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Cyclists and Automated Vehicles' Interactions: Literature Review, Conceptual Framework, and Future Directions

Jinyang Zhao, Serge P. Hoogendoorn, and Haneen Farah

***Abstract*—Future traffic will include automated vehicles (AVs) that will interact with other road users, including cyclists. These interactions need to be safe for AVs to be accepted by society. To accomplish this, the interaction process needs to be studied from both the AV's point of view (AV's passenger) and cyclists' point of view. Insights from current interactions between drivers of conventional vehicles (CVs) and cyclists, and the factors contributing to safe interactions, can inform industry of the design of AVs to interact safely and in socially acceptable ways with cyclists. This paper provides a synthesis of the current literature on the interactions between AVs/CVs and cyclists, from four different points of view: 1) from CV drivers' point of view when interacting with cyclists; 2) from cyclists' point of view when interacting with CVs; 3) from AVs driver-seat passengers' point of view when interacting with cyclists; and 4) from cyclists' point view when interacting with AVs. The literature review included publications between the years 2015-2025 and resulted in 89 relevant scientific papers. Fifty-one papers focused CVs and cyclists interactions, at intersections, and in overtaking maneuvers, while thirty-eight papers focused on cyclists and AVs interactions. Key factors that influence AV-cyclist interactions were identified, including infrastructure, environment, factors influencing vehicle and cyclist behaviors, and rules and regulations. These elements and the factors influencing them were summarized in a conceptual framework. Future research directions are proposed based on the literature review and knowledge gaps identified and were structured following the proposed conceptual framework.**

***Index Terms*—Automated vehicles, conventional vehicles, cyclists, interactions, literature review, conceptual framework.**

I. INTRODUCTION

AUTOMATED vehicles (AVs) are expected to bring many benefits to society, among these improving traffic safety and people's quality of life [1]. The Society of Automotive Engineers (SAE) International classification system [2] categorizes vehicles into six levels of automation, ranging from no automation (Level 0) to full automation (Level 5). While at lower levels of automation (SAE levels 1-3) humans are still responsible for certain driving tasks and/or taking over control in certain situations, at high levels of automation (SAE levels 4 and 5), the vehicle can handle the full driving task without the involvement of the human driver, especially at the highest level (Level 5). The expectations of this technology are high, and automated driving will influence the composition and performance of our road traffic in the future. However, there are still many challenges that we need to overcome before this innovative technology can be safely integrated into our road network, and with other road users, especially vulnerable road users, like cyclists. In the remainder of this paper, we use AV to refer to automated vehicles at Level 4 or Level 5. For lower levels of automation, we will specifically mention the automation level.

According to the World Health Organization (WHO) statistics, each year road crashes still cause 1.19 million deaths, and a great share of these fatalities (56%) are among Vulnerable Road Users (VRUs) [3]. Among VRUs killed in road traffic worldwide, about 71,000 cyclists are killed every year which represents 6% of the annual global road traffic deaths [4]. In the Netherlands, cyclists' fatalities constitute a significant share of road fatalities, amounting in 2022 to 39% [5]. AVs could potentially contribute to reducing VRUs' fatalities. Research on AVs, however, has so far mostly focused on the traffic efficiency and safety of these vehicles on highways [6]. In comparison, the safety of AVs' interactions with VRUs, have received little attention. Therefore, research in the past few years has begun to focus as well on integrating these vehicles in more challenging environments, such as urban traffic, as the next deployment use case for AVs [7].

The rapid advancement of sensing and computing technologies enables higher levels of AVs to adhere to traffic rules and operate safely on regulated roads. However, the question of how AVs could navigate more ambiguous and complex environments safely and efficiently has not yet been thoroughly studied [8]. It is unclear how AVs will be integrated into the full range of existing types of roads, and, more importantly, how they will be integrated with the full range of road users, especially VRUs, such as cyclists [9]. Unlike vehicle drivers and passengers, cyclists lack structural crash protection (e.g., cabin, seatbelt, airbags). AVs will interact with cyclists, in urban and rural areas, in addition to human drivers [10]. However, limited research [11], [12] has been conducted on the interaction between AVs and cyclists compared to the interactions between AVs and human-driven vehicles [8], [13]. Hence, there is a need for research on how AVs can proactively maximize the safety of their interactions with cyclists in the

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The authors are with the Department of Transport and Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2628 CN Delft, The Netherlands (e-mail: J.Zhao-8@tudelft.nl).

