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DOI
10.1016/j.trip.2023.100986

Publication date
2024

Document Version
Final published version

Published in
Transportation Research Interdisciplinary Perspectives

Transportation Research Interdisciplinary Perspectives 23 (2024) 100986

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

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

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ARTICLE INFO

Keywords:
Scenarios
Methodology
Cyclist
Automated vehicle
Bicycle
Vulnerable road user
Automated driving system

ABSTRACT

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.

Introduction

Automated vehicles present a unique challenge for the safety of vulnerable road users (VRUs). Human road users exhibit unpredictable behaviour and interact according to social and cultural norms (Tabone 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). VRUs 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 VRUs 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 (eHMIs), which serve as communication tools between automated vehicles and other road users like pedestrians and cyclists (Bazilinskyy et al., 2019; Dey 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

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https://doi.org/10.1016/j.trip.2023.100986
Received 8 May 2023; Received in revised form 31 August 2023; Accepted 28 November 2023
Available online 31 December 2023

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 VRUs. 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 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 (Díaz Fernández et al., 2022; Kuehn et al., 2015; Uittenbogaard et al., 2016). As of early 2023, reports of 546 automated vehicle collision reports were publicly available online (State of California Department of Motor Vehicles, 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:

1. To identify the types and characteristics of scenarios used in previous research on cyclists and automated vehicles.
2. To identify the typical behavioural characteristics of automated vehicles and the types of novel situations that may arise with increasing degrees of vehicle automation.
3. 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.

Methods

In this paper, 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.

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.

Fig. 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 Fig. 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 ($n = 2$).

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

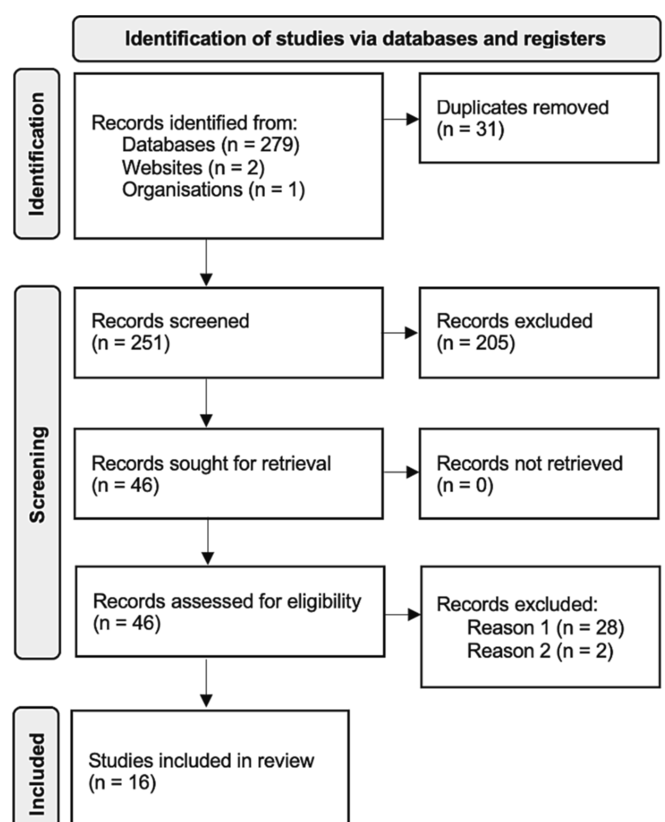

Fig. 1. PRISMA flow diagram of the literature review.

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 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 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.

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 min. The interviews started with an introduction to the present project, followed by round table introductions. As shown in Table 1, the interview guide was divided into four main topics.

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 A 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.

Table 1
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… 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?

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 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 & 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.

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 human–machine interfaces (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

Table 2
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. (2022)	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 VRUs	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)	Photos	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).
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 VRUs", as identified by Markkula et al. (2020) (Stange et al., 2022, p. 167).
Nuñez 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.
Vlakveld et al. (2020)	Video animations	15	Cyclists' intention to yield for automated vehicles where the cyclist has the right of way.	1009 participants	Situations at unsignalized intersections that frequently result in bicycle-car accidents (Räsänen & Summala, 1998; Schepers et al., 2011).
Wilbrink et al. (2018)	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 × 3 vehicle types × 3 window types × 2 visual complexity levels of the surroundings × 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.

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 7) was calculated by subtracting the means of *frequency of occurrence in the*

Table 3
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	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 VRUs than the cyclist	0	x			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	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	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	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	x		x

Note. 1: Bazilinskyy 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.

