidents. To show what phantom braking might look like in practice, we demonstrated the phenomenon in a VR cycling simulator using four conditions representing automated vehicle sensors: inaccurate, conservative, liberal, and perfect automated vehicles (see Figure 7.1 of **Chapter 7**). It is plausible that automated vehicle manufacturers opt for the conservative approach to their sensors, leading to less frequent missing of obstacles or hazards on the road but also increased braking for irrelevant sensor data, i.e., *phantoms*.

The results from the expert interviews of **Chapter 5** also revealed that differences in vehicles' implicit communication cues, mainly related to driving style, will shape cyclists' interaction with automated vehicles in the future. In the interviews, a gradual deceleration when approaching intersections was preferred, allowing sufficient time to assess the vehicle's intentions. Sudden braking and small gap sizes may be perceived as efficient from an automation standpoint but can create uncertainty and potentially reduce vulnerable road users' trust in automated vehicles. In **Chapter 5**, we recommend that the driving style is uniform across vehicle manufacturers to ensure predictability in traffic, reducing cognitive load and the potential for miscommunication in traffic scenarios involving negotiation and ambiguity. Future research should aim to pinpoint an optimal driving style for automated vehicles that aligns with cyclists' safety and perceptual needs.

Summarising the findings answering *RQ3*, 20 scenarios were identified, categorised into crossing, passing, overtaking, and merging interactions. Notably, scenarios with high accident likelihood, such as *the right-turning vehicle* and *dooring*, alongside those requiring a higher

degree of negotiation, such as the *discontinued bike lane* or passing scenarios, demand focused attention in research. Additionally, the phenomenon of phantom braking and the necessity for uniform driving styles in automated vehicles are emphasised as potentially affecting cyclist safety. Together, these findings highlight the importance of developing automated vehicle programming that promotes predictable behaviours to improve safety and trust in future automated traffic systems.

8.1.3 Ethical considerations

This section addresses the ethical and practical aspects of integrating cyclists into future automated traffic environments, guided by the findings from the exploratory interview study of **Chapter 2** and the systematic literature review in **Chapter 3**. The following research question was formulated to evaluate ethical considerations in cyclist-automated vehicle interactions:

RQ4: What ethical and practical considerations should inform design and policy to accommodate cyclists in future automated traffic?

This research question is intended to encourage discourse and reflection on the moral obligations and practical demands that shape the development of solutions promoting cyclist safety in the future of automation. Emphasising ethical considerations is necessary for ensuring the traffic systems of tomorrow are aligned with the interests and requirements of all road user groups, including cyclists.

Key findings

- Focus on ethical designs and policies that improve safety and support active, equitable transport without shifting the burden of safety onto cyclists.
- Avoid designing automated systems that rely on personal devices for cyclist detection.
- Encourage ongoing research and policy-making for solutions that ensure mobility justice.

To accommodate cyclists in future automated traffic, design and policy must prioritise safety without imposing the burden of safety on vulnerable road users. Considering the ongoing technological advancements and the proliferation of the Internet of Things (IoT), connectivity will likely become a standard feature for new devices, including bicycles and cyclist wearables. In **Chapter 3**, 41% of the 92 HMI concepts identified involved a connectivity feature or technology with the potential of connecting multiple road users to transmit messages.

The efficacy of intelligent transport systems involving connected road users, such as bike-to-everything communication, is contingent on widespread adoption, which may not be realistically achievable in the short term. Our research advocates that automated vehicles must detect cyclists explicitly and communicate detection. However, this communication should be delivered through on-vehicle interfaces, as opposed to requiring devices on the bicycle or wearables for cyclists.

The exploratory interview study of **Chapter 2** shed light on reservations about on-bike HMIs, particularly regarding their utility value for cyclists and the ethical concern of shifting the burden of safety onto cyclists, who are typically more vulnerable than vehicle occupants. Mandating vulnerable road users to be equipped with a wearable or a device embedded in their personal vehicle, be it their bicycle, e-scooter or wheelchair, to ensure automated vehicles are safe and efficient in future traffic could potentially discourage people from choosing active modes of transport due to the associated costs, malfunction, and risk of theft of the additional

devices. Without widespread adoption of these devices, the vulnerable road users opting out will potentially be at greater risk of accidents than their connected counterparts.

The historical precedence of automotive-oriented mobility paradigms presents a cautionary tale (Gaio & Cugurullo, 2022): Ensuring mobility justice and that the advancement of automated vehicles does not marginalise active modes of transport is essential. While the biohacking community shows that implantable technologies for connectivity are theoretically possible, the trade-offs between safety and privacy and the potential for mass surveillance pose serious ethical dilemmas. Researchers or vehicle developers proposing systems that base automated vehicle safety on connected vulnerable road users should consider the ethical implications of such solutions and perhaps instead focus their efforts elsewhere, such as improved vehicle sensors and algorithms, until the prerequisite devices (or potential biohacking solutions) are ubiquitous for other purposes than automated vehicle safety.

From a cyclist's perspective, policies should prioritise active transport and consider infrastructure changes that benefit cyclists and pedestrians. There might be other solutions to automated vehicle safety in urban areas with vulnerable road users that do not involve additional communication devices or connected automated vehicles. Rethinking infrastructure use and city design to promote sustainability and equity among road users, speed reductions of vehicles or other calming measures where segregation of road users is not possible could help maintain safety and promote a more inclusive approach to urban mobility. However, the feasibility or the effects of alternative solutions were not explored in the studies outlined in this dissertation. In conclusion, the exploration into ethical and practical considerations emphasises the necessity of designing future automated traffic systems with cyclist safety in mind, without shifting the burden of safety onto the cyclists themselves. Our findings suggest a focus on safety-enhancing designs and policies that support active transport and equitable infrastructure, avoiding reliance on personal devices for cyclist detection. This approach would not only adhere to ethical standards but also align with the broader goal of promoting inclusive and sustainable urban mobility. It is advised that future researchers and policymakers continue the work evaluating solutions and safety measures that promote equity and mobility justice for all road users.

8.1.4 HMI solutions

The findings from our previous research questions have shown the way cyclists interact with vehicles today shapes their expectations of interaction with automated vehicles. To investigate cyclists' interactions with automation, scenarios were developed, and vehicle behaviour that are particularly important to consider in this interaction were identified. A recurring topic throughout the studies presented in this dissertation is HMIs as a potential solution for improving cyclists' interaction with automated vehicles. When describing cycling in the age of automation, we can easily envision a future without human drivers to interact with. In such a future, substituting humans by adding more technology seems like a plausible solution. So far, the ethical considerations of HMI solutions have been discussed, but we have not dealt with the HMI solutions themselves. The question remains:

RQ5: What key features do cyclists want in HMIs, and how should these HMIs be designed to accommodate the characteristics of cyclists?

Exploring the interplay of cyclist safety and technology, the following section of HMI solutions delves into the design and potential of HMIs to enhance cyclist-automated vehicle interactions. A vital part is developing HMI design strategies tailored to cyclists, accommodating their communication needs and behavioural patterns.

A consolidation of the studies presented in this thesis is necessary to address *RQ5*: The interview data from **Chapter 2** and the literature review of **Chapter 3** laid the basis for the HMI design study of **Chapter 4**. Through the triangulation of data in **Chapter 5**, cyclists' movement patterns in traffic were further elaborated on. Lastly, the experimental field study of **Chapter 6** provided insights into cyclists' gaze behaviour and HMI functionality through interviews. Finally, the HMI concepts of **Chapter 4** are presented as imperfect but potential HMI solutions, incorporating insights gained throughout this dissertation.

