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

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ABSTRACT

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

1. Introduction

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

Research on AV-VRU interaction focuses primarily on the effects of eHMIs on the crossing behaviours of pedestrians (Dey et al., 2020; Rasouli and Tsotsos, 2020), on designing the interaction of AVs (Schieben et al., 2019) and on AV acceptance (Merat et al., 2017). When cyclists are included in eHMI studies, they are rarely the main subject of study: None of the eHMI concepts identified by Dey et al. (2020) solely targeted cyclists, and only a few empirical studies focus specifically on

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cyclist interaction with AVs (Bazilinskyy et al., 2023; Berge et al., 2022a; Hagenzieker et al., 2020; Hou et al., 2020; Kaβ et al., 2020; Rodríguez Palmeiro et al., 2018; Utriainen and Pöllänen, 2021; Nuñez Velasco et al., 2021; Vlakveld et al., 2020). Cyclists are vulnerable road users (Holländer et al., 2021), but differ from pedestrians in eye-gazing behaviour. Trefzger et al. (2018) found that cyclists are more preoccupied with looking on the road and gaze less frequently at vehicles than pedestrians. Cyclists also differ in speed and movement patterns compared to pedestrians: While pedestrians usually interact with vehicles at crossings, cyclists regularly share the road and travel parallel to vehicles, experiencing passing, merging, and overtaking situations (Berge et al., 2023). To ensure the safety of cyclists in automated traffic, targeting them as a specific road user group in research is vital. Currently, there is no overview of technologies and solutions for cyclists to improve their interaction with AVs.

With transport systems increasingly becoming part of the Internet of Things (IoT) (Behrendt, 2019), it has been suggested that interconnectivity between infrastructure, AVs, conventional vehicles, and VRUs is essential for the successful full-scale deployment of AVs (Farah et al., 2018; Sanchez et al., 2016). Interconnectivity could increase visibility among road users, making them mutually aware of each other's locations and trajectories, which in turn could be a significant safety improvement (Owens et al., 2018), resulting in a reduction in conflicts and better traffic flow (Papadoulis et al., 2019). At the same time, the rising security and privacy issues accompanying VRU connectivity tend to be overlooked and understudied (Hasan and Hasan, 2022). Although some researchers have questioned whether VRUs should depend on additional devices for safety in traffic with AVs (Berge et al., 2022a; Tabone et al., 2021), the discussion in academic and media circles regarding the ethical considerations surrounding connectivity for VRUs remains limited. In light of the proliferation of IoT and technological advances, it is plausible to expect that most new devices will have some form of connectivity in the near future. Therefore, we argue that a technological approach to support systems for cyclists merits further investigation in research, to establish a foundation for future studies and promote ethical discourse.

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

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

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

2. Methods

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

2.1. Selection of literature

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

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

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

2.2. Sample

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

2.3. Analysis and coding of concepts

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

The full classification taxonomy was applied to each of the 92 identified concepts. The physical and functional characteristics of the concepts were coded based on the descriptions or information available in the publications, varying from text and illustrations, to photos, animations, and videos demonstrating the concept in use. Certain concepts had multiple features, e.g., a concept could have HMI placements as an on-bike device and a cyclist wearable and utilise more than one modality of communication. Each of these features was recorded with separate values divided by commas within the applicable sub-categories. The variables pertaining to usability and realism in real-world traffic, such as *11. Complexity of implementation,* required interpretation during coding and relied on the coder's knowledge and understanding of the feasibility of the technology available today. The data from the 92 concepts were analysed descriptively using frequency counts and pivot tables in Microsoft Excel.

2.4. Taxonomy definitions

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

In total, there are 13 taxonomical categories used for coding the concepts: terminology, target road user, HMI placement, number of interfaces, number of messages, modality of communication, communication strategy, connectivity, functionality, type of concept, the complexity of implementation, support for people with special needs, and finally, concept evaluation. Table 1 shows an overview of the variables and their definitions. The variables directly adapted from Dey et al. (2020) are noted in the table. A full description and rationale of the variables can be found in Appendix B.

3. Results

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

3.1. Terminology

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

3.2. Target road user

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

Table 1
Taxonomy definitions.

	Variable	Definition
1	Terminology	The words used to describe a concept.
2	Target road user	The type of road user targeted by a concept.
3	HMI placement	The location of the interface or location of the message conveyed to its intended recipient.
3.1	Cyclist wearables	The interface is located on the cyclist.
3.2	On-bike devices	The interface is located on the bicycle.
3.3	Vehicle systems	The interface is located on or within the motorised vehicle.
3.4	Infrastructural systems	The interface is located on infrastructure.
4	Number of interfaces	The number of modalities capable of communicating a piece of information between the system and the human road user(s).
5	Number of messages	The number of messages communicated through an interface. Adapted from Dey et al. (2020).
6	Modality of communication	The way communication is achieved by a concept.
6.1	Visual	The concept communicates through visual perception and sight.
6.1.1	Colour	The colour of visual modalities.
6.2	Auditory	The concept communicates through the sense of hearing.
6.3	Motion	The concept communicates through the action or process of moving or being moved.
6.4	Wireless	The message is delivered through a signal transmission on a frequency spectrum.
7	Communication strategy	The way the system addresses road users when communicating its message. Adapted from Dey et al. (2020).
7.1	Unicast	The system communicates and delivers its messages targeted to a single road user.
7.2	Broadcast	The system broadcasts its messages to non-targeted road users.
7.3	Multicast	The system targets and delivers its message to multiple road users at the same time.
8	Connectivity	The concept has the capacity for interconnection by signal transmission between systems or users.
9	Functionality	The intended functionality or purpose of the message(s) communicated to its recipient(s).
9.1	Information systems	Systems informing road users about a particular arrangement or sequence of events.
9.2	Warning systems	Systems intending to convey messages of caution or urgency to their users.
9.3	Support systems	Systems conveying messages with a behavioural component of the cyclist or bicycle to its user, such as information about a cyclist's current or future behaviour.
10	Type of product	The concept stage of development (i.e., whether it is conceptual, a prototype, or an end product).
11	Complexity of implementation	The complexity of implementing a concept in real traffic scenarios. Adapted from Dey et al. (2020).
11.1	Ready to use	Technology is ready to use today.
11.2	New technology required	The concept requires new technology but does not depend on widespread implementation or infrastructural changes to function.
11.3	New technology and large-scale changes required	The concept requires new technology but depends on widespread implementation or infrastructural changes to function.
11.4	Highly aspirational	The concept uses technology that is not yet developed or available.
12	Support for people with special needs	The concept accommodates the special needs of visually, auditory, or cognitively impaired persons through multimodal

(*continued on next page*)

Table 1 (*continued*)

	Variable	Definition
		communication. Adapted from Dey et al. (2020).
13	Evaluation of concept	The concept has been evaluated in a scientific publication. Adapted from Dey et al. (2020).