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.

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.

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 2 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.

As shown in Table 2, 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 (Bazilinskyy et al., 2022; 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 3 depicts the environmental, spatial, and temporal attributes and the road user and vehicle characteristics of the scenarios identified in the literature sample.

As shown in Table 3, 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.

Group interviews with traffic safety and automation experts

Five themes and 16 sub-themes were identified in the thematic analysis. Table 4 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.

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:

Table 4
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	More connectivity among road users.
		Changes	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.
		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.

N4: *"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"*.

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 conerns 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:

N2: *"The best is to turn on all your* lights *and wear a reflective vest and still think you are invisible"*.

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:

D3: *"There [should be] a distance* between *parked cars and the cyclists' lane because when they open the doors"*.

N3: *"I also think good separation from other road users…"*

N2: *"And a comfortable surface to cycle on"*.

N3: *"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"*.

N2: *"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"*.

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

N2: *"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"*.

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:

N4: *"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?"*

N3: *"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]"*.

N4: *"I agree that it is like that (…),* comfort *is an overarching term for safety"*.

N2: *"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"*.

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 3.3.1).

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:

D2: *"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"*.

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:

D3: *"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"*.

D1: *"But what do we need as cyclists then?"*

D3: *"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"*.

D2: *"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"*.

D4: *"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"*.

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:

D2: *"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 …"*

Interviewer: *"What if there are* multiple *road users around you?"*

D2: *"The only thing that* can't *be misinterpreted is slowing down, I guess"*.

D3: *"I agree"*.

D2: *"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"*.

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

D2: *"Would it not be* dangerous *to include a light, showing you are detected? Because then you would also assume that it works"*.

D4: *"But if it does detect you…"*

D2: *"Then it will brake, I guess. But if the light is off then it will always…"*

D4: *"At the same time: what if it's detecting something further way?"*

D3: *"It has to detect* ***you****, and not someone else"*.

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

N2: *"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"*.

N3: *"Therefore, one must look for changes in speed and…"*

N2: *"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…"*

N4: *"If you see green and* yellow*, two flashes - it means I've seen you, but I'm going to drive"*.

N2: *"[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"*.

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:

D2: *"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"*.

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:

D4: *"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"*.

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

N1: *"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"*.

D4: *"There will be a group of people who will just trust"*.

D3: *"Some will, but I won't"*.

D2: *"But if you grow up with* automated*"*.

D4: *"That's true"*.

D2: *"But I guess we're now talking about four lifetimes [from now]"*.

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:

D3: *"It's not so much the* technique… *It's a matter of liability". (D3)*

D1: *"Yeah, I think so, too"*.

Interviewer: *"How so? Could you explain the liability?"*

D3: *"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"*.

D4: *"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…"*

D1: *"But it will never happen"*.

D3: *"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"*.

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 VRUs 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.

D4: *"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"*.

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

N3: *"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"*.

N4: *"There are those sudden stops. For quite a while, [the vehicles] will behave differently from* normal *cars and block the road"*.

N3: *"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"*.

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.

D4: *"(…) 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 (…)"*.

D3: *"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"*.

D1: *"Is it going to stop? You still have these different brands: Apple cars will stop immediately; Toyota cars will stop from 30 metres"*.

D3: "Maybe there will *be regulations for that"*.

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.

D2: "*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*".

D1: "*Scenario is* more *the description of what could happen and what has happened*".

D4: "*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*".

D3: "*I think it's a* rather *semantic discussion… and technical field they speak about use cases and the rest of us speak about scenarios*".

D2: "*I think use* cases *is a group of scenarios. I think it's useful to group all intersections*".

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 provides an overview of the scenarios and a description of each scenario.

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.