Key findings

- Cyclists expect detection by automated vehicles and vehicles' to convey their recognition of cyclists.
- The optimal HMI solution is an omnidirectional eHMI visible from all vehicle angles.
- This eHMI should provide cues of detection as well as indicate the vehicle's automated driving mode.
- Messages from an eHMI must be tailored for visibility at varying distances.

A survey of previous literature in **Chapter 3** resulted in 92 HMI concepts sorted into four categories according to the interface placement: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems. Four general modes of communication were identified: visual, auditory, motion-based, and wireless, where the most common way of communicating was visual (77% of 92 concepts). The review showed an abundance of HMIs with the potential to aid cyclists in future traffic with automated vehicles. As such, the field of cyclist-oriented HMIs in an automated vehicle context is in development, where few of the identified concepts have been evaluated or tested to improve the interaction between cyclists and automated vehicles. As a result, our studies developing HMI solutions started from scratch by identifying the needs and characteristics of cyclists, which translated into the two HMI concepts presented in **Chapter 4**.

The analysis of the interview data in **Chapters 2 and 4** revealed that the critical concern of cyclists in interactions with automated vehicles is to be adequately detected by these vehicles. Furthermore, the interviewed cyclists preferred automated vehicles to clearly signal their awareness of the cyclist's presence. Other desired HMI features were providing information about the presence and location of other road users, features that facilitate connectivity between road users, and information about automated driving modes (**Chapter 6**).

The focus on solutions for improving the interaction between automated vehicles and vulnerable road users has revolved around pedestrians: Most on-vehicle HMIs are designed for and evaluated in the context of pedestrians (Dey, Habibovic, Löcken, et al., 2020). As cyclists are two-wheelers with higher speeds than pedestrians and share the roads with vehicles, one can assume that cyclists' characteristics differ from pedestrians and that HMIs must be designed accordingly. In **Chapter 5**, how cyclists interact with vehicles in crossing, passing, merging, and overtaking scenarios were illustrated, implying that they move around the vehicle in any direction. The eye-tracking data presented in **Chapter 6** also showed that cyclists tend to sample stimuli in their environment intermittently: The participants' gaze behaviour was divided intermittently between the road and the vehicle they interacted with. Revisiting *RQ2* findings, the cyclists' gaze shifted from the bike path and the vehicle's lower parts at a distance, to the bumper, hood, and windshield near the driver's typical position in right-side driving countries as they got closer. Taken together, the movement patterns and gaze behaviour imply cyclists would benefit from an HMI that is visible from all around the vehicle, with messages delivered

on the lower parts of the vehicle at a distance but in the height of the hood and windows at closer proximities.

Two HMI concepts that aim to accommodate cyclists' needs and characteristics were introduced in **Chapter 4**: The on-bike mobile application CycleSafe and an omnidirectional on-vehicle eHMI LED light band placed on the grill and along the lower parts of the windows on the sides and back of the vehicle (Figure 8.4).

On-bike devices appear popular among cyclists, but their utility value for communicating with automated vehicles is unclear and, in some cases, disregarded (as seen in **Chapter 2**). Accounting for the ethical challenges related to on-bike devices and cyclist wearables, the omnidirectional eHMI is suggested as the most appropriate concept for facilitating safe interactions between cyclists and automated vehicles in the years to come. However, neither of the concepts has been evaluated or tested with cyclists throughout our studies. Likewise, the effects of different modes of communication, intensity, or colours, nor the concepts' feasibility or legality for implementation in real-life traffic, have not been assessed. Thus, our recommendations are not meant to be finite but rather help build the foundation of the design of HMIs for cyclists in future automated traffic.



Figure 8.4. The omnidirectional eHMI concept is illustrated with a proximity indicator (left) and the on-bike mobile application CycleSafe (right).

In conclusion, cyclists desire informed detection by automated vehicles and HMIs to convey vehicles' recognition of cyclists' presence. The design should account for cyclists' unique behavioural characteristics while advocating solutions promoting road user equity. The overall findings suggest the most appropriate HMI solution as an omnidirectional eHMI that provides visible cues of detection and automated driving mode from all around the vehicle and delivers messages adjusted for different proximities. Further empirical testing is needed to develop and validate the eHMI concept and evaluate its real-world application.

8.2 Scientific recommendations

As we plan for the potential integration of automated vehicles into urban environments, the interaction between these vehicles and cyclists arises as a critical area of concern. The insights provided throughout this dissertation shed light on the current and future interplay of cyclist-automated vehicle interactions, revealing recommended considerations for communication, safety, and coexistence. The necessity for continuing research on this topic is evident, as it will provide the empirical foundation shaping the development of future traffic systems and automated vehicle technology tailored to cyclists' needs. The following sections present a series of topics for future research. These recommendations aim to further develop the field of cyclist-

automated vehicle interaction from the vulnerable road users' perspective, with the ultimate goal of creating inclusive traffic environments for all road users.

8.2.1 Scenario-based and long-term research

Chapter 5 provides a foundation for scenario-based research with its collection of 20 prototypical scenarios of cyclist-automated vehicle interaction. The scenarios are suitable for studying realistic and specific situations, performing safety assessments, and evaluating the effects of HMIs. Future studies should extend these scenarios to examine how cyclist-automated vehicle interaction evolves as automated driving systems advance and become more widespread. By integrating longitudinal or long-term studies, it is possible to observe how these dynamics change over time as automated technology progresses. This approach will aid in uncovering new challenges and refine the need for and use of additional communication interfaces such as HMIs.

8.2.2 Cyclist-centric and ethical HMI design strategies

The research outlined in the preceding chapters of this dissertation emphasises the necessity of HMIs tailored to cyclists. It builds a foundation for future research on the topic of HMIs for improving the safety of cyclists in traffic with automated vehicles. The findings suggest that cyclists expect detection from automated vehicles and would like to acknowledge this detection explicitly. Cyclists' behavioural patterns also indicate the messages an automated vehicle relays should be visible from all around the vehicle. In *Chapter 4*, a visual omnidirectional eHMI concept was proposed that could satisfy these requirements. However, this eHMI was not tested or evaluated empirically.

Future researchers should explore the effects of various HMI communication modalities, including visual, auditory, and motion-based signals, to determine the most effective means of conveying information to cyclists. Considering the diverse environmental conditions, individual preferences of cyclists, and complexity of urban traffic, a multi-modal approach may offer the flexibility required for effective communication. In the case of multi-modal signals involving motion-based cues such as vibration or haptic feedback, an on-bike system like CycleSafe (*Chapter 4*) could be beneficial. However, improvements in these HMI concepts should be rooted in user-centric design and human information-processing principles, incorporating feedback from cyclists throughout an iterative design process.

Given the hesitancy around on-bike devices (*Chapter 2*), the ethical implications of imposing additional equipment on cyclists to be safe from automated vehicles must be addressed. Research should also consider the legal framework governing HMI deployment, ensuring that the proposed solutions are not only technically feasible within the near future but also permissible under current and evolving traffic and vehicle standards and regulations.

8.2.3 Automated vehicle programming

Future research on automated vehicle programming should involve developing better vehicle sensors and algorithms. In particular, automated vehicle programming could account for the proactive safety behaviours observed in cyclists, with the aim of not just preventing accidents but creating a safe and pleasant traffic environment for all road users.