3.3. HMI placement

The most common placement of the system or interface was cyclist wearables (39% of all concepts), closely followed by on-bike devices (38% of all concepts) and vehicle systems (33% of all concepts). About one in four concepts had placements on infrastructure or projections on infrastructure. One out of three concepts was categorised as having more than one placement. For instance, De Angelis et al. (2019b) describe a multi-agent system with a display mounted on the bicycle's handlebars and a display placed on infrastructure. Another example by Matviienko et al. (2018, 2019a, 2019b) portrays a wearable system with interfaces embedded in the cyclist's helmet and on the bicycle's handlebars. Fig. 1 shows an overview of the HMI placement of the concepts categorised as cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems.

3.4. Number of interfaces and messages

Table 2 shows the number of interfaces and messages identified in the analysis. The analysis showed 41 concepts (45%) with one interface conveying messages to a recipient. The other half of the concepts used more than one interface for communication: two (25 concepts, 27%), three (10 concepts, 11%), four (8 concepts, 9%), and more than four (4 concepts, 4%). It was not possible to count the exact number of interfaces for four concepts, which were marked as unclear.

Table 2
Number of interfaces and messages of concepts.

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

Note. N = 92.

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

3.5. Modality of communication

The most common communication modality was visual with abstract/light (54% of visual concepts). For instance, a concept coded as visual and abstract/light could describe a light blinking on the bicycle's handlebars or an abstract shape that does not resemble text, symbols, or anything anthropomorphic projected on the ground. As seen in Fig. 2, four out of five concepts communicated their message visually. For

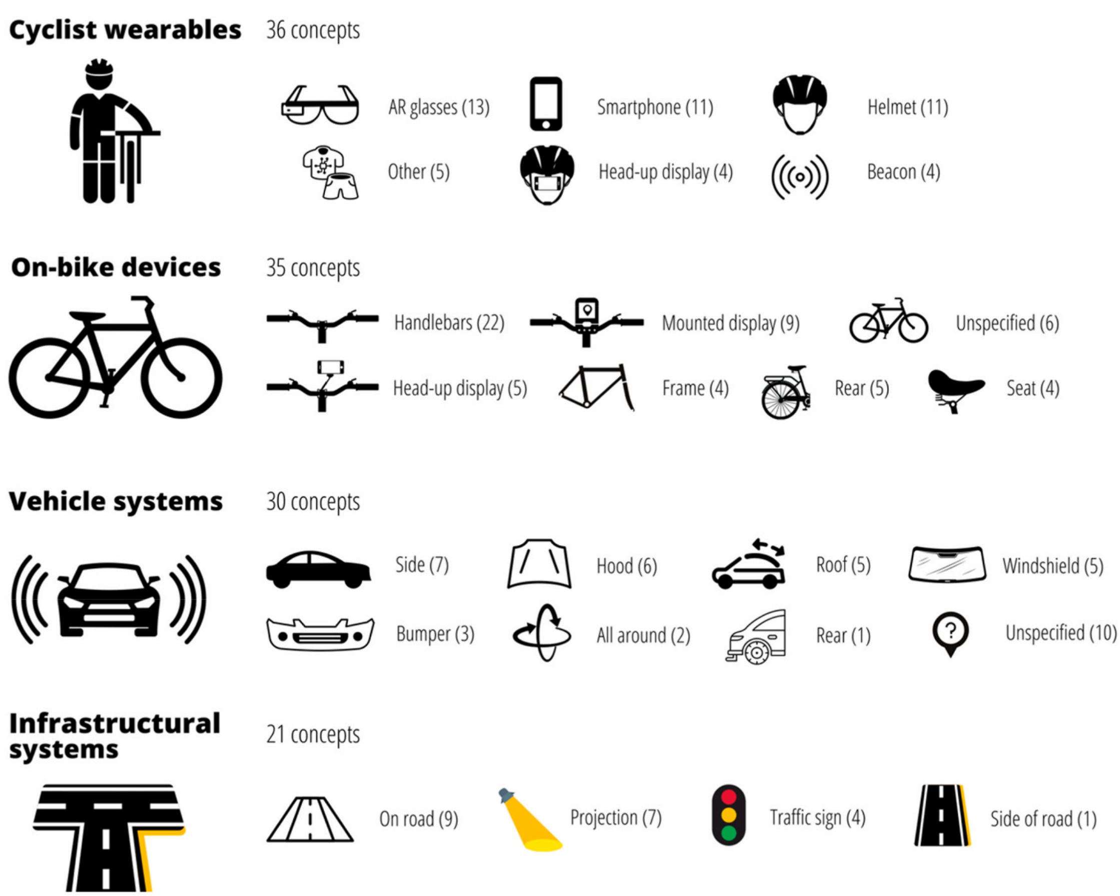

Fig. 1. An overview of the 92 concepts categorised according to their placement on the cyclist (wearables), bicycle, vehicle, or infrastructure.
Note. As a concept could be a multi-agent system, a concept can be categorised into more than one category.