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future. A starting point would be to learn from safe interactions between Conventional Vehicles (CVs) and cyclists.

A distinctive aspect that is typically found in studies on the interactions of VRUs with AVs is VRUs' knowledge, trust and acceptance of AVs as a new technology, and how these might change as VRUs gain experience in interacting with AVs [14]. Communication technologies, such as External Human-Machine Interfaces (e-HMIs) as novel technology, were found to support safe interactions according to Berge et al. [15]. Cyclists need to feel comfortable and safe sharing the road with AVs. Notably, trust and acceptance are also relevant in the present traffic system, even in the absence of automation [16]. However, AVs can influence road users' trust and acceptance, which might impact VRUs and AVs interactions [13].

Lessons from current interactions between cyclists and CVs in traffic can inform the design of safer AVs. For example, insights from the interaction process between CVs and cyclists can be applied to obstacle avoidance systems in AVs [17], which is important for the improvement of AV's interaction with surrounding road users. However, because of differences in cyclists' trust and acceptance of AVs (compared to CVs), and differences in the AV's driving dynamics, these conventional, well-proven traffic interaction mechanisms are only partially useful in the context of AVs [18], [19], [20]. In addition, passengers of AVs, especially those of high automation levels, will observe how the automated system resolves space-sharing conflicts with cyclists. Therefore, the success of AVs (SAE Level 4 +) also depends largely on the level of passengers' acceptance of the AV interaction with its surrounding environment and other road users. While passengers may seem like mere observers in interactions between the AV and surrounding cyclists, recent research on passenger gaze behavior and visual attention proves that passengers are not completely passive [7]. Although they may not actively intervene in the driving task, these studies reveal that they remain attentive and actively aware of the driving environment. For lower levels of automated vehicles (SAE Levels 1-3), this is also relevant, as a low level of trust and acceptance can lead to an increased rate of transitions of control, which might have negative consequences for traffic performance. As a result, the perspective of passengers in terms of perceived safety, acceptance and trust should not be overlooked in automated driving research. This is particularly important when exploring these interactions in complex urban driving environments [21]. From here, AVs' passenger point of view also needs to be considered.

Therefore, the main aim of this paper is to summarize the current knowledge and identify the research gaps regarding the interaction behavior between AVs and cyclists, and the factors that could affect these interactions. Because CVs are currently much more dominant on our roads, and cyclists are used to interacting with them, we assume that the factors impacting the interaction behaviors between CVs and cyclists are very likely to also affect the interaction process between AVs and cyclists. Therefore, this study will first summarize previous research on the interactions between human-driven vehicles and cyclists to learn from current interactions, then the limited available studies on the interactions of AVs with cyclists will be reviewed, both from the point of view of AVs' passengers, as well as the point of view of cyclists. Based on this review we identify the research gaps and research needs, develop a conceptual framework, and propose future research directions.

TABLE I

KEYWORDS USED FOR PAPER SEARCHING

Category	**Synonyms used**
Targeted vulnerable road user	bicyclist, cyclist, bike/r, rider, bicycle
Targeted vehicle user	driver, car user, vehicle user, vehicle passenger, car passenger
Automation	Vehicle automation, autonomous vehicle, automated vehicle, self-driving car, driverless vehicle
Interaction	interaction, following behavior, overtaking behavior, passing behavior, crossing behavior, communication, safety perception, risk perception, driving style

This paper will answer the following research questions:

1) What can we learn from current interactions between CVs/AVs and cyclists?

2) Which determinants need to be included in a conceptual framework to investigate AVs–Cyclists interactions, and how do these determinants relate to each other?

3) What are the remaining knowledge gaps and future research directions given the proposed conceptual framework?

II. LITERATURE REVIEW METHODOLOGY

The literature review methodology followed the preferred reporting items for systematic reviews and meta-analysis (PRISMA) 2020 method [22]. The search databases Transport Research International Documentation (TRID), Web of Science, Scopus, and Google Scholar were searched for relevant papers. The search included studies from 2015 to 2025. To ensure all relevant and key papers were identified, Backward Snowballing [23] and Forward Snowballing were used to identify missed papers in the reference lists of included papers. As the field currently lacks a standardized nomenclature, we performed keyword searches by combining terms from four categories, as summarized in Table I.