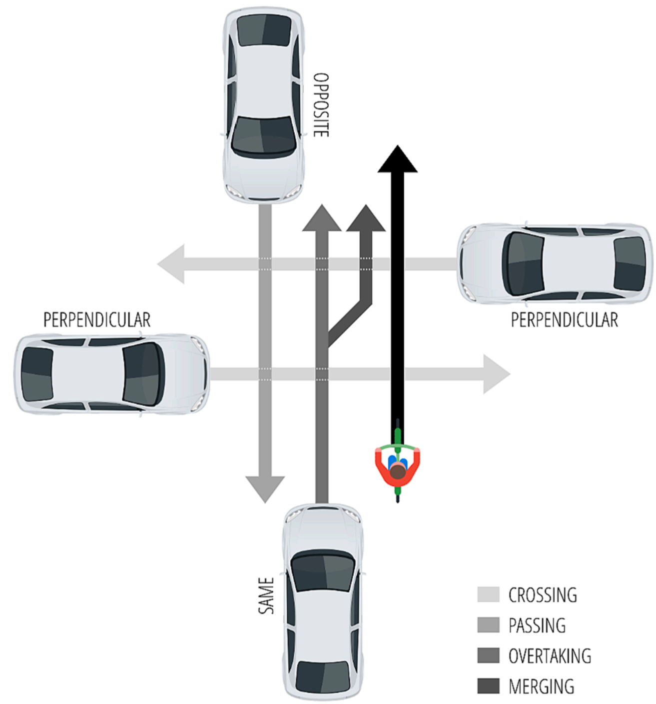

Fig. 2. Illustration of the four scenario groups and the directions of movement. *Note.* The dotted lines indicate that the vehicle can change direction. If more than one vehicle is involved in a scenario, the scenario can belong to more than one group.

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. Fig. 2 illustrates the scenario groups and the directions of movement of the involved parties.

Scenario group 1: Crossing scenarios. Fig. 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.

As seen in Fig. 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

Table 5
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 overtaking	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.

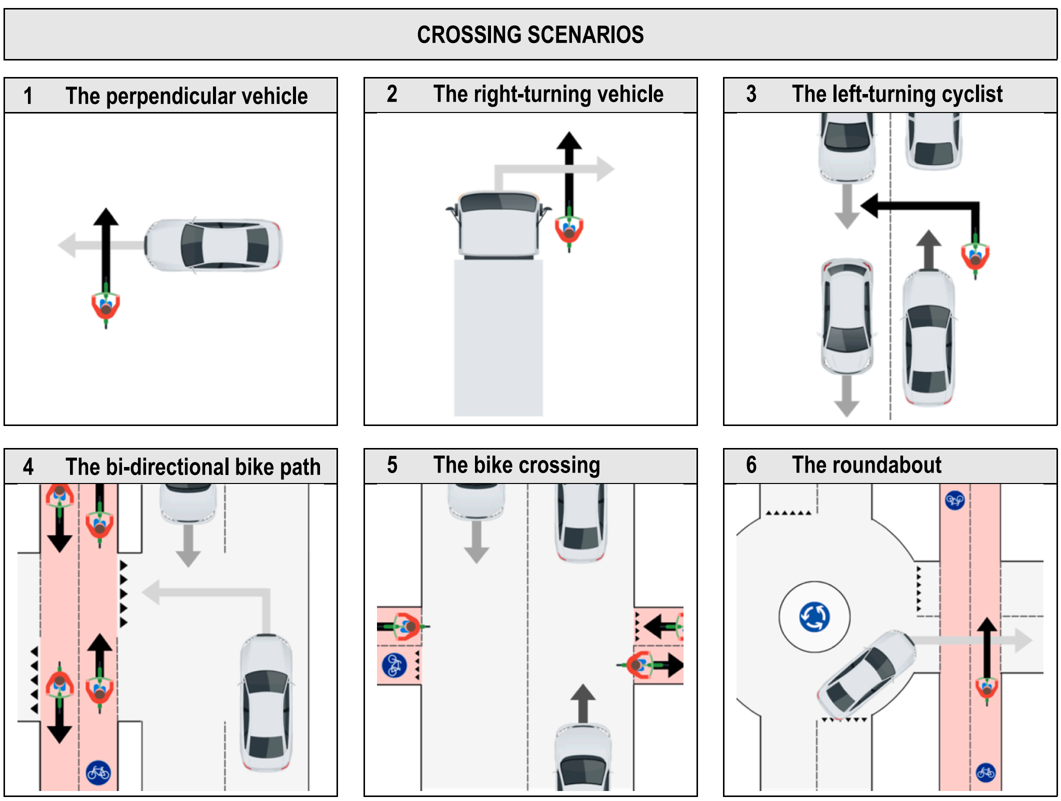

Fig. 3. Illustrations of the six crossing scenarios. *Note.* The infrastructural layouts may vary regarding the number of legs, lanes, and other environmental details (e.g., barriers, traffic signs, colours). In Scenario 1, the vehicle may approach perpendicularly from the left or right. Scenarios 1, 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.

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 Fig. 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.

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 Fig. 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 Fig. 5).

The points of interaction occur before, during, and after the takeover. As seen in Fig. 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. Fig. 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.