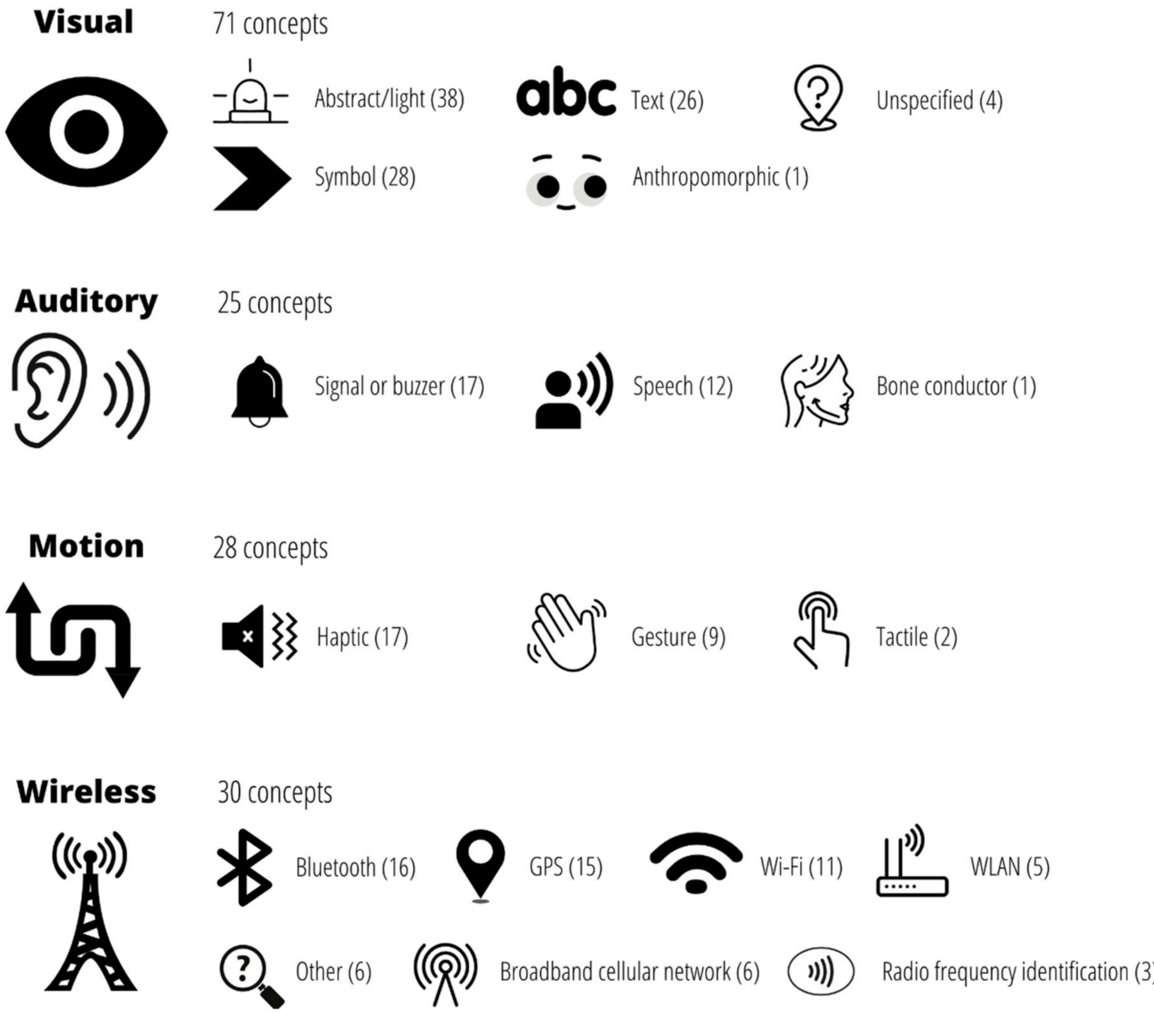

Fig. 2. An overview of the modalities of communication identified in the concepts.
Note. N = 92. As a concept could communicate through more than one interface, a concept could be categorised into more than one category. Four concepts coded as having an unspecified mode of communication are not represented in the figure.

visual interfaces, red (19%), green (18%), and yellow (13%) were the most common colours used (see Fig. 3).

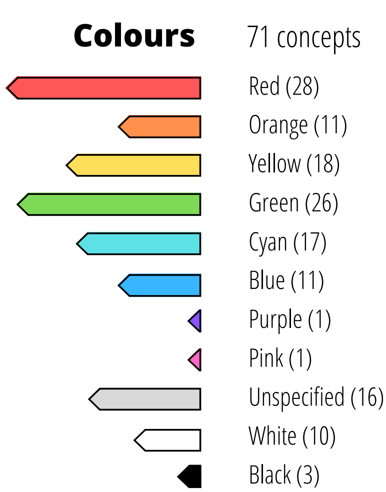

Fig. 3. The colours used in the 71 visual concepts. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Note. A concept could be coded with more than one colour.

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

There is potential for road user connectivity in 41% of the concepts: 38 of 92 concepts described a connectivity feature or technology with the potential of connecting multiple agents to transmit messages. As seen in Fig. 2, concepts specifying wireless communication utilised technology such as Bluetooth (53%), GPS (50%), and Wi-Fi (37%). Six concepts had wireless as their only communication mode and were typically cooperative communication systems or vehicle-to-everything systems.

Table 3 shows the results from the pivot table analysis of the concepts' HMI placement and modality of communication. Almost all concepts with interfaces on infrastructure used a visual mode of communication. Visual mode of communication was the most common modality for on-bike devices (77%, 27 out of 35 concepts) and vehicle systems (77%, 23 out of 30 concepts). Wireless and visual were the most common modes of communication for cyclist wearables (64%, 23 out of 36 concepts, respectively). When opting for a motion-based mode of communication, the interface of choice was mainly on bicycles (78%, 18 out of 23 concepts).

Table 3
Pivot table of HMI placement and modality of communication.

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

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

3.6. Communication strategy

We investigated whether the concepts used targeted or non-targeted communication strategies and whether they address single or multiple road users. Table 4 shows that half of the concepts targeted a single road user (47 out of 92 concepts), while 41% (38 out of 92 concepts) broadcasted their messages, and 23% (21 out of 92 concepts) targeted their communication to multiple users. The majority of cyclist wearables and on-bike devices delivered messages to a targeted, single road user. About two out of three vehicle systems broadcasted their messages to multiple road users in a non-targeted manner.

3.7. Functionality

The 92 concepts were categorised into three groups of systems based on their functionality: information systems, warning systems, and support systems. A system could be classified as having more than one function and therefore coded within more than one system sub-group. Fig. 4 shows an overview of the functionality of the concepts.