Considering cyclists' proactive safety strategies identified in *Chapters 2 and 5*, it would be beneficial if automated vehicles could recognise and interpret cyclists' implicit communication, such as body language and placement on the road, indicating environmental scanning or hazard anticipation. By incorporating such behaviours, automated vehicles can shift from reactive to proactive safety measures, potentially slowing down or widening the distance when encountering cyclists displaying anticipatory actions.

Knowledge and implementation of proactive safety behaviours in automated vehicle programming could also accommodate the differences among individual cyclists. A cyclist exhibiting anxious or inexperienced behaviour would probably prefer other distances and acceleration and deceleration patterns in vehicles to a confident or highly experienced cyclist. Future research could explore these differences.

Phantom braking has the potential to unexpectedly introduce rear-end collision risks, particularly for cyclists trailing an automated vehicle (*Chapters 5 and 7*). The effects of phantom braking on cyclists and other road users remain an important topic to further explore through research. Developing and implementing a standardised approach to sensor responsiveness, effectively minimising phantom braking by erring on the side of caution without overreacting to non-hazardous stimuli, are also crucial directions to prioritise in research and development both in academia and the industry.

Focusing on the effects of implicit communication, our findings in *Chapter 5* emphasise the importance of uniform driving styles in automated vehicles. Differences in implicit communication cues through speed control, acceleration and deceleration patterns, and braking could influence road user interaction with automated vehicles, especially in scenarios involving negotiation and interpretation. Consistent driving behaviour across manufacturers would add a layer of predictability to traffic and potentially increase the safety of all road users. Researching the effects of differences in driving styles on vulnerable road users and developing the optimal automated vehicle behaviour across manufacturers are key in future research.

8.2.4 Behavioural studies on trust, overreliance, and complacency

Understanding cyclists' psychological responses and behavioural adaptations to automated vehicles is vital for promoting safe traffic environments for cyclists. The preliminary data from the demonstration and testing of the effects of phantom braking in the bicycle simulator in *Chapter 7* indicated complacent behaviour by the cyclist. This means that the cyclist also retained speed in the instances where the vehicle did not brake for the pedestrian in the simulated environment. Complacency or overreliance on other traffic participants might be particularly problematic with automated vehicles, as their behaviour currently differs from the average human road user in the transition period between conventional and automated vehicles in the years to come. The complexities and potential risks introduced by automated vehicle behaviour require further study.

Furthermore, future research should focus on cyclists' trust in automated vehicles and how this affects their vigilance and interaction strategies, both short term with varying degrees of automation but also with fully automated vehicles. As automated vehicle technology advances, the nuances of cyclist-automated vehicle interaction should be explored. We need more knowledge on how cyclists will interpret the intent of automated vehicles in various traffic scenarios, as well as their expectations of automated vehicle capabilities. Investigations into how cyclists interpret automated vehicle behaviour and manage their mental workload and

situational awareness in novel situations such as phantom braking will provide insights into the safe coexistence of cyclists and automated vehicles. Moreover, understanding the propensity for rear-end accidents due to phantom braking remains an important topic. Cyclist safety was not assessed in the simulator study in *Chapter 7*, e.g., whether phantom braking leads to more frequent rear-end accidents. The effects of phantom braking in automated vehicles on safety and the occurrence of rear-end accidents is an important aspect to pursue in future research.

In *Chapter 7*, a VR cycling simulator (see Figure 8.5) was used to illustrate phantom braking. Cycling simulators offer a promising approach to examining the effects of potentially hazardous and high-risk behaviour without compromising safety, as they allow observation and analysis of cyclist interactions with automated vehicles in the immersive confines of a simulated environment. Our simulator only allows forward motion without steering, and the bicycle has no tilt or pitch. Although cycling simulators have been validated in previous research (e.g. Haasnoot et al., 2023; O'Hern et al., 2017; Shoman & Imine, 2021), their use is still relatively new. Different configurations and setups of cycling simulators should be further explored to assess the validity of the data collected and to provide recommendations according to the aim of the research, e.g., the necessity of advanced and realistic bicycle mechanics to study cyclists' interaction with vehicles reliably.



Figure 8.5. The VR cycling simulator (2023) of the Mobility of eXtended Reality lab at Delft University of Technology.

8.3 Practical implications

The findings from this dissertation not only contribute to academic discourse but also have implications for policy-making and the practical application of automated vehicle technology, city planning, and developing regulations promoting equity in the transport system. The understanding of cyclists' needs and expectations, coupled with the exploration of HMIs and the ethical considerations surrounding automated vehicle deployment and HMI design, emphasises the necessity of informed policy development. This section concerns recommendations for policymakers, offering guidance on creating policies that protect and enhance the safety and well-being of cyclists in an increasingly automated future. From

ensuring privacy protection in passive connectivity solutions to supporting mixed-use infrastructure and encouraging ethical technology development, these policy recommendations aim to shift the future of urban mobility towards a model that values safety, inclusivity, and sustainability. By addressing these points, policymakers can play an important role in shaping an urban traffic system that accommodates the implementation of automated vehicles while safeguarding the interests and safety of vulnerable road users such as cyclists.

8.3.1 Regulatory framework for automated driving and communication systems

Society could benefit from policies that address the integration of automated vehicles into environments with vulnerable road users, focusing on automated vehicle standards for sensors and systems that can reliably detect cyclists and effectively communicate vehicle intentions, as informed by the findings from *Chapters 2, 4, and 5*. Placing requirements on automated vehicle manufacturers to explore and mitigate the effects of phantom braking as well as develop a universal standard for uniform driving styles across fully automated vehicles' to promote predictability in traffic would also be welcomed regulatory safety measures based on our findings.

The development of two HMI concepts in *Chapter 4* illustrates the potential of effective communication interfaces between cyclists and automated vehicles. It is recommended that policymakers establish guidelines that mandate the accessibility, appearance, and effectiveness of HMIs, ensuring they are designed for clear, omnidirectional communication that caters to the characteristics and needs of all road users, including cyclists. These standards could be developed with input from academia and the cycling community to ensure they resonate with cyclists' actual needs and practices.

Drawing from *Chapters 2 and 3*, highlighting concerns about equipping cyclists with devices for communication with automated vehicles, policymakers could develop regulations and incentives that protect user privacy and ensure the affordability of passive connectivity technologies. Connected road users are likely inevitable. Still, legislators and policymakers must be proactive to ensure the solutions developed for future transport systems are aligned with the overall goals of sustainable and safe city environments, promoting equity, well-being, and public health. Policies should address the non-mandatory nature of such devices for cyclist safety, ensuring inclusivity and avoiding imposing the burden of safety on vulnerable road users.

8.3.2 Support and funding for cyclist-automated vehicle research

Further investments in research focusing on the interaction between cyclists and automated vehicles are vital for creating policies reflecting cyclists' diverse experiences and characteristics. There is a need for more research on the effects of automated vehicles on vulnerable road users, particularly cyclists, before standards for automated vehicle capabilities and HMIs targeting vulnerable road users can be set. Funding through, e.g., research grants, collaborative platforms, and pilot programs, could target research proposals concerning the effects and efficacy of HMI design strategies on different types of cyclists and automated vehicle behaviour, such as phantom braking and implicit communication through differences in driving styles. These areas were identified as important aspects for future research throughout the studies presented in this dissertation.