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 6 shows the variables identified as potential challenges in the 20 scenarios.

Survey results

The results from the descriptive analysis of the survey with the interviewed traffic safety and automation experts are seen in Table 7, 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 overtaking* (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.

As shown in Table 7, 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

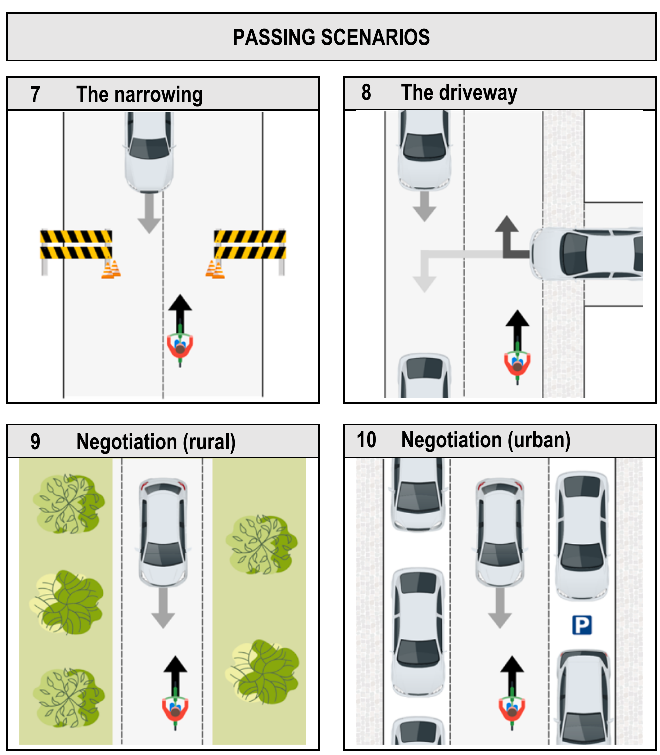

Fig. 4. Illustrations of the four passing scenarios. *Note.* The infrastructural layouts may vary in lanes, vegetation, and other environmental details (e.g., barriers, traffic signs, colours). As indicated by the different shaded arrows of direction, Scenario 8 can be interpreted as a passing, crossing, 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.