As seen in Fig. 4, two-thirds of the concepts were coded as information systems. However, the most common functionality among the concepts was a warning system communicating an alert of an imminent or potential conflict or collision (36% of all concepts). For instance, the smart bicycle helmet concepts by Von Sawitzky et al. (2021) warned the cyclist of the potential door opening of parked cars on the side of the road, while Matviienko et al.'s (2018) helmet and bicycle warning concept for children warned the user of a potential left or right collision at junctions, as well as vehicles appearing from behind obstacles. Eight of the concepts (17% of the 46 warning system concepts) were warning systems about other road users approaching from the rear. Engbers et al.'s (2018) front and rear-view assistant concept for older cyclists was coded as both conflict or collision and approaching from the rear, as the concept involved a bicycle equipped with a radar detecting road users from the front of the bicycle, as well as a camera detecting road users approaching the cyclist from behind.

Table 4
Pivot table of HMI placement and communication strategy.

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

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

One out of four concepts was categorised as a warning system and the sub-category *other*, see Fig. 4. These concepts describe systems that warned the user of an unspecified event without indicating that the event is a collision or conflict.

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

Table 5 shows the results of the pivot table analysis of HMI placement and functionality. Almost all vehicle systems (97%, 29 out of 30 concepts) and infrastructural systems (85%, 18 out of 21 concepts) had functionality coded as an information system. The main functionality of information systems concepts is to inform the user or other agents in the system of an entity, object, or event. For instance, the six-vehicle system concepts by Dey et al. (2018) all aimed to inform VRUs about the vehicle's current or future behaviour. De Angelis et al. (2019b)'s concepts involved different types of interfaces placed on infrastructure, showing countdown timers for a green light.

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

3.8. Type of concept

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

3.9. Complexity of implementation

The results from the descriptive analysis show that almost half of the concepts (see Table 6, 38 out of 92 concepts) require new technology that depends on large-scale deployment or infrastructure changes to function in future roads with automated vehicles. About one in five concepts require new technology without large-scale deployment or changes, and 34% (31 out of 92 concepts) can use technology today. Only 4% of the concepts are highly aspirational, awaiting the development of novel technology. As seen in Table 6, more concepts using wireless communication require large-scale deployment or changes to work (63%, 19 out of 30 wireless concepts).

3.10. Support for people with special needs

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

3.11. Evaluation of concepts

Out of the 92 concepts, 50 were evaluated in a scientific publication. About half of the concepts were evaluated quantitatively, while 38% used mixed methods involving objective data as well as qualitative data like interviews or observations. Table 7 provides an overview of the results from the descriptive analysis of eight coded categories for the evaluation of the concepts.

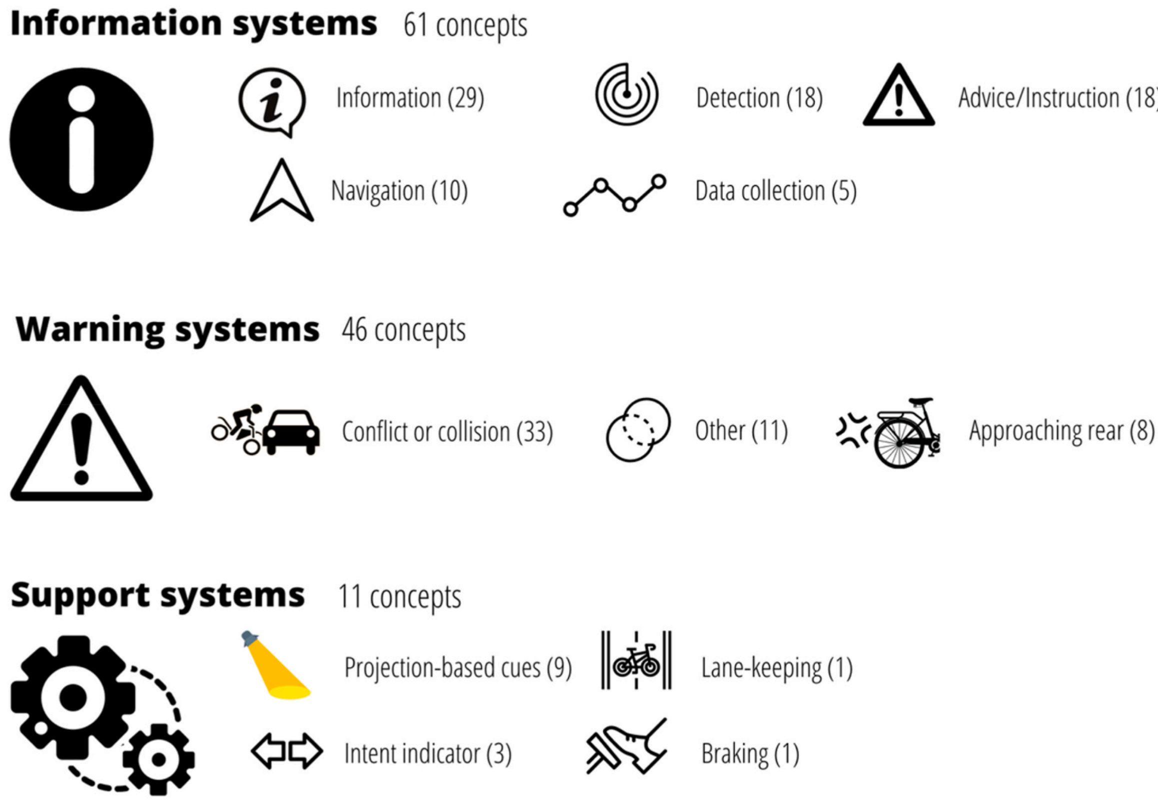

Fig. 4. Overview of the coding results for functionality.
Note. N = 92. As a concept could have more than one function, a concept can be categorised into more than one category.

Table 5
Pivot table of HMI placement and functionality.

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

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

Table 6
Pivot table of the modality of communication and complexity of implementation.

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

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

Most concepts were evaluated in a simulated, virtual, or digital environment, with a total of 72% of the concepts evaluated in one of these environments. In half of the evaluations, the type of scenario was not specified. 26% of the scenarios identified had no interaction with other road users. Out of the scenarios with interaction, the most common scenario was a vehicle approaching the cyclist from a perpendicular direction. When specified, almost all concepts were evaluated in daylight, most in indirect sunlight with clean roads, meaning there was no rain or ice on the road (see Table 7). It was most common to test concepts in non-segregated traffic; there was no bike lane in 44% of the concepts. About one in four evaluations had scenarios with a separate bike path.

