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

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A R T I C L E I N F O

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A B S T R A C T

Cyclists are expected to interact with automated vehicles (AVs) in future traffic, yet we know little about the nature of this interaction and the safety implications of AVs on cyclists. On-bike human–machine interfaces (HMIs) and connecting cyclists to AVs 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 AVs. 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-AV interaction and on-bike HMIs. From the analysis, seven themes were identified: Interaction, Bicycles, Culture, Infrastructure, Legislation, AVs, 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 AVs. 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 AVs: Responsibility for safety should lie with AV 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 AV-cyclist interaction.

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, Buckley, Crist, & Lappin, 2018), and human road users can be expected to interact with vehicles of varying degrees of automation for decades to come (Litman, 2020; Owens, Greene-Roesel, Habibovic, Head, & Apricio, 2018).

Active transport like walking and cycling is beneficial to public health (Raser et al., 2018) and promises substantial reductions in CO_2 emissions (McDonald, Fulton, & Mason, 2015). While AVs are assumed to produce fewer emissions than conventional vehicles

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(Milakis, Van Arem, & Van Wee, 2017), active transport remains more sustainable (Creger, Espino, Sanchez, & Institute, 2019). Trends indicate that cycling is on the rise in urban areas (EPINION, 2019; Harms & Kansen, 2018; OECD/ITF, 2013; Pucher & Buehler, 2017), and it is likely that cyclists will be interacting with AVs in future traffic.

Cyclists are vulnerable road users (VRUs) (Holländer, Colley, Rukzio, Butz, & Butz, 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 AVs, as cyclists might base their behaviour and interaction strategies on incorrect expectations of AV behaviour (Vissers, van der Schagen, Van, & Hagenzieker, 2017). To ensure cyclists' safety in future traffic, exploring solutions for enhancing AV-cyclist communication becomes vital.

Dey et al. (2020) suggested that present solutions for enhancing AV-VRU 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 AVs and VRUs.

Among the technical solutions for enhancing AV-cyclist interaction, there are bicycle-to-vehicle connectivity and VRU 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 VRUs is essential to use vehicle automation to its full advantage (Farah, Erkens, Alkim, & van Arem, 2018; Owens et al., 2018; Sanchez, Blanco, & Diez, 2016). Cyclists could be connected to AVs and the road infrastructure through their bicycles (Jenkins, Duggan, & Negri, 2017; Meinken, Montanari, Fowkes, & Mousadakou, 2007; Piramuthu, 2017; Scholliers, van Sambeek, & Moerman, 2017; Shin, Un, & Huang, 2013), or through wearables such as smartphones (Anaya, Merdrignac, Shagdar, Nashashibi, & Naranjo, 2014; Engel, Kratzsch, David, Warkow, & Holzknecht, 2013; Liebner, Klanner, & Stiller, 2013; Scholliers et al., 2017; Wu et al., 2014) and helmets (Hernandez-Jayo, Perez, & De-La-Iglesia, 2016). However, little is known about the consequences of equipping cyclists with devices to communicate with AVs in terms of reliance, liability, and responsibility of the AVs and the cyclists (OECD/ITF, 2019; Owens et al., 2018).

Solutions for enhancing AV-cyclist interaction from a human factors perspective mainly revolve around external on-vehicle human–machine interfaces (eHMIs). eHMIs substitute the lack of explicit human-to-human communication cues with driverless AVs 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, Dodou, & De Winter, 2019; Dey et al., 2020). Out of the eHMI concepts considered by Dey 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, Blascheck, Raschke, Hausmann, & Schlegel, 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, Mahadevan, Somanath, Sharlin, and Oehlberg (2020), as their findings for eHMIs for cyclists differed from pedestrians.

A cyclist-specific solution for enhancing communication between AVs 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, Heuten, & Boll, 2019), turn-indicators (Dancu et al., 2015), and navigation systems (Dancu et al., 2015; Pielot, Poppinga, Heuten, & Boll, 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

Table 1
Interview topics and a selection of questions from the interview guide.