8.3.3 Promotion of active transport in urban planning

Chapters 2 and 3 highlight a request for a less car-centric approach to urban traffic design, advocating for infrastructure and policies that support active transport. Policymakers could pursue reforms that reallocate urban space towards cycling and walking, consider reducing vehicle speeds in shared environments, and promote a more sustainable and health-conscious urban mobility ecosystem.

Moreover, *Chapters 2 and 5* emphasise the importance of designing infrastructure that safely accommodates different road user groups. Policymakers can advocate for developing infrastructure with separated, designated lanes and enhanced crossing points in city areas, discouraging direct contact between vehicles and vulnerable road users. Separation of cyclists and vehicles without physical barriers is acceptable, but from the cyclists' point of view, city centres prioritising active modes of transport over motorised traffic would be desirable.

By implementing these policy-driven recommendations, governments and regulatory bodies can address the challenges of integrating automated vehicles into urban environments, ensuring that advancements in automation enhance, rather than compromise, the safety and rights of cyclists and other vulnerable road users.

8.4 Conclusion

As this dissertation comes to an end, the analyses and discussions presented throughout converge on a joint understanding: The relationship between cyclists and automated vehicles hinges on informed interactions, mutual detection, and clear communication. It is recommended that evolving automated vehicle technology adapt to cyclists' behavioural patterns and anticipatory strategies, who expect reliable and clear detection communication from the vehicles (*RQ1*).

The role of explicit and implicit communication (*RQ2*) is likely to transform correspondingly to the increasing degrees of automation on the roads, accentuated by the absence of human drivers. The shift of human drivers becoming passengers or completely removed from the task of driving amplifies the importance of intuitive and predictable vehicle behaviour. Moreover, the shift suggests HMIs as solutions to fill the social void of automated vehicles, particularly in ambiguous situations with high negotiation demands.

In response to *RQ3*, the investigation into common cyclist-automated vehicle scenarios and vehicle behaviours such as phantom braking underlines the necessity for consistent, predictable vehicle actions. Exploring and mitigating phantom braking in automated vehicles, as well as the adoption of uniform driving styles across vehicle manufacturers, would promote predictability, have the potential to prevent accidents, and ensure safe coexistence between cyclists and automated driving systems.

Ethical considerations took centre stage in addressing *RQ4*, with advocacy for automated driving systems that protect cyclists without imposing the responsibility of safety upon them. Future transport policies should reflect this sentiment, developing approaches that support safety, active transport, and equitable infrastructure without relying on connected vulnerable road users and mandatory personal devices in traffic.

Finally, answering *RQ5* and outlining HMI solutions, the research suggests that HMIs designed for cyclists should not only indicate their detection by vehicles but also be tailored to cyclists' movement patterns and gaze behaviour. The proposed omnidirectional eHMI concept could be a promising means to improve cycling safety. Still, the eHMI design requires further development and validation to ensure its efficacy in shared traffic.

Reaching the end of our exploration of cycling in the age of automation, the studies throughout this dissertation provide an increased understanding of cyclists' needs and expectations of automated vehicles and HMI solutions tailored to cyclists' characteristics in bridging the gap between humans and technology. To conclude, the main contributions of this dissertation include a thorough investigation of cyclists' expectations for future interactions with automated vehicles. It emphasises the need for reliable detection by automated vehicles, and the importance of placing the responsibility of safety on vehicle developers rather than on the cyclists themselves. The dissertation provides objective data and self-reported insights into cyclist-automated vehicle interactions, as well as an experimental evaluation of whether cyclists can visually detect the presence or absence of a driver. Moreover, it introduces a collection of 20 scenarios of cyclist-automated vehicle interaction, serving as a resource for safety assessments and HMI research. A comprehensive literature review of existing HMIs for cyclists was conducted, identifying 92 concepts with placements on the vehicle, bicycle, cyclists, and infrastructure. Lastly, the dissertation provides design recommendations for cyclist-centric HMIs, proposing an omnidirectional on-vehicle eHMI communicating detection and automated driving mode.

As we advance into the age of automation, this body of work offers insights into the prospects of enhancing cyclist-automated vehicle interaction with HMIs. By taking the cyclists' perspective, the research lays the groundwork for continued innovation and exploration of strategies to develop inclusive and equitable automated transport systems of tomorrow.

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Appendices

Appendix A: Interview guide for “Co cyclists need HMIs in future automated traffic? An interview study”

[All notes in italic are cues or explanations and not necessarily conveyed to the participant]

Topic: Background (5 min)

First, I thought we would start off with some background questions.

1. Where do you live?
2. How old are you?
3. What do you do for a living?
4. How often do you go cycling? *(frequency, distance)* If at all, where? *(urban or rural)*.
Winter?
5. Do you own a bike? *(shared rental, regular or electric etc.)*
If yes: What kind?
If no: Do you use rental or shared bikes?
6. When it comes to using new technology, would you consider yourself ...
 - a. An early adopter?
 - b. Among the last to try
 - c. Somewhere in between?

Topic: Current traffic interaction (12 min)

I would like to know about your experience with cycling ...

7. Could you start by describing a typical (cycling) trip?
8. How would you describe the interaction with motorised vehicles?
9. Do you encounter any challenges while cycling? Please elaborate.
Probe for unsafe situations, workload, situational awareness when interacting with motorised vehicles.
10. As a cyclist, what do you think would make you feel safer in traffic?
(Improved infrastructure, bike lanes, bike paths, better/enhanced bikes)

We are doing interviews in different countries and would like to see if there are any differences in cycling culture ...

11. How would you describe the cycling culture in [country]?

Traffic safety culture definition: "Common norms for desired or normal behaviour in traffic, shared expectations of other road users and common values/priorities (e.g., safety, accessibility, courtesy)".

Topic: The future of cycling (12 min)

Imagine the future, where cars are fully automated, and there is no longer a human driver behind the wheel (*there might not even be a wheel*).

12. How will this impact you as a cyclist?

For instance, some of the interaction between road users are based on behavioural cues like facial expressions, hand gestures and/or eye contact.

13. *Follow-up:* What will change?

14. How do you think (*situations from question 9*) will change when cars are automated and driverless?

In the future, where cars are automated and there's no driver to interact with...

15. As a cyclist, what kind of information would you need from an automated vehicle?

Cues if stuck: eHMLs: (Projected) light or sound signals indicating intended behaviour, text-based signs on the car ("stop", "turning right" etc.), a sign indicating fully AV.

Topic: Bicycles and technology (25 min)

For my next question, I want you to continue thinking of the future. Imagine the future of cycling, with new and exciting technological progress.

16. I want you to think of your perfect bicycle (*does not have to be realistic*).

- a. What would it look like?
- b. What kind of features would it have? (*Enhancements, jetpacks, electric, non-electric, connected, apps, anything goes*)
- c. What kind of technology?

In the future, where cars are automated and driverless:

17. Imagine a system or device that helps you interact with automated vehicles.

- a. How should this device be designed?
 - i. *On-bike (attached or detachable)*
 - ii. *Integrated in bike (in the frame or handlebars)*
 - iii. *As a wearable (phone app, AR glasses, etc.)*
- b. How should the device communicate with the cyclist?
 - i. *Audio*
 - ii. *Light*
 - iii. *Vibration/haptics (handlebars or seat)*
 - iv. *Display screen or cyclometer*
- c. Would you be interested in using such a device? Why/why not?

18. If you could receive information about other road users such as automated vehicles through a device or system on your bike (*like the one you just imagined*) ...