Table 8 shows that the scenarios used for prototype evaluation were relatively simple; only 6% involved more road users than the cyclist and a vehicle, and 12% involved two vehicles or more throughout the entire scenario. Interestingly, 12% of the evaluations did not involve a cyclist. These concepts were evaluated using photos of infrastructure and the bicycle's handlebars, with no cyclists or vehicles present, such as the concepts by De Angelis et al. (2019b).

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

Table 7
The method, type of data collection, scenario setup, task of cyclist, time of day, weather conditions, cycling infrastructure, and road condition used in the evaluation of the concepts.

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

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

Table 8
The number of simultaneous road users and vehicles per trial.

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

Note. N = 50.

nine and ten, while three included elderly cyclists with an average age of 70.

4. Discussion

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

4.1. Type of systems

4.1.1. Cyclist wearables

From the 92 concepts, the most common systems were cyclist wearables and on-bike devices. Cyclist wearables are usually lightweight and can be utilised across bicycles. One in three cyclist wearable concepts was embedded in a helmet. HindSight, for instance, is a concept in which a camera on the cyclist's helmet notifies the cyclist of approaching road users outside the cyclist's field of view (Schoop et al., 2018). Moreover, thirteen of the cyclist wearable concepts in this study used AR to communicate with the cyclist, and five of these concepts were already commercially available AR glasses (Cosmo Connected, 2022; Everysight, 2022; Garmin, 2022a; Julbo, 2022; Solos Smartglasses, 2018). AR technology enhances the real-world environment by adding a virtual layer of computer-generated perceptual information in real-time (Milgram and Kishino, 1994). Among the academic conceptual concepts, Von Sawitzky et al.'s (2020b) augmentation concepts create a digital overlay of a smart bicycle path indicating whether the gap allows for safe crossing, while a later concept warns the cyclist of a potential vehicle door opening ahead (Von Sawitzky et al., 2021).

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

4.1.2. On-bike devices

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

4.1.3. Vehicle systems

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

4.1.4. Infrastructural systems

Out of the 92 concepts identified in our study, 21 were infrastructural systems that communicated with the system's user through interfaces on the road surface, projections, or traffic signs. Eighteen of the infrastructural systems were coded as information systems, aiming to inform the user about a particular arrangement or sequence of events. The main function of these systems was to detect elements or entities in the cyclist's environment or advise or instruct the cyclist on desired behaviour through normative messages. Traditionally, traffic lights, signs, and markings regulate road users' normative behaviour. In a survey on the effect of text, colour, and perspective of eHMIs, egocentric interfaces instructing the user to "walk" or "stop" were regarded as clearer than allocentric displays informing the user of the vehicle's intended behaviour (e.g., the vehicle displaying it "will stop" or "will not stop") (Bazilinskyy et al., 2019). Communicating through designs and interfaces familiar to users, such as traffic signs or road markings, may relieve cognitive load and shorten the learning process and is in line with the design principles of consistency (see Constantine and Lockwood, 1999; Norman, 2013). When designing a system to support cyclists in automated traffic, it would be recommended to rely on the modes of communication and messages the cyclists are familiar with. Nevertheless, incorporating messages about AV behaviour into normative infrastructural systems may have legal implications from a liability point of view: Advising an action from VRUs based on AVs' behaviour may be particularly challenging when the AV encounters multiple cyclists or pedestrians as there can be confusion as to which road user the AV is addressing (Bazilinskyy et al., 2019; Tabone et al., 2021).

4.2. Modality of communication

4.2.1. Visual communication

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

The majority of the cyclist wearables communicated visually. AR glasses communicating visually offer unicast and individualised messages to the user, alleviating the uncertainty as to which road user is addressed when a message is broadcast by an on-vehicle eHMI. The functionality of academic AR prototype concepts could potentially be integrated into commercially available AR glasses and be utilised to improve the interaction of cyclists and vehicles, both conventional and automated. Although no differences in perceived safety or mental workload were noticed, augmented warning messages caused cyclists to increase their distance from a potential hazard earlier than swerving when a hazard occurred (Von Sawitzky et al., 2021). Similar augmentation concepts for supporting pedestrians' crossing behaviour in automated traffic have been suggested (Hesenius et al., 2018; Tabone et al., 2021, 2022).

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

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

4.2.2. Auditory communication

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

4.2.3. Motion-based communication

Half of the on-bike concepts in our study use motion-based communication, mostly through the use of vibro-haptic feedback in the handlebars or bicycle seat. While visuotactile communication methods like touch screens may not be a feasible cyclist support system, combining visual cues with haptic feedback may be a solution for complex situations with a high mental workload: Visuo-haptic, multimodal communication was found to be more effective for multiple tasks in high workload conditions (Burke et al., 2006). Eight of the concepts identified in our study were categorised as warning systems for alerting the cyclist of another road user approaching from behind, and half of these concepts used motion-based communication to alert the cyclist. Engbers et al. (2016) found that haptic feedback had a higher acceptance rate than visual warnings. The system received similar positive feedback in a later study, where haptics was described as intuitive and easy to distinguish from vibrations caused by the cycling itself (Engbers et al., 2018). Using haptics to warn about other road users approaching from the rear may benefit situational awareness, particularly in rural areas where other road users do not frequently approach from behind. In urban environments with a higher sensory input, however, cyclists may find a passive system that does not notify the user less strenuous: In a study on passive versus active on-bike warning systems, the participants preferred a passive system alerting the vehicle rather than the cyclist over a system eliciting audio-visual or haptic warnings (De Angelis et al., 2019a).

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

4.2.4. *Wireless communication*

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

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

4.3. *Knowledge gaps and recommendations for future research*

4.3.1. *On-vehicle eHMIs targeting cyclists*

With conventional vehicles equipped with intelligent transport systems like detection, lane-keeping, and braking systems, and automated vehicles with their lidar and radar sensors and continuously developed algorithms, the necessity of on-vehicle cyclist support systems like eHMIs can be questioned. In their position paper, De Winter and Dodou (2022) conclude that road users seem to want and accept eHMIs, as eHMIs can add to implicit communication and fill the void of social interaction with driverless vehicles in terms of eye contact. Moreover, eHMIs have the potential to communicate multifaceted messages, indicating the vehicle's functional state, both in terms of sensors and whether the automated system is active (De Winter and Dodou, 2022). In sum, vehicle systems such as eHMIs seem to be a welcomed addition that could potentially enhance VRU interaction with AVs.