Topic	Question
Current traffic interaction	*I would like to know about your experience with cycling …*
	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	*Imagine a future where cars are fully automated, and there is no longer a human driver behind the wheel …*
	How will this impact you as a cyclist?
	How do you think *[challenge(s) already mentioned by the participant]* 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	*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) …*
	What would it look like?
	What kind of features would it have?
	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 (like the one you just imagined) …
	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?

Sawitzky, Wintersberger, Löcken, Frison, & Riener, 2020) and head-up displays (HUDs) (Dancu et al., 2015; Hou et al., 2020; Matviienko et al., 2019) for cyclists. However, the potential of on-bike HMIs to enhance AV-cyclist interaction remains largely unstudied.

Investigating the factors that constitute cyclist interaction today might offer insight into cyclists' needs for AV 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 AV-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 AV-cyclist interaction by exploring the factors that constitute cyclist interaction in traffic, both in current environments and in future scenarios with AVs. Moreover, we investigate whether on-bike HMIs are desired by cyclists and potential design strategies of on-bike HMIs to enhance the interaction between AVs and cyclists.

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 min. The interviews started with a short introduction of the project and demographic questions, followed by open-ended questions sectioned into three topics. Table 1 shows the interview topics and selected questions from the interview guide. For the complete interview guide please refer to Appendix A.

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.

2.1. 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). Interviewing cyclists in two countries with different shares of cyclists and cycling culture 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 groups[1], and Twitter[2]. 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, Bunce, & Johnson, 2006).

Table 2 provides an overview of the interview participants. The sample of 30 participants consisted of 11 females and 19 males. 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 AVs and human factors.

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, Nikitas, & Tchouamou Njoya, 2020; Gössling, Cohen, & Hares, 2016; Liu, Nikitas, & Parkinson, 2020; Pettigrew, Nelson, & Norman, 2020). Table 3 presents the six steps of our thematic analysis process.

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

[1] Syklistforeningen i Oslo and Dutch Cycling Embassy
[2] SWOV Institute for Road Safety Research

Table 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

Table 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

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, Guest, Thairu, & Johnson, 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).

3. Results

3.1. Overview of results

Seven overarching themes and 47 sub-themes that constitute cyclist interaction today and in future scenarios with AVs were identified in the analysis: Interaction, Bicycles, Culture, Infrastructure, Legislation, AVs, and HMI. Table 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 Fig. 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 AVs (28 co-occurrent

Table 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)	
	Theft (6)	
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 AV capabilities (30)	
	Cyclist needs (24)	
	Challenges (24)	
	eHMI (18)	
	Future applications of AVs (6)	
Human-machine interface (30)	Functionality (30)	
	Perceptions and attitudes (30)	
	Design strategies (27)	Display (21)
		Audio (12)
		Haptics (10)
		Lights (8)
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 theme or sub-theme occurred in.

codes each), implying that these themes are closely associated. Similar claims can be made for AVs and HMI (35 co-occurrent codes), and Bicycles and HMI (30 co-occurrent codes).

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

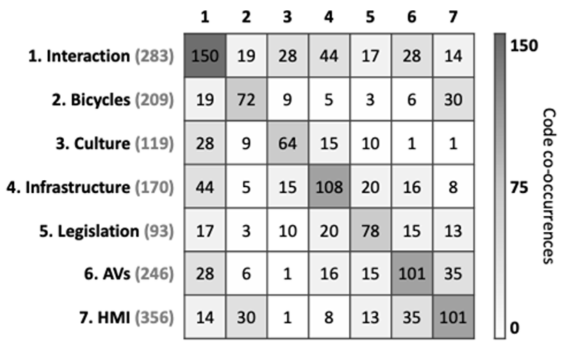

Fig. 1. Code co-occurrence of the main themes. The numbers on the diagonal indicate the total number of code co-occurrences for that theme. The numbers displayed after each theme indicate the total number of coded quotations within each theme.

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 recurringly 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.