- a. What are the benefits of such a system?
- b. What kind of traffic information would be useful to receive?
- c. What kind of information about cyclists would be useful for the automated vehicle?

Cues: Connected vs detected, map trajectory of cyclist to avoid conflicts etc.

- d. What are the disadvantages of such a system?

Cues: Increased mental workload, trust, overreliance

Appendix B. List of included publications in the literature review of “Support systems for cyclists in automated traffic: A review and future outlook”

	Reference	Publication type	Location
1	Benderius et al. (2018)	Journal article	Sweden
2	Boreal Bikes Gmb (2021)	Commercial/industry publication	Germany
3	Céspedes et al. (2016)	Conference paper	Chile, Colombia
4	Cohda (2017)	Commercial/industry publication	Australia
5	Colas (2017)	Commercial/industry publication	France
6	Cosmo Connected (2022)	Commercial/industry publication	France
7	Dancu et al. (2015)	Conference paper	Sweden
8	De Angelis, Fraboni, et al. (2019)	Conference paper	Italy
9	De Angelis, Stuver, et al. (2019)	Journal article	Italy
10	Delft University of (2021)	Commercial/industry publication	Netherlands
11	Dey et al. (2018)	Conference paper	Netherlands
12	Engbers et al. (2018)	Journal article	Netherlands
13	Engbers et al. (2016)	Journal article	Netherlands
14	Engel et al. (2013)	Conference paper	Germany
15	Englund et al. (2019)	Conference paper	Sweden
16	Erdei et al. (2020)	Journal article	Germany
17	Erdei et al. (2021)	Journal article	Germany
18	EverySight (2022)	Commercial/industry publication	Israel
19	Ford Motor Company (2017)	Commercial/industry publication	USA
20	Garmin (2022a)	Commercial/industry publication	USA
21	Garmin (2022b)	Commercial/industry publication	USA
22	General Motors (2012)	Commercial/industry publication	USA
23	Ginters (2019)	Conference paper	Latvia
24	Grimm et al. (2009)	Patent	USA
25	Hagenzieker et al. (2020)	Journal article	Netherlands
26	Harrison (2011)	Patent	Australia
27	Heijmans (2022)	Commercial/industry publication	Netherlands
28	Hernandez-Jayo et al. (2015)	Poster	Spain
29	Hou et al. (2020)	Conference paper	Canada
30	Jenkins et al. (2017)	Conference paper	USA
31	Jones et al. (2007)	Conference paper	USA
32	Julbo (2022)	Commercial/industry publication	France
33	Kaß et al. (2020)	Conference paper	Germany
34	Kiefer and Behrendt (2016)	Journal article	UK
35	Liebner et al. (2013)	Conference paper	Germany
36	Lindström et al. (2019)	Conference paper	Sweden
37	Matthiesen et al. (2018)	Patent	USA
38	Matviienko et al. (2018)	Conference paper	Germany

39	Matviienko, Ananthanarayan, Brewster, et al. (2019)	Conference paper	Germany
40	Matviienko, Ananthanarayan, El Ali, et al. (2019)	Conference paper	Germany
41	Nissan Motor (2015)	Commercial/industry publication	Japan
42	Oczko et al. (2020)	Conference paper	Germany
43	Prati et al. (2018)	Journal article	Italy
44	Rashdan et al. (2020)	Conference paper	Germany
45	Raßhofer et al. (2007)	Book section	Germany
46	Schaffer et al. (2012)	Journal article	Germany
47	Schoop et al. (2018)	Conference paper	USA
48	Shin et al. (2013)	Conference paper	Taiwan
49	Solos (2018)	Commercial/industry publication	USA
50	SWARCO (2022)	Commercial/industry publication	Denmark
51	Terranet (2021)	Commercial/industry publication	Sweden
52	Tome Software (2019)	Commercial/industry publication	USA
53	James and Prokhorov (2016)	Patent	USA
54	Umbrellium (2017) 25/06/2024 20:50:00	Commercial/industry publication	UK
55	Verstegen et al. (2021)	Conference paper	Netherlands
56	Vlakveld et al. (2020)	Journal article	Netherlands
57	Von Sawitzky, Grauschopf, et al. (2020)	Conference paper	Germany
58	Von Sawitzky et al. (2021) 25/06/2024 20:50:00	Journal article	Germany
59	Von Sawitzky, Wintersberger, et al. (2020)	Conference paper	Germany
60	Westerhuis et al. (2021)	Journal article	Netherlands
61	Yoshida et al. (2015)	Conference paper	Japan
62	Van Brummelen et al. (2016)	Conference paper	Canada

Appendix C. Taxonomy definitions in “Support systems for cyclists in automated traffic: A review and future outlook”

1. Terminology

In this category, we map the words used to describe a concept. The terminology was deduced from the title, abstract, or keywords of the academic articles. For commercial concepts, the terminology was chosen from the words used to describe their product.

2. Target road user

This dimension pertains to the type of road user targeted by a concept. Cyclists are the main road user group of interest in this study; however, a concept could target more than one type of road users. Other relevant road users targeted are pedestrians and the vehicles themselves, including the driver or onboard passenger.

3. HMI placement

This category describes the location of the interface conveyed messages to its intended recipient. If a concept offers multimodal communication, all locations of the interfaces are categorised, meaning that a concept could have more than one placement. The placement of the concepts was further divided into four subcategories: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems.

3.1 Cyclist wearables. A concept is categorised as a cyclist wearable if the communication device is located on the cyclist. A cyclist wearable is subcategorised as a helmet, smartphone, AR-glasses, a head-up display mounted on the helmet, a beacon or tag that was not specified as a smartphone, or as other, which included backpacks and belts.

3.2 On-bike devices. To be categorised as an on-bike device, the system or interface of communication is located on the bicycle. More specifically, concepts categorised as on-bike devices had HMI placements such as on the handlebars, a mounted display between the handlebars, a head-up display extended from the handlebars, and systems placed on the frame, seat, and rear of the bicycle. The category ‘unspecified’ includes concepts mentioning placement on the bicycle but without pinpointing the exact location.

3.3 Vehicle systems. In this category, the communication device is located on or within the motorised vehicle, either on the bumper, hood, rear, roof, side, windshield, or all around the vehicle. Concepts described as being on or in the vehicle without specifying the exact placement were coded as unspecified.

3.4 Infrastructural systems. Within this category, the interface with the message of communication is located on infrastructure, e.g., a traffic sign, on the road, or on the side of the road. Devices using projections were also categorised as infrastructural systems, as the message of communication is communicated on an infrastructural surface like the road.

4. Number of interfaces

We counted the number of interfaces identified within a concept in this category. An *interface* can be defined as a relation between two distinct entities selectively allowing communication of information from one entity to the other. In other words, an interface allows a user to interact with a device, program, or machine. The number of interfaces is distinguished by the number of modalities capable of communicating information between a machine and a human road user. For instance, a concept alerting the cyclist through vibrating handlebars and a signal from a speaker would be counted as two interfaces: one on the handlebars and one through the speaker.

5. Number of messages

This category describes the number of different messages communicated through an interface. An interface can transmit multiple messages, but only one message at a time. As in Dey, Habibovic, Löcken, et al. (2020), the number of messages is coded as one message if the same message is communicated through multiple interfaces independently or simultaneously (e.g., a light on the handlebars of the bicycle paired with haptic feedback in the seat, both conveying the same message). If an interface conveys a message as a continuous process (e.g., projected lights around a bicycle, changing colours indicating the proximity of other road users or entities in the environment), it is also coded as one message.