These keywords were grouped using the Boolean operators "AND"/ "OR". The search was finalized in Oct 2024 and after peer review updated in July 2025, resulting in 89 papers after screening. The selection criteria for inclusion of papers were: (1) written in English; and (2) included interactive behavior between the targeted vehicle user and targeted vulnerable road user (either in the real world or in virtual reality, such as driving or cycling simulators).

This review focuses on interactions between standard bicycles and passenger vehicles, therefore, studies specifically targeting electric bicycles (e-bikes) or trucks were, despite their importance and relevance, excluded during the selection process, to maintain a manageable scope for the paper, and since e-bikes and trucks significantly differ in their behaviors

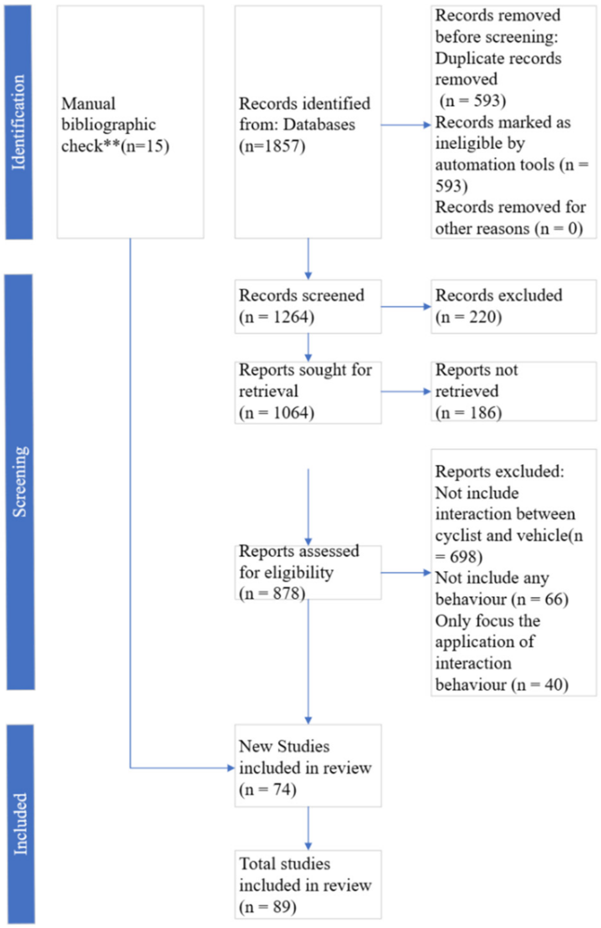

Fig. 1. PRISMA method for publication identification, screening, eligibility and inclusion. ** means that through the snowball method, 15 more relevant documents were found.

from standard bicycles and cars, respectively. In this way, the exclusion criteria included: (1) papers focusing on electric bicycles or e-bikes; (2) papers focusing on trucks; and (3) papers having no available full-text. Furthermore, it is not the aim of this paper to investigate the capabilities and limitations of the different AV system characteristics, and their impact on the interaction behavior between AVs and cyclists, and therefore this aspect was also excluded from this paper.

The flow of studies through the review process is shown in Fig. 1. The combined database searches identified 1857 records, which were reduced to 1264 after removing duplicates (178 duplicates). From these, 220 records were excluded after checking the titles and keywords, and 186 reports were excluded since full text could not be retrieved, resulting in 858 full-text articles assessed for eligibility. We have identified 74 articles eligible for inclusion (see Fig. 1). Fifteen additional records were identified through backward and forward snowballing check, including two papers published in 2014. So, this resulted at the end with 89 papers.

III. INTERACTIONS BETWEEN CONVENTIONAL/ AUTOMATED VEHICLES AND CYCLISTS

In the following subsections, we review previous studies focusing on the interactions between vehicles and cyclists from four different perspectives: Interactions of drivers of CVs and cyclists from: (A) CV drivers' point of view and (B) cyclists' point of view; and interactions of AVs and cyclists from: (C) AVs' point of view and (D) cyclists' point of view. For each perspective, we identify the main themes investigated and summarize the findings.