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

4.3.2. *The effect of modality on performance and safety*

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

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

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

4.3.3. *Increased complexity and representative test scenarios*

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

4.3.4. *The implications of connected VRUs and inclusive transport systems*

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

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

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

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

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

5. Limitations

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

Most of the concepts identified in our study have not been tested or evaluated with AVs. Interpreting the need for and necessity of the systems based on the results from evaluations with or without other road users is challenging. However, in the new and emerging field of AV-cyclist interaction, we argue that the inclusion of concepts not primarily designed for vehicle interaction is beneficial if the concept technology is deemed to have the potential to be adapted for use with vehicles. In our study, we define potential as the ability of the technology or device to be developed or adapted for use in the context of vehicles with automation capabilities beyond SAE level 2. For instance, the Bicycle Light Communication System by Westerhuis et al. (2021) is intended to support cyclists in traffic with other cyclists by displaying their speed, braking, and turning intentions. Although the concept was tested and evaluated in the context of cyclists, the information emitted by the light communication system could be interpreted by AV sensors and used to calculate cyclists' behaviour and trajectories. Other concepts, such as the on-bike warning system by Erdei et al. (2021), were evaluated in the context of testing signal perception and the effects of communication modalities among cyclists. The authors argued that warning systems could increase cycling safety by informing the user of imminent critical situations related to other road users or high-risk cycling conditions, but they did not specify the exact functionality of their warning system. Still, such proof-of-concept studies show the potential for further development of cyclist support systems in the context of conventional motorised vehicles and AVs. The inclusion of concepts that have not been tested nor evaluated with AVs in the present study provides a broader overview of the technologies available to cyclists. A broader overview contributes to uncovering more knowledge gaps in the literature and may be beneficial to future research, testing, and development of concepts for supporting cyclists in future automated traffic.

6. Conclusion

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

CRediT authorship contribution statement

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

Research data

A document containing the sample and coding of the concepts is available at the 4TU.ResearchData repository at https://doi.org/10.4121/c.6202309.

Declaration of competing interest

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

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This project was presented as a poster with an extended abstract at the 10th International Cycling Safety Conference (Berge et al., 2022b).

Appendix A. List of included publications

	Reference	Publication type	Location
1	Benderius et al. (2018)	Journal article	Sweden
2	Boreal Bikes GmbH (2021)	Commercial/industry publication	Germany
3	Céspedes et al. (2016)	Conference paper	Chile, Colombia
4	Cohda Wireless (2017)	Commercial/industry publication	Australia
5	Colas (2017)	Commercial/industry publication	France
6	Cosmo Connected (2022)	Commercial/industry publication	France
7	Dancu et al. (2015)	Conference paper	Sweden
8	De Angelis et al. (2019a)	Conference paper	Italy
9	De Angelis et al. (2019b)	Journal article	Italy
10	Delft University of Technology (2021)	Commercial/industry publication	Netherlands
11	Dey et al. (2018)	Conference paper	Netherlands
12	Engbers et al. (2018)	Journal article	Netherlands
13	Engbers et al. (2016)	Journal article	Netherlands
14	Engel et al. (2013)	Conference paper	Germany
15	Englund et al. (2019)	Conference paper	Sweden
16	Erdei et al. (2020)	Journal article	Germany
17	Erdei et al. (2021)	Journal article	Germany
18	Everysight (2022)	Commercial/industry publication	Israel
19	Ford Motor Company & Virginia Tech Transportation Institute (2017)	Commercial/industry publication	USA
20	Garmin (2022a)	Commercial/industry publication	USA
21	Garmin (2022b)	Commercial/industry publication	USA
22	General Motors (2012)	Commercial/industry publication	USA
23	Ginters (2019)	Conference paper	Latvia
24	Grimm et al. (2009)	Patent	USA
25	Hagenzieker et al. (2020)	Journal article	Netherlands
26	Harrison (2011)	Patent	Australia
27	Heijmans (2022)	Commercial/industry publication	Netherlands
28	Hernandez-Jayo et al. (2016)	Poster	Spain
29	Hou et al. (2020)	Conference paper	Canada
30	Jenkins et al. (2017)	Conference paper	USA
31	Jones et al. (2007)	Conference paper	USA
32	Julbo (2022)	Commercial/industry publication	France
33	Kaβ et al. (2020)	Conference paper	Germany
34	Kiefer and Behrendt (2016)	Journal article	UK
35	Liebner et al. (2013)	Conference paper	Germany
36	Lindström et al. (2019)	Conference paper	Sweden
37	Matthiesen et al. (2018)	Patent	USA
38	Matviienko et al. (2018)	Conference paper	Germany
39	Matviienko et al. (2019a)	Conference paper	Germany
40	Matviienko et al. (2019b)	Conference paper	Germany
41	Nissan Motor Corporation (2015)	Commercial/industry publication	Japan
42	Oczko et al. (2020)	Conference paper	Germany
43	Prati et al. (2018)	Journal article	Italy
44	Rashdan et al. (2020)	Conference paper	Germany
45	Raβhofer et al. (2007)	Book section	Germany
46	Schaffer et al. (2012)	Journal article	Germany
47	Schoop et al. (2018)	Conference paper	USA
48	Shin et al. (2013)	Conference paper	Taiwan

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(*continued*)

	Reference	Publication type	Location
49	Solos Smartglasses (2018)	Commercial/industry publication	USA
50	SWARCO (2022)	Commercial/industry publication	Denmark
51	Terranet (2021)	Commercial/industry publication	Sweden
52	Tome Software (2019)	Commercial/industry publication	USA
53	Toyota Motor Engineering and Manufacturing North America Inc (2016)	Patent	USA
54	Umbrellium (2017)	Commercial/industry publication	UK
55	Verstegen et al. (2021)	Conference paper	Netherlands
56	Vlakveld et al. (2020)	Journal article	Netherlands
57	Von Sawitzky et al. (2020a)	Conference paper	Germany
58	Von Sawitzky et al. (2021)	Journal article	Germany
59	Von Sawitzky et al. (2020b)	Conference paper	Germany
60	Westerhuis et al. (2021)	Journal article	Netherlands
61	Yoshida et al. (2015)	Conference paper	Japan
62	Van Brummelen et al. (2016)	Conference paper	Canada

Appendix B. Taxonomy definitions

1. Terminology

In this category, we map the words used to describe a concept. The terminology was deduced from the title, abstract, or keywords of the academic articles. For commercial concepts, the terminology was chosen from the words used to describe their product.