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 utilisation, 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)

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.

3.4.1. Norway

The interviewees portrayed Norwegian road infrastructure as tailored to cars since the 1970s. Since then, cyclists have been described stereotypically 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)

3.4.2. 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.

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 bicycles lanes and bicycles 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 unsignalised 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 AVs 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 AVs. They argued that complete separation may delay the trust process between cyclists and AVs. A few of them also pointed out that AVs' 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 AVs 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.

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 AV 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)*

3.7. Automated vehicles

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

Some of the interviewees argued the transition period from semi-automated vehicles to fully AVs 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, AVs are expected to react faster and more rational, make fewer mistakes and be more predictable in traffic compared to humans. AVs 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. AV algorithms reflect human input and may be shaped by the attitudes and prejudices of programmers. If AVs 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 AVs should mimic human behaviour, replicate subtle cues, and adapt to sudden movements.

The consensus among the participants was that it is the AVs' responsibility to ensure other road users' safety. It was assumed that AV 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, AVs programmed to be conservative might lead to risk-taking and frustration, and traffic safety might be affected by AVs' 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 AVs at the time of the interviews. There was an expectation that AVs would be connected and share information about the environment with other road users and infrastructure. The interviewees assumed that future AVs 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 AV 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 AVs in mixed traffic. They were concerned about how AVs would interpret rule-breaking behaviour and understand informal rules. A few cyclists questioned if AV intelligence will be advanced enough to adapt to cyclists' versatility and unpredictability and whether unexpected behaviour such as frequent stopping by conservative AVs would affect safety and traffic flow.

Some cyclists prefer more distance between cyclists and AVs than with human drivers. Being informed about AVs' capabilities and limitations or receive training with AVs might substitute this need, some cyclists suggested. The interviewees assumed that cycling with AVs 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 AV 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 AV signalises 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 AVs:

> *"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 AVs 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 AVs 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 AV 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 AV'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)*

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 AVs 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 AV.

> *"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 AVs: AV technology should be sufficiently able to detect cyclists before AVs are released in traffic. If AVs start relying on data collected from VRUs' devices, some of the interviewees feared that this might decrease safety, as the AV 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 kilometers 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 AV. 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 AVs, 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 AV 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 AVs.

> *"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 AVs and infrastructure. The device could provide each bicycle with a unique ID and broadcasts info like the cyclist's speed and position to AVs and infrastructure. With a display type of interface, the device could exchange this information between the bike and the AV. 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.

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 AVs: Interaction, Bicycles, Culture, Infrastructure, Legislation, AVs, and HMIs. The following sections discuss the implications of the findings for cycling today and future interactions of cyclists with AVs, 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 AVs and infrastructure rather than connected bicycles.

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, Helman, Buttress, Newman, & Hutchins, 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 (Cripton et al., 2015; Melhuus, Siverts, Enger, & Schmidt, 2015). Schepers, Kroeze, Sweers, and Wüst (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, Sørensen, & de Jong, 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, Sørensen, & Amundsen, 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, Bjørnskau, & Sørensen, 2012).

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 AVs. Segregation of cyclists and AVs has been noted as ideal in other interview studies (Botello, Buehler, Hankey, Mondschein, & Jiang, 2019). However, our interviewees did argue that their scepticism towards sharing facilities with AVs might change as they become more experienced with AVs. This finding is in line with Blau, Akar, and Nasar (2018), where cyclists were more likely to prefer protected facilities over sharing the road with AVs.

The theme of AVs depicts how our cyclists expect future AVs to embody equal or better capabilities than human drivers. AVs 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 AVs 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 AVs (Kooij, Flohr, Pool, & Gavrila, 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 AVs. As a behavioural cue, eye contact of the driver may encourage cyclists to continue pedalling (Bazilinskyy, Dodou, Eisma, Vlakveld, & De Winter, 2021). However, some of the interviewees claimed that they do not use eye contact at all but instead rely on vehicles' motion cues. Risto, Emmenegger, Vinkhuyzen, Cefkin, and Hollan (2017) identified movement gestures as the vehicles' primary mode of expressing intent. Indeed, in future AV-cyclist interaction, interpreting AVs' motion cues and movement patterns might suffice (Habibovic, Andersson, Nilsson, Lundgren, & Nilsson, 2016; Lee et al., 2020; Moore, Currano, Strack, & Sirkin, 2019; Sripada, Bazilinskyy, & de Winter, 2021).