A. Interactions of CVs and Cyclists: Driver's Point of View

This section considers the interactions between CVs and cyclists from the CV drivers' point of view (i.e., human drivers). Following the inclusion criteria, 37 publications were found. The main themes identified include ***(1) overtaking behavior, (2) crossing behavior at intersections or roundabouts, and (3) drivers' safety perceptions and attitudes with respect to interacting with cyclists***.

1) Overtaking Behavior: Researchers studied the factors affecting ***overtaking behavior***. Rubie et al. [24] reviewed 42 studies up to May 2019, and identified key factors that influence the lateral distance when a vehicle overtakes a cyclist. These include vehicle-related factors, road infrastructure-related factors, cyclist-related factors, and driver-related factors. Table II summarizes the key studies which were not included in the review paper by Rubie et al. [24], including research methods, sample sizes, road types, and main aim of each study. For the ***vehicle factors***, more attention is paid to the impact of different types of vehicles (e.g., trucks, buses or passenger cars) on overtaking behavior. Clear evidence was shown that smaller lateral overtaking distances were maintained when cyclists were overtaken by buses compared to cars. Trucks and buses are not within the scope of this study, so we will not delve further into the literature on this topic. For **driver-related factors**, for example, Kovaceva et al. [25] observed that female drivers were more likely to choose accelerative overtaking strategy compared to flying overtaking strategy, although no significant differences in lateral overtaking distances were observed between these two overtaking strategies. Regarding ***road geometric design related factors***, wider roads and higher speed limits are generally associated with larger lateral overtaking distance. Mecheri et al. [26] study showed that on roads with narrower lanes and wider shoulders drivers maintain smaller lateral clearance from cyclists. The findings regarding the impact of bicycle infrastructure on the lateral overtaking distance varies across studies. The study by Schakel et al. [27] reported no significant difference, while the study by Debnath et al. [28] reported a negative impact of a dedicated bicycle infrastructure on the lateral overtaking distance. A more recent study by Lindsey et al. [29] showed that drivers were more likely to encroach to adjacent lanes when overtaking on roads with no bicycle facilities than on roads with striped or buffered bike lanes, indicating that the introduction of bike lanes may reduce driving behaviors with potential risks.

Research studies investigating ***cyclist-related factors***, such as gender, age or cyclist experience, *as* summarized in the review paper by Rubie et al [24], yielded inconclusive outcomes. For example, Sando et al. [30] observed that drivers maintain larger lateral overtaking distances from female cyclists compared to male cyclists, while Haworth et al. [31] reported no significant difference. Some researchers focused

TABLE II

KEY STUDIES ON CVS-CYCLISTS INTERACTIONS IN OVERTAKING MANEUVER

Method	Study	Sample size	Country	Road	Main aim
Naturalistic data	Fraser *et al.* [32, 33]	52 participants 108 unsafe cases 216 safe cases	Western Australia	Urban & rural	Determine the risk factors associated with unsafe events involving a vehicle.
	Moll *et al.* [36]	10 participants 2028 interactions	Spain	Rural	Analyze how road characteristics, cyclists' configurations, and overtaking strategies influence the duration of overtaking of cyclists.
	Pérez-Zuriaga *et al.* [39]	10 participants 1580 interactions	Spain	Rural	Analyze how cyclists' group size and roads' cross-section related factors influence driver overtaking behavior.
	López *et al.* [38]	1355 interactions	Spain	Rural	Analyze how road geometry influences the overtaking maneuver performance.
	Rasch *et al.* [41]	81 interactions	Sweden	Rural	Investigate how visibility affects drivers' behavior when overtaking cyclists.
	Reh *et al.* [42]	4217 interactions	Germany	Urban	Investigate what factors influence the lateral distance that vehicles maintain from cyclists during overtaking.
Vehicle driving simulator	Moll, *et al.* [37]	30 participants	Spain	Rural	Same as Moll *et al.* [36], but also to investigate the differences between drivers' behavior in the simulator and in reality.
	Rossi *et al.* [40]	67 participants	Italy	Urban & rural	Investigate the influence of real-time coaching programs on drivers' behavior while overtaking cyclists.
	Calvi *et al.* [43]	46 participants	Italy	Rural	Test the effectiveness of Augmented Reality in improving the safety of interactions between vehicles and cyclists.
Field experiment & Survey	Feizi *et al.* [44]	2838 interactions	USA	Urban & rural	Identify the effect of overtaking distance laws on drivers' perceptions and behaviors when overtaking bicycles.
Test track experiment	Rasch *et al.* [19]	18 participants	Sweden	Test track	Investigate how oncoming traffic and position of the cyclist within the lane influence the overtaking behavior.
Video based experiment	Oshiro *et al.* [45]	20 participants	Japan	Campus road	Clarify the appropriate number of communications between drivers and cyclists.
	Petersen *et al.*[46]	30 participants	USA	-	Determine what combinations of information would allow drivers to correctly predict a cyclist's intentions.