2. Target road user

This dimension pertains to the type of road user targeted by a concept. Cyclists are the main road user group of interest in this study; however, a concept could target more than one type of road users. Other relevant road users targeted are pedestrians and the vehicles themselves, including the driver or onboard passenger.

3. HMI placement

This category describes the location of the interface conveyed messages to its intended recipient. If a concept offers multimodal communication, all locations of the interfaces are categorised, meaning that a concept could have more than one placement. The placement of the concepts was further divided into four subcategories: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems.

3.1 Cyclist wearables

A concept is categorised as a cyclist wearable if the communication device is located on the cyclist. A cyclist wearable is subcategorised as a helmet, smartphone, AR-glasses, a head-up display mounted on the helmet, a beacon or tag that was not specified as a smartphone, or as other, which included backpacks and belts.

3.2 On-bike devices

To be categorised as an on-bike device, the system or interface of communication is located on the bicycle. More specifically, concepts categorised as on-bike devices had HMI placements such as on the handlebars, a mounted display between the handlebars, a head-up display extended from the handlebars, and systems placed on the frame, seat, and rear of the bicycle. The category 'unspecified' includes concepts mentioning placement on the bicycle but without pinpointing the exact location.

3.3 Vehicle systems

In this category, the communication device is located on or within the motorised vehicle, either on the bumper, hood, rear, roof, side, windshield, or all around the vehicle. Concepts described as being on or in the vehicle without specifying the exact placement were coded as unspecified.

3.4 Infrastructural systems

Within this category, the interface with the message of communication is located on infrastructure, e.g., a traffic sign, on the road, or on the side of the road. Devices using projections were also categorised as infrastructural systems, as the message of communication is communicated on an infrastructural surface like the road.

4. Number of interfaces

We counted the number of interfaces identified within a concept in this category. An *interface* can be defined as a relation between two distinct entities selectively allowing communication of information from one entity to the other. In other words, an interface allows a user to interact with a device, program, or machine. The number of interfaces is distinguished by the number of modalities capable of communicating information between a machine and a human road user. For instance, a concept alerting the cyclist through vibrating handlebars and a signal from a speaker would be counted as two interfaces: one on the handlebars and one through the speaker.

5. Number of messages

This category describes the number of different messages communicated through an interface. An interface can transmit multiple messages, but only one message at a time. As in Dey et al. (2020), the number of messages is coded as one message if the same message is communicated through multiple interfaces independently or simultaneously (e.g., a light on the handlebars of the bicycle paired with haptic feedback in the seat, both conveying the same message). If an interface conveys a message as a continuous process (e.g., projected lights around a bicycle, changing colours indicating the proximity of other road users or entities in the environment), it is also coded as one message.

6. Modality of communication

Modality of communication describes how communication is achieved by a concept and is classified as visual, auditory, motion, or wireless means of communication. Multimodal concepts are categorised by all forms of communication, meaning a concept could be categorised within more than one sub-category.

6.1 Visual

This category pertains to retrieved concepts that communicate through visual perception and sight. Visual modalities are coded according to the following sub-categories.

- **Anthropomorphic:** The concept communicates visually using a human form or attributes, like a waving hand.
- **Abstract/light:** Abstract visual shapes or light-based modalities communicating intuitively through an open-to-interpretation interface without the specific use of text, symbols, or anthropomorphic shapes, e.g., a blinking light on the bicycle's handlebars.
- **Symbol:** The use of recognisable and commonly used symbols like a stop sign, zebra crossing lines, arrows, or other types of symbols used to communicate.
- **Text:** The explicit use of text or numbers on an interface, e.g., advice or instructions such as "go", "stop", or "safe to pass", or information-based text displaying distance or speed, or a countdown timer with numerical text.
- **Unspecified:** Visual means of communication that are not specified.

Another sub-category of visual modalities of communication is the **colour (6.1.1)** used in these concepts, identified as black, blue, cyan, green, orange, pink, purple/violet, red, white, yellow, and unspecified.

6.2 Auditory

Concepts communicating through the sense of hearing are categorised as auditory. The following sub-categorised are used to describe auditory modalities.

- **Speech:** Communication is expressed as articulate sounds, e.g., a voice instructing the cyclist to "turn left now" or a cyclist using voice-based commands to control a system.
- **Signal or buzzer:** The use of a non-speech-related audio signal or buzzing noise.
- **Bone-conductor:** Audio transmitted by sound waves vibrating bone. While bone conduction could be considered a motion-based modality of communication, we have chosen to place it as a sub-category of auditory modalities as it is difficult for the user to distinguish between sound conducted through bone compared to via air.

6.3 Motion

Concepts communicating through the action or process of moving or being moved would be categorised as using motion as their modality of communication. Furthermore, motion is sub-categorised into three categories.

- **Haptic:** The technology actively applies force, vibration, or motion to communicate with the user, e.g., vibrating handlebars or bicycle seat.
- **Tactile**: The message of communication is tangible; delivered through touch, e.g., the cyclist communicates a message to a system by pressing a button.
- **Gesture:** Gesture-based communication, such as a display with a waving humanoid or a cyclist using hand or head movements to communicate with a system.

6.4 Wireless

Concepts categorised as wireless deliver their message of communication through signal transmission on a frequency spectrum. Wireless is categorised according to the technology utilised to transmit the message.

- **GPS:** Global Positioning System, a satellite-based radio navigation system.
- **Bluetooth:** Short-range wireless technology standard for exchanging data between fixed and mobile devices.
- **Wi-Fi:** Wireless fidelity trademarked; wireless network protocols based on the IEEE 802.11 family of standards.
- **WLAN:** Wireless local area network, without specifying they are based on the IEEE 802.11 standard.
- **Broadband cellular network:** 3G, 4G, and 5G.
- **Radio frequency identification:** Radio waves to identify a tagged object passively.
- **Other:** Global Navigation Satellite System (without specifying the system uses GPS), real-time locating systems (RTLS), dedicated short-range communications (DSRC), and Global System for Mobile Communications (GSM).