6. Modality of communication

Modality of communication describes how communication is achieved by a concept and is classified as visual, auditory, motion, or wireless means of communication. Multimodal concepts are categorised by all forms of communication, meaning a concept could be categorised within more than one sub-category.

6.1 Visual. This category pertains to retrieved concepts that communicate through visual perception and sight. Visual modalities are coded according to the following sub-categories:

- **Anthropomorphic:** The concept communicates visually using a human form or attributes, like a waving hand.
- **Abstract/light:** Abstract visual shapes or light-based modalities communicating intuitively through an open-to-interpretation interface without the specific use of text, symbols, or anthropomorphic shapes, e.g., a blinking light on the bicycle's handlebars.
- **Symbol:** The use of recognisable and commonly used symbols like a stop sign, zebra crossing lines, arrows, or other types of symbols used to communicate.
- **Text:** The explicit use of text or numbers on an interface, e.g., advice or instructions such as “go”, “stop”, or “safe to pass”, or information-based text displaying distance or speed, or a countdown timer with numerical text.
- **Unspecified:** Visual means of communication that are not specified.

Another sub-category of visual modalities of communication is the **colour (6.1.1)** used in these concepts, identified as black, blue, cyan, green, orange, pink, purple/violet, red, white, yellow, and unspecified.

6.2 Auditory. Concepts communicating through the sense of hearing are categorised as auditory. The following sub-categorised are used to describe auditory modalities:

- **Speech:** Communication is expressed as articulate sounds, e.g., a voice instructing the cyclist to “turn left now” or a cyclist using voice-based commands to control a system.
- **Signal or buzzer:** The use of a non-speech-related audio signal or buzzing noise.
- **Bone-conductor:** Audio transmitted by sound waves vibrating bone. While bone conduction could be considered a motion-based modality of communication, we have chosen to place it as a sub-category of auditory modalities as it is difficult for the user to distinguish between sound conducted through bone compared to via air.

6.3 Motion. Concepts communicating through the action or process of moving or being moved would be categorised as using motion as their modality of communication. Furthermore, motion is sub-categorised into three categories:

- **Haptic:** The technology actively applies force, vibration, or motion to communicate with the user, e.g., vibrating handlebars or bicycle seat.
- **Tactile:** The message of communication is tangible; delivered through touch, e.g., the cyclist communicates a message to a system by pressing a button.
- **Gesture:** Gesture-based communication, such as a display with a waving humanoid or a cyclist using hand or head movements to communicate with a system.

6.4 Wireless. Concepts categorised as wireless deliver their message of communication through signal transmission on a frequency spectrum. Wireless is categorised according to the technology utilised to transmit the message:

- **GPS:** Global Positioning System, a satellite-based radio navigation system.
- **Bluetooth:** Short-range wireless technology standard for exchanging data between fixed and mobile devices.
- **Wi-Fi:** Wireless fidelity trademarked; wireless network protocols based on the IEEE 802.11 family of standards.
- **WLAN:** Wireless local area network, without specifying they are based on the IEEE 802.11 standard.
- **Broadband cellular network:** 3G, 4G, and 5G.
- **Radio frequency identification:** Radio waves to identify a tagged object passively.
- **Other:** Global Navigation Satellite System (without specifying the system uses GPS), real-time locating systems (RTLS), dedicated short-range communications (DSRC), and Global System for Mobile Communications (GSM).

7. Communication strategy

This category defines how the system addresses road users when communicating messages. It describes whether the communication is targeted or non-targeted and whether the message is intended for single or multiple users (adapted from Dey, Habibovic, Löcken, et al. (2020)). The concepts are categorised into three categories, where a concept can communicate in more than one way.

- **Unicast:** The system communicates and delivers its messages targeted to a single road user, e.g., vibrating bicycle handlebars.

- **Broadcast:** The system broadcasts its messages to non-targeted road users, e.g., a light on the rear of the bicycle indicating whether the cyclist is speeding up or braking.
- **Multicast:** The system targets and delivers its messages to multiple road users at the same time, e.g., a projection of a cyclist symbol on the road, indicating whether it is safe to change lanes.

8. Connectivity

Connectivity is a dimension that classifies whether the concept has the capacity for interconnection by signal transmission between systems or users.

9. Functionality

This dimension classifies the intended functionality of the message(s) communicated through the device or system, as described by the authors of each original article. Functionality is the intended message communicated to its recipient or the *purpose* of the messages communicated. The dimension of functionality is further categorised into three sub-categories: information systems, warning systems, and support systems. A concept could have more than one functionality and be categorised into more than one sub-category.

9.1 Information systems. Concepts categorised within information systems aim to inform the user about a particular arrangement or sequence of events, such as details about objects' or other road users' location or behaviour. Within information systems, we have defined the following sub-categories of functionality:

- **Navigation:** The system provides the user with navigational cues.
- **Information:** The system provides information about the vehicle, the cyclist, or the bicycle's state, e.g., whether the vehicle is stopping or going, if the cyclist is receiving a call, or the current speed of the bicycle.
- **Advice/Instruction:** Normative messages conveying desired behaviour of the recipient or other commands contingent on the recipients' actions, e.g., displays with the messages "go" or "do not cross".
- **Detection:** The concept detects elements or entities in its environment without the intention of warning the recipient of an immediate conflict or danger.
- **Data collection:** The concept collects and sends data about its users or entities in the environment, e.g., bicycle speed, location, and user data.

9.2 Warning systems. Concepts within this sub-category intend to convey messages of caution or urgency to its users. While a warning system is essentially an information system, the difference lies in the function of the message: The purpose is to prepare the user of a conflict so they can act accordingly to mitigate or avoid it. Warning systems are further differentiated into three sub-categories:

- **Conflict/collision:** The system warns the user of an imminent conflict or collision.
- **Approaching rear:** The system warns the user of an entity approaching from behind, e.g., a vehicle approaching the rear of a bicycle.
- **Other:** The system alerts the user of an unspecified event of urgency.

9.3 Support systems. Similar to information systems, concepts coded as a support system have functionality conveying messages about an arrangement or sequence of events. The difference between information and support systems is in the nature of the message: support systems convey messages with a behavioural component of the cyclist's current or future behaviour, such as braking or turning. The functionality of support systems is categorised in the following sub-categories:

- **Braking system:** The system communicates to other road users that the bicycle is actively reducing its speed, i.e., indicating that the cyclist is braking.
- **Projection-based cues:** These concepts project messages indicating the current or potential behaviour of the cyclist, e.g., symbols, lights, or other visual elements on the ground or field of view indicating the potential trajectory of the cyclist or bicycle.
- **Intent indicator:** A functionality similar to projection-based cues; however, the intent indicator conveys messages of the active intent of the cyclist, such as a turn indicator located on the bicycle.
- **Lane-keeping system:** The system informs the user to stay within a pre-defined area while cycling, e.g., a head-up display or a screen outlining the boundaries of the road.

10. Type of product

In this category, the concepts were coded according to their current state of development, whether they were conceptual, a prototype, or an end product.

11. Complexity of implementation

This dimension describes the complexity of implementing a concept in real-world traffic scenarios. Some concepts can be aspirational and practically unrealistic to implement in today's traffic environments without technological advances, full-scale adoption by other road users, or extensive infrastructure changes. The concepts are coded within four sub-categories adapted from Dey, Habibovic, Löcken, et al. (2020, p. 13):

- **Ready to use:** Technology is ready to use today.
- **New technology required:** Requires new technology but does not depend on large-scale deployment or infrastructure changes to function.
- **New technology and large-scale changes required:** Requires new technology but depends on large-scale deployment or infrastructure changes to function.
- **Highly aspirational:** Uses technology that is not yet developed or available.

12. Support for people with special needs

Adapted from Dey, Habibovic, Löcken, et al. (2020), this category describes whether the concept accommodates the special needs of visually, auditory, or cognitively impaired persons via multimodal communication.

13. Evaluation of concept

Evaluation of concept is a category describing whether the technology, device, or system has been evaluated in a scientific publication. If an evaluation has not been conducted, the concept is coded as unknown, in line with the evaluation of concept dimension by Dey, Habibovic,

Löcken, et al. (2020). If a concept has been evaluated, it is further classified into the following 13 sub-categories:

- **Method of data collection:** Automatic recording, eye-tracking device, questionnaire, interview, observation, or video recording.
- **Methodology:** Qualitative, quantitative, or mixed methods.
- **Method of evaluation:** Naturalistic, controlled outdoor, simulator (screen-based), simulator (VR headset-based), video or animation, or photo.
- **Direction of movement:** The behaviour and/or direction of the cyclist and other road users (if applicable) during the data collection, e.g., whether the cyclist is cycling straight ahead, turning left or right, and the direction of the other road user (opposite, perpendicular, or same/parallel trajectory relative to the cyclist).
- **Task:** The task of the cyclist during the evaluation of the concept.
- **Time of day:** Daylight conditions, evening conditions, night-time conditions, or unspecified.
- **Weather conditions:** Direct sunlight, indirect sunlight, rain, snow, or unspecified.
- **Road condition:** Clean roads, water on the road, snow on the road, or unspecified.
- **Cycling infrastructure:** Mixed traffic with no bike lane, mixed traffic with a bike lane, separated bike path, or unspecified.
- **Number of simultaneous road users per trial.**
- **Number of vehicles per trial.**
- **Sample size:** Number or unknown.
- **Sample age:** Median or mean age of the sample, or unknown.

Appendix D. Interview guide for “Triangulating the future: Developing scenarios of cyclist-automated vehicle interactions from literature, expert perspectives, and survey data”

Introduction (10 min)

To be presented orally to participants

Thank you for agreeing to take part in this interview. I expect the duration to be about 2 hours.
[Short background info about the project]

I would like to record this interview. I will use the recordings to transcribe our interview. Your viewpoints will be made anonymous, and your information will be treated confidentially. Further details should be in the information letter and informed consent you have received. But before I start the recording, do you have any questions?

Warm-up (5 min)

Shortly say something about your **educational background, your current position or title at [organisation], and how many years you have been working with transport-related topics.**

Cycling safety (25 min)

1. Perceived safety and pleasant interactions

- a. In an ideal world, how would we design for pleasant cycling?
- b. How do we design for cyclists to feel safe? (perceived/subjective safety)
- c. How do we design for safe cyclist interactions (with vehicles)?
- d. Which strategies do you use to stay safe when cycling?
- e. Which types of preventive actions, behaviours, or mechanisms do you think plays a role when cycling?

Automation (25 min)

2. Automated vehicles

- a. How do you envision the future of cycling with automated vehicles?
- b. How will the way we communicate in traffic change during the transition period?
- c. What kind of information do cyclists need to be safe in traffic with...
 - i. Conventional vehicles?
 - ii. Semi/partially automated vehicles (e.g., L2 vehicles, with a steward)?
 - iii. Fully automated vehicles (with or without onboard passengers)?

Definitions (15 min)

3. Use cases

- a. How would you define a use case (for cyclist interaction with vehicles)?

4. Scenarios

- a. What is a scenario?
- b. In a scenario, which elements should be described?

Use cases and scenarios (35 min)

5. Use case and scenario development

- a. Where and when do cyclists interact with vehicles today?
- b. Are there any new types of situations when interacting with partially automated vehicles?
- c. Where and when do you think cyclists will interact with fully automated vehicles?
- d. Which use cases are most relevant or important to test in cycling research?

- e. What kind of factors or elements do we need to account for? Why?
- f. Which one of these [previously mentioned] factors is the most important to account for in research?
- g. How much complexity (number of factors) is feasible in research?

Wrapping up (5 min)

6. Do you have anything else to add?

Appendix E. ChatGPT output of the meta-summaries of the interview data for “Understanding cyclists’ perception of driverless vehicles through eye-tracking and interviews”

Table E1. ChatGPT output for post-Session 1 interviews

<i>Q1: How did they interact with the vehicle?</i>
<i>Participants interacted with the vehicle by observing its speed, direction, and the presence of a driver. They adjusted their cycling behaviour based on these observations, with some slowing down or altering their path to avoid potential collisions. Many participants noted changes in the vehicle's behaviour across the rounds, with some noticing the vehicle moved earlier or slower in later rounds. The presence or absence of a driver in the vehicle influenced some participants' reactions, with some feeling more cautious or curious when they realised the vehicle was driverless.</i>
<i>Q2: What did they look at?</i>
<i>Participants' attention was primarily drawn to the front of the vehicle, with many focusing on the headlights, speed, and direction. Some tried to identify the driver or make eye contact, but this was often hindered by factors such as dark glass or personal vision issues. A few participants noted the vehicle's behaviour, such as whether it would stop, and some observed the vehicle's colour, size, and brand. However, there was little mention of specific motion cues, and many did not notice whether there was a driver in the vehicle.</i>
<i>Q3: Did anything stand out? If so, what?</i>
<i>Participants' experiences with the automated vehicle varied, with some noting differences in speed, presence of a driver, and the vehicle's behaviour across different rounds. A few participants noticed the absence of a driver in some rounds, leading to feelings of curiosity, confusion, and increased caution. Others focused on the vehicle's speed, direction, and their distance from it, with some noting changes in these aspects across rounds. However, a significant number of participants did not notice any standout features or differences between the vehicles, treating the automated vehicle similarly to regular cars they encounter in daily life.</i>
<i>Q4: Did they interact differently with this vehicle as opposed to vehicles in daily life? How?</i>
<i>Participants' interactions with automated vehicles varied, with some treating them as they would regular vehicles, while others exhibited heightened caution. Factors influencing these interactions included the vehicle's speed, the controlled experimental environment, and the absence of a driver. Some participants felt safer due to the predictability of the automated vehicle, while others were more cautious due to the unfamiliarity and perceived unpredictability of the vehicle. The presence or absence of a driver did not significantly affect most participants' interactions, with many focusing more on the vehicle's behaviour and their own safety.</i>

Table E2. ChatGPT output regarding post-Session 2 interview questions about interaction behaviour and safety

Q5: To what extent did the interaction affect their cycling behaviour?

The interactions with automated vehicles affected the cycling behaviour of the participants to varying degrees. Some participants felt the need to be more cautious, often slowing down to identify the presence of a driver, while others felt safe and unaffected due to the controlled nature of the experiment and the slow speed of the vehicle. The task of identifying the presence of a driver was a common focus, with some participants changing their cycling strategies to better observe the vehicle. However, a few participants expressed trust in the technology and did not feel the need to differentiate between human-driven and automated vehicles, suggesting that their cycling behaviour would remain consistent regardless of the presence of a driver.

Q6: Describe how their cycling behaviour was affected.

The presence of automated vehicles affected the cycling behaviour of most participants, with many expressing a need to predict the vehicle's motion and identify whether a driver was present. This often led to increased caution and changes in speed or route. However, the majority felt safe due to the slow speed of the vehicles and some became more confident as they familiarised themselves with the vehicle's behaviour. Many participants expressed a desire for automated vehicles to be distinguishable from regular vehicles and for some form of communication about the vehicle's intentions.

Q7: Did they feel safe? Elaborate.

The majority of the 37 participants felt safe interacting with automated vehicles during the experiment, attributing their comfort to factors such as the slow speed of the vehicle, trust in the technology, and the controlled experimental environment. Some participants expressed a desire for clear communication from autonomous vehicles, such as visual signs indicating their intentions or their driverless status, to enhance safety. A few participants felt less safe or had mixed feelings, citing concerns about real-world scenarios, the need for increased vigilance, and the unsettling experience of a car moving towards them without a driver. Overall, while participants generally felt safe, there were suggestions for improvements and some reservations about interacting with driverless vehicles outside of a controlled experiment.

Table E3. ChatGPT output for post-Session 2 interview questions about cyclists' information needs

Q8: Would they like to be able to distinguish the vehicle from a normal vehicle? If so, how?

The majority of the 37 participants expressed a desire to distinguish automated vehicles from traditional ones, suggesting various methods such as signs, markings, or unique vehicle designs. A smaller group felt no need for such distinction, citing reasons such as trust in the system's safety, potential distraction, or a preference for treating all vehicles the same. Some participants were undecided or expressed nuanced views, suggesting that while distinction might not be necessary, some form of visual communication from the vehicle could be beneficial. Overall, the need for clear identification of automated vehicles was linked to factors such as safety, predictability of vehicle behaviour, and accountability in case of accidents.

Q9: Would the participant like additional communication from the vehicle? If so, what kind? Describe placement, colour, and modality of communication if possible.

The majority of the 37 participants expressed a desire for additional communication from autonomous vehicles, with a strong preference for visual signals, such as lights or signs, directly from the vehicle itself. These signals could indicate the vehicle's intentions or confirm the cyclist's detection. A few participants suggested the use of auditory signals or haptic feedback, but these were generally seen as secondary to visual cues. However, a small number of participants felt that additional communication was unnecessary, preferring to rely on their own visual perception and existing traffic rules.

Table E4. ChatGPT output for post-Session 2 interview wrap-up

Q10: How realistic did they find the experiment setup?

Participants had mixed views on the realism of the experimental setup involving automated vehicles and cyclists. Some found it very realistic, citing the behaviour of the automated vehicle and the environment as closely mirroring real-world conditions. However, others felt it lacked realism due to factors such as the absence of other road users, the predictability of the vehicle's behaviour, and the knowledge that they were in a controlled experiment. Suggestions for improvement included adding more complexity and unpredictability to the experiment, such as varying vehicle speeds, including more road users, and conducting the experiment in unfamiliar or more typical cycling environments.

Q11: Anything else?

Participants in the study had varied responses, with many suggesting ways to increase the realism of the experiment. These included varying the vehicle's position, adding more people and bicycles to the environment, and introducing more moving objects or obstacles. Some participants found it challenging to identify whether there was a driver in the vehicle due to factors such as glass reflection and signage. Others questioned the purpose of certain elements of the experiment, such as the presence of pedestrians and the person holding letters, while a few expressed interest in the study's focus and potential implications for cycling speed.

About the author



Siri Hegna Berge was born in Trondheim, Norway, on January 1, 1986. In 2016, she obtained a Bachelor's degree in Psychology of Learning with an Emphasis on Behavioral Analysis from Oslo and Akershus University College of Applied Sciences. Her academic journey continued to the University of Oslo, where she specialised in human-computer interaction for her master's thesis, a project she undertook in collaboration with SINTEF Digital. In 2018, she earned the degree of Master of Philosophy in Psychology from the University of Oslo.

Berge continued her professional journey as a Research Psychologist at the Institute of Transport Economics: Norwegian Centre for Transport Research (TØI). Her role at the Department of Safety, Security, and Behaviour allowed her to apply her theoretical knowledge in a practical setting. Working on various transport research projects in the interdisciplinary environment of TØI sparked an increased interest in the interaction between humans and technology and the safety implications of human factors in transport.

In 2020, she started her doctoral studies in human factors at the Traffic and Transportation Safety Lab at the Department of Transport and Planning, Faculty of Civil Engineering and Geosciences, at Delft University of Technology in the Netherlands (TU Delft). During her stay at TU Delft, she also served on the Ethics Review Board, assisted in teaching activities, reviewed submissions, and presented at international journals and conferences.

Upon completing her doctoral studies at TU Delft in 2024, she continues working with traffic safety and human factors as a Research Psychologist at TØI.

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Author contributions

Chapters 2 to 7 of this dissertation are based on published papers and collaborative research efforts. The following section highlights the specific contributions of each author to the papers included in their respective chapters.

Berge, S. H. was the primary contributor to the papers outlined in *Chapters 2 to 5*. In *Chapter 2*, Berge, S. H. wrote the original draft and was in charge of the investigation, methodology, and formal analysis with the support and supervision of Hagenzieker, M., Farah, H. and De Winter, J. The papers in *Chapters 3, 4, and 5* had similar author contributions: Berge, S. H. wrote the original draft and performed the majority of the planning, analysis, and data collection tasks with the support and supervision of Hagenzieker, M. and De Winter, J. In *Chapter 5*, Cleij, D. also contributed to the planning and supervision. All co-authors of the papers in *Chapters 2 to 5* reviewed and edited the drafts.

For the paper in *Chapter 6*, Berge, S. H., De Winter, J., and Dodou, D. performed the analyses and wrote the original draft collaboratively. Farah, H. was the project administrator and supervisor, who planned, conceptualised, and executed the field tests together with Berge, S. H., Dodou, D., Afghari, A. P., and Papadimitriou, E. Moreover, Reddy, N., Dong, Y., and Raju, N. assisted in the data collection. Farah, H. also contributed to the qualitative analysis and editing of the paper draft. All co-authors reviewed the paper draft.

In *Chapter 7*, De Winter, J. contributed substantially to the concept, performed the analyses, and wrote the original draft in collaboration with Berge, S. H. Furthermore, Berge, S. H. planned and executed the data collection with support and supervision from De Winter, J. and Hagenzieker, M. Feng, Y. contributed with resources and facilitated the development of the VR cycling simulator. All co-authors reviewed and edited the paper draft.

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The VR cycling simulator and virtual environment used in *Chapter 7* were developed by the Mobility in eXtended Reality Lab and the XR zone of the New Media Centre at Delft University of Technology, which were financially supported by the Outdoor Mobility Digital twin project.

Digital resources

A range of digital resources have aided in writing this dissertation, one of which is an AI-driven conversational agent built on the GPT-4 platform. This agent has served as a dynamic tool, enabling an iterative process of discussion and feedback, contributing to initial brainstorming and refinement of syntax. It is important to clarify that while this conversational agent generated text in response to specific queries and prompts, all of the final interpretations, articulations, and conclusions are the author's own.

The use of AI was supplementary and, in the future of AI literacy, likely comparable to the use of other automated research tools (e.g., Grammarly, ATLAS.ti, IBM SPSS Statistics, Microsoft Excel, and Microsoft Word). The purpose of this acknowledgement is to maintain transparency of the tools applied during the writing of this dissertation.

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