on the impact of cyclists' group configurations on the driver interaction behavior. Fraser et al. [32], [33] found that drivers' interaction patterns with groups of cyclists were very different compared to their interactions with a single cyclist, with over 80% of the unsafe events (*'crashes'*, *'near crashes'* or *'crash-relevant events'*, based on definitions used in [34]) occurring when vehicles were travelling in the same direction as the group of cyclists. This is significantly higher than the 17% to 19% reported for interactions with individual cyclist [35]. Therefore, it is important to study how the size of the cycling group influences drivers' interactions. Moll et al. [36] conducted a similar type of study on two-lane rural roads in Spain. The authors compared cyclists' risk perceptions in overtaking behavior using a bicycle equipped with a camera and a laser range finder in different group configurations: one bicycle, two bicycles in parallel, two in line, and different groups of three cyclists. It was found that when cyclists rode two abreast, the lateral clearance of the overtaking driver was lower. When an individual cyclist was overtaken by a vehicle, the overtaking speed was higher. Moll, et al. [37] replicated this study in a vehicle driving simulator and obtained similar results, confirming the usefulness and validity of using the driving simulator for investigating a driver interaction with cyclists [36]. López et al. [38] and Pérez-Zuriaga et al. [39] increased the number of cyclists in the group up to 10 and rode in different configurations. Road geometry, as a key factor, was also studied in the context of group of cyclists: wider lanes increase the clearance and decrease the driver speed when overtaking individual and medium-sized group of cyclists, however, the presence of a centerline becomes more important when overtaking larger groups–its presence leads to lower clearance and higher speed [38].

Rossi et al. [40] investigated the impact of a real-time coaching program on driver behavior when overtaking. The results showed that this coaching program had a significant positive effect on safety, by prompting drivers to reduce driving speed and acceleration during overtaking and adopting safer acceleration strategies.

Rasch et al. [19], [41] focused **on *the impact of oncoming traffic and visibility*** when overtaking a cyclist. In a test track experiment [19], drivers overtook a robot cyclist while encountering an oncoming (balloon) vehicle. The results showed that the safety margin was reduced when the cyclist rode closer to the center of the lane and the overtaking vehicle had a shorter time gap to the oncoming (balloon) vehicle. Drivers (especially women) preferred accelerative over flying

TABLE III
KEY STUDIES ON DRIVER-CYCLIST CROSSING INTERACTIONS AT INTERSECTIONS

Method	Study	Sample size	Country	Road	Main aim
Vehicle driving simulator & Bicycle simulator	Zhang *et al.* [47]	17 pairs of drivers and cyclists	Germany	Unsignalized intersection	Identify interaction patterns between drivers and cyclists, to discern the patterns that would be accepted by both.
Vehicle driving simulator	Elhenawy *et al.* [48]	67 participants	Australia	Roundabout/ unsignalized intersections	Investigate if drivers with cycling/motorcycle experience act differently during risky interactions.
	Fournier *et al.* [49]	48 participants	USA	Signalized intersections	Investigate the impact of cycling frequency and treatment (e.g. bike lanes with/without sharrow, intersection merge lane and bike box) familiarity on driver behavior at each treatment type.
	Bella *et al.* [50-52]	42 participants	Italy	Signalized intersection	Analyze the effectiveness of three countermeasures (baseline, colored paved markings and raised island) at bicycle crossroads during driver–cyclist interaction.
	Duivenvoorden *et al.* [53]	30 participants	Netherlands	Rural (un)signalized intersection	Analyze how the number of cyclists, their approaching direction, and actions affect drivers' speed and workload.
Vehicle driving simulator & Test track experiment	Boda *et al.* [54, 55]	47 participants& 44 participants	Modelled after Carson City, Nevada	Unsignalized intersection	Investigate the driver's braking reaction process and quantify the discomfort experienced by drivers when cyclists cross their travel path.
Video data	Zhang *et al.* [56]	206 interactions	Germany	Intersection	Identify the patterns of implicit communication of human drivers with cyclists.
	Silvano *et al.* [57]	187 interactions	Sweden	Unsignalized roundabout	Investigate the factors influencing drivers' yielding decisions to cyclists on a typical roundabout.
Field experiment	Kwiatkowski *et al.* [58]	507 observations	Poland	Unsignalized junctions	Analyze the behavior of drivers approaching the intersection when a cyclist is preparing to cross.
	Bella *et al.* [59]	304 interactions	Italy	Signalized intersection	Evaluate how specific marking scheme for the two different bicycle configurations affect drivers' speed, yielding decision, and attention interacting with cyclists.