7. Communication strategy

This category defines how the system addresses road users when communicating messages. It describes whether the communication is targeted or non-targeted and whether the message is intended for single or multiple users (adapted from Dey et al., 2020). The concepts are categorised into three categories, where a concept can communicate in more than one way.

- **Unicast:** The system communicates and delivers its messages targeted to a single road user, e.g., vibrating bicycle handlebars.
- **Broadcast:** The system broadcasts its messages to non-targeted road users, e.g., a light on the rear of the bicycle indicating whether the cyclist is speeding up or braking.
- **Multicast:** The system targets and delivers its messages to multiple road users at the same time, e.g., a projection of a cyclist symbol on the road, indicating whether it is safe to change lanes.

8. Connectivity

Connectivity is a dimension that classifies whether the concept has the capacity for interconnection by signal transmission between systems or users.

9. Functionality

This dimension classifies the intended functionality of the message(s) communicated through the device or system, as described by the authors of each original article. Functionality is the intended message communicated to its recipient or the *purpose* of the messages communicated. The dimension of functionality is further categorised into three sub-categories: information systems, warning systems, and support systems. A concept could have more than one functionality and be categorised into more than one sub-category.

9.1 Information systems

Concepts categorised within information systems aim to inform the user about a particular arrangement or sequence of events, such as details about objects' or other road users' location or behaviour. Within information systems, we have defined the following sub-categories of functionality.

- **Navigation:** The system provides the user with navigational cues.
- **Information:** The system provides information about the vehicle, the cyclist, or the bicycle's state, e.g., whether the vehicle is stopping or going, if the cyclist is receiving a call, or the current speed of the bicycle.
- **Advice/Instruction:** Normative messages conveying desired behaviour of the recipient or other commands contingent on the recipients' actions, e.g., displays with the messages "go" or "do not cross".
- **Detection:** The concept detects elements or entities in its environment without the intention of warning the recipient of an immediate conflict or danger.
- **Data collection:** The concept collects and sends data about its users or entities in the environment, e.g., bicycle speed, location, and user data.

9.2 Warning systems

Concepts within this sub-category intend to convey messages of caution or urgency to its users. While a warning system is essentially an information system, the difference lies in the function of the message: The purpose is to prepare the user of a conflict so they can act accordingly to mitigate or avoid it. Warning systems are further differentiated into three sub-categories.

- **Conflict/collision:** The system warns the user of an imminent conflict or collision.
- **Approaching rear:** The system warns the user of an entity approaching from behind, e.g., a vehicle approaching the rear of a bicycle.
- **Other:** The system alerts the user of an unspecified event of urgency.

9.3 Support systems

Similar to information systems, concepts coded as a support system have functionality conveying messages about an arrangement or sequence of events. The difference between information and support systems is in the nature of the message: support systems convey messages with a behavioural component of the cyclist's current or future behaviour, such as braking or turning. The functionality of support systems is categorised in the following sub-categories.

- **Braking system:** The system communicates to other road users that the bicycle is actively reducing its speed, i.e., indicating that the cyclist is braking.
- **Projection-based cues:** These concepts project messages indicating the current or potential behaviour of the cyclist, e.g., symbols, lights, or other visual elements on the ground or field of view indicating the potential trajectory of the cyclist or bicycle.
- **Intent indicator:** A functionality similar to projection-based cues; however, the intent indicator conveys messages of the active intent of the cyclist, such as a turn indicator located on the bicycle.
- **Lane-keeping system:** The system informs the user to stay within a pre-defined area while cycling, e.g., a head-up display or a screen outlining the boundaries of the road.

10. Type of product

In this category, the concepts were coded according to their current state of development, whether they were conceptual, a prototype, or an end product.

11. Complexity of implementation

This dimension describes the complexity of implementing a concept in real-world traffic scenarios. Some concepts can be aspirational and practically unrealistic to implement in today's traffic environments without technological advances, full-scale adoption by other road users, or extensive infrastructure changes. The concepts are coded within four sub-categories adapted from Dey et al. (2020, pp. 13).

- **Ready to use:** Technology is ready to use today.
- **New technology required:** Requires new technology but does not depend on large-scale deployment or infrastructure changes to function.
- **New technology and large-scale changes required:** Requires new technology but depends on large-scale deployment or infrastructure changes to function.
- **Highly aspirational:** Uses technology that is not yet developed or available.

12. Support for people with special needs

Adapted from Dey et al. (2020), this category describes whether the concept accommodates the special needs of visually, auditory, or cognitively impaired persons via multimodal communication.

13. Evaluation of concept

Evaluation of concept is a category describing whether the technology, device, or system has been evaluated in a scientific publication. If an evaluation has not been conducted, the concept is coded as unknown, in line with the evaluation of concept dimension by Dey et al. (2020). If a concept has been evaluated, it is further classified into the following 13 sub-categories.

- **Method of data collection:** Automatic recording, eye-tracking device, questionnaire, interview, observation, or video recording.
- **Methodology:** Qualitative, quantitative, or mixed methods.
- **Method of evaluation:** Naturalistic, controlled outdoor, simulator (screen-based), simulator (VR headset-based), video or animation, or photo.
- **Direction of movement:** The behaviour and/or direction of the cyclist and other road users (if applicable) during the data collection, e.g., whether the cyclist is cycling straight ahead, turning left or right, and the direction of the other road user (opposite, perpendicular, or same/parallel trajectory relative to the cyclist).
- **Task:** The task of the cyclist during the evaluation of the concept.
- **Time of day:** Daylight conditions, evening conditions, night-time conditions, or unspecified.
- **Weather conditions:** Direct sunlight, indirect sunlight, rain, snow, or unspecified.
- **Road condition:** Clean roads, water on the road, snow on the road, or unspecified.
- **Cycling infrastructure:** Mixed traffic with no bike lane, mixed traffic with a bike lane, separated bike path, or unspecified.
- **Number of simultaneous road users per trial.**
- **Number of vehicles per trial.**
- **Sample size:** Number or unknown.
- **Sample age:** Median or mean age of the sample, or unknown.

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