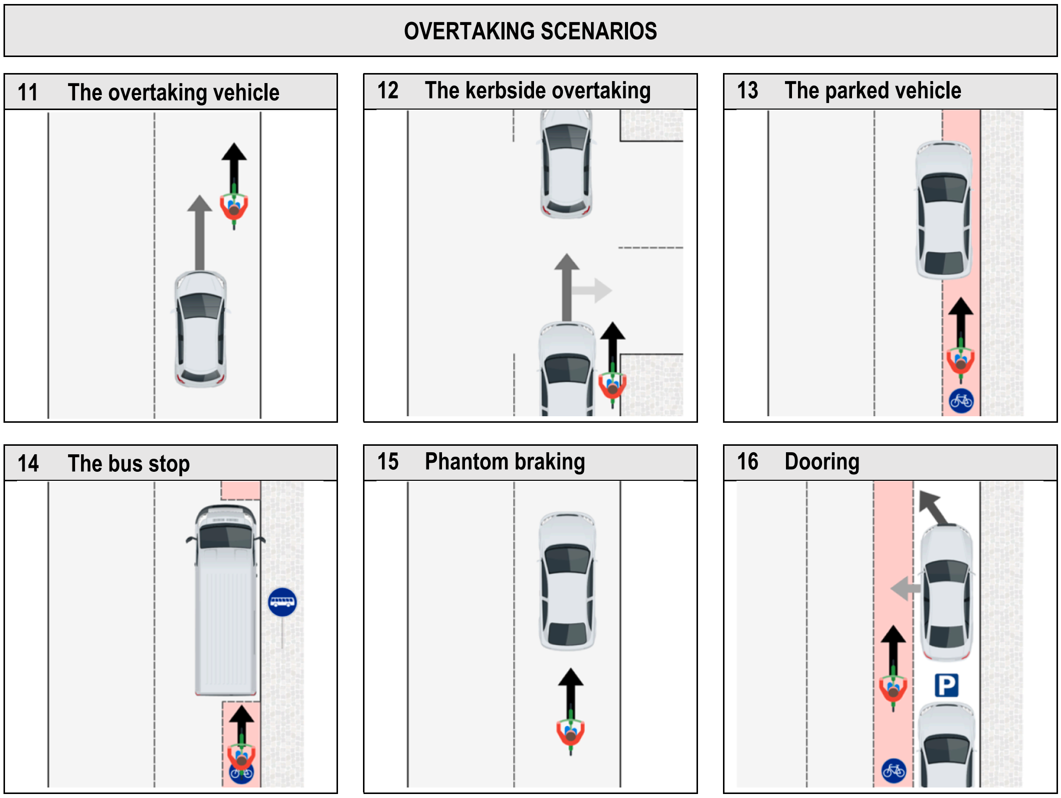

Fig. 5. Illustrations of the six overtaking scenarios. *Note.* The infrastructural layouts may vary in terms of legs, lanes, vegetation, and other environmental details (e.g., barriers, traffic signs, colours).

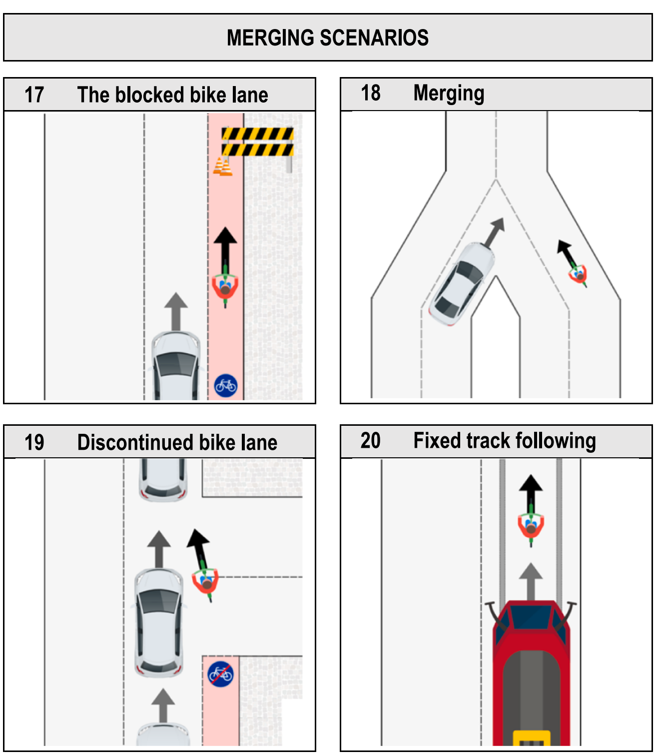

Fig. 6. Illustrations of the four merging scenarios. *Note.* The infrastructural layouts may vary in terms of legs, lanes, vegetation, and other environmental details (e.g., barriers, traffic signs, colours).

Table 6
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

Table 7
The results from the descriptive analysis of the survey with the interviewed experts.

#	Scenario	Accident likelihood	Occurrence	*n*
	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 overtaking vehicle	2.63	−0.57	7
12	The kerbside overtaking	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. The variable was calculated by subtracting the means of *frequency of occurrence in the future* from the means of *frequency of occurrence today* per scenario.

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 7, 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 7). 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.

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 VRUs, 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.

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.

Scenario recommendations

The results from the survey indicated that Scenario 2, T*he 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 overtaking* 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 VRUs, such as cyclists overtaking on both sides of the vehicle (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 VRU 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.

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 and 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 VRUs 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 VRUs such as cyclists and to ensure the safe and reliable operation of automated vehicles.

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 VRUs such as cyclists. For instance, braking early in front of a VRU 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 VRUs 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. (2022) 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 VRU interaction with automated vehicles (De Winter & Dodou, 2022). Still, most eHMIs are designed for and tested on pedestrians (Dey 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.

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 VRUs (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 VRU behaviour. As such, the decision-making of automated vehicles may be based on incorrect expectations of VRU 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 VRUs, 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-VRU interactions with a holistic perspective by comprehensively examining anticipatory behaviours elicited by drivers and VRUs as well as accident and near-miss data.

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 paper. 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.

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.

CRediT authorship contribution statement

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

Data availability

A REFI-QDA Standard project file with anonymised interview transcripts and the thematic analysis and a Microsoft Excel Spreadsheet file with the descriptive analysis of and raw data from the questionnaire are available at 4TU.ResearchData at https://doi.org/10.4121/e4324d0c-2a82-4f03-8cbb-64dd207cd522.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement 860410, the Institute of Transport Economics: Norwegian Centre for Transport Research, SWOV Institute for Road Safety Research, and The Research Council of Norway.

Appendix A. Interview guide

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 h.

[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)

Do you have anything else to add?

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