overtaking maneuvers. A naturalistic study [41] showed that drivers reduced their lateral gaps in conditions of limited visibility or approaching oncoming vehicles, but the reduction in speed was not statistically significant. The study [42] reached similar conclusion, and further found that drivers maintain larger lateral distance from a cyclist at night. Several studies used the insights from these naturalistic field tests to develop driver models that can be implemented in active safety systems [18]. Calvi et al. [43] tested the effectiveness of Augmented Reality (AR) warnings to improve the safety of overtaking interactions using a vehicle driving simulator. AR highlighted the area around the cyclist to indicate a safety zone, and an overtaking safety area. It was found that AR systems assisted drivers in maintaining a larger distance from cyclists while at the same time reducing the frequency of entering the oncoming lane, reducing the risk of head-on accidents.

To identify the effect of ***overtaking distance laws*** on overtaking behavior, Feizi et al. [44] showed from field experiment data that overtaking lateral distances were significantly larger in locations with a five-foot overtaking law compared to locations with a three-foot law, or no specific law. Additionally, from the survey results, it was found that 70% of the surveyed drivers had little knowledge of the traffic laws related to the lateral distance required when overtaking cyclists.

Some researchers focused on ***communication*** between drivers and cyclists during the overtaking process. Oshiro et al. [45] investigated the number of communications between drivers and cyclists using a video-based experiment where both parties could use emoji messages via a mobile app to communicate with each other. In the video, a vehicle overtook a bicycle from behind. One emoji sent by drivers showed the information, '*I'm aware of you*' and the other emoji sent from cyclists showed the information, '*It is okey to overtake*'. It was found that two-way communication was perceived as safer and more comfortable from the driver's point of view compared to one-way communication. However, from a cyclist's point of view, one-way communication, sending a message to vehicles, was preferred. In [46], it was found that drivers understood a cyclist's straight-arm signal best, while a combination of lane position, hand gestures and head rotation better predicted riding intentions.

2) *Crossing Behavior:*

Crossing behavior, at intersections and roundabouts, was also the focus of several studies in literature. Table III summarizes the key studies on driver-cyclist crossing interactions.

Zhang et al. [56] analyzed video data of a driver and cyclist approaching the intersection form the same approach and identified three drivers' yielding strategies: (1) not yielding, drivers, who should yield to cyclists, crossed the intersection first while forcing right-of-way; (2) active yielding, drivers, who were in front of cyclists, gave the right-of-way; (3) passive yielding, drivers, who were behind cyclists, had to give the right-of-way. Based on these findings, Zhang et al. [47] conducted a vehicle-bicycle coupled simulator experiment. It was found that in half of all cases, drivers crossed the intersection after the cyclists, suggesting that drivers were likely to yield to cyclists. Similarly, Kwiatkowski et al. [58] observed that although drivers had priority at crossings, over half of them still preferred to give cyclists the priority. In an earlier empirical study by Silvano et al. [57] on typical roundabouts in Sweden, it was shown that drivers' probabilities to yield were higher when the vehicle speed was lower and when the cyclists were closer to the conflict zone. The cyclist's speed had little impact on a driver's decision to yield. The authors concluded that by keeping the vehicle speed below 20 km/h, driver's yielding probability can be improved.

Elhenawy et al. [48] found that drivers with cycling experience contribute