Our analysis indicated that cyclists prefer AVs to communicate recognition explicitly. Similar findings are shown in Merat, Louw, Madigan, Wilbrink, and Schieben (2018), where cyclists and pedestrians reported that they would prefer to receive communication about AVs' status and behaviour, particularly about detecting VRUs. 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, Dietrich, Núñez Velasco, De Winter, & Happee, 2019; Habibovic et al., 2018; Lundgren et al., 2017; Mahadevan, Somanath, & Sharlin, 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 AVs' current state rather than instructing VRUs 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 (Eisma et al., 2019) or directional eHMIs that can address specific road users (Dietrich, Willrodt, Wagner, & Bengler, 2018).

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 AV 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 AVs 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 AVs if the utility value is beyond guaranteeing their safety. For instance, the device could function as a navigation system or a cyclocomputer. 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 VRU connectivity, where most solutions involve using smartphones or wearables (Dasanayaka, Hasan, Wang, & Feng, 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 AV of VRUs' 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 AVs. Our interviewees disapproved of a device merely connecting AVs 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 VRUs and AVs with sufficient development of AV 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 Europe[3]. 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, Wolsink, Esseveldt, & Ferwerda, 2020).

In summary, the consensus among our participants was that the primary responsibility of safety lies with the AV. Being dependent on a device that might malfunction, be misplaced or stolen was not desired. There were also concerns about how AVs 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 AVs and planning for active transport, where they expressed concern about a VRU device requirement for recognition by AVs: While a device might increase safety, a requirement might not be egalitarian and could pose privacy issues (Botello et al., 2019).

[3] According to Statista (2020)

The ethical aspect of safety and responsibility of AVs versus VRUs 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 AVs. 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 AVs, 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 AVs, cycling connectivity may become an option rather than a requirement. Various simple, inexpensive, and optional on-bike HMIs can be envisioned as a starting point, such as a vibrating handlebar or integration with existing cyclocomputers.

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 AV-cyclist interaction.

Future studies should further investigate to what extent additional, explicit behavioural cues of AVs, such as eHMIs, are necessary to ensure safe and desired interaction between cyclists and AVs. 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 AVs, on-vehicle eHMIs, and smart infrastructure systems.

5. Conclusion

Our analysis showed that cyclists' primary need in AV-cyclist interaction is sufficient detection by AVs. Moreover, cyclists prefer that the AVs communicate recognition explicitly. The findings strengthen the notion that on-bike HMIs are potential solutions for enhancing interaction between cyclists and AVs. Previous studies on enhancing AV-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 VRUs on a larger scale to test the findings'generalisability and explore other, perhaps more viable, solutions for enhancing AV-cyclist interaction.

CRediT authorship contribution statement

Siri Hegna Berge: Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft. **Marjan Hagenzieker:** Conceptualisation, Funding acquisition, Supervision, Validation. **Haneen Farah:** Supervision, Writing – review & editing. **Joost de Winter:** Conceptualisation, Funding acquisition, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Research data

A REFI-QDA Standard project file with anonymised interview transcripts, analysis, document groups, code groups, and codes, along with text files containing the same information are available at the 4TU.ResearchData repository at https://doi.org/10.4121/15164103.v1.

Appendix A. Interview guide

[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: eHMIs: (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?
        On-bike (attached or detachable)
        Integrated in bike (in the frame or handlebars)
        As a wearable (phone app, AR glasses, etc.)
    b. How should the device communicate with the cyclist?
        Audio
        Light
        Vibration/haptics (handlebars or seat)
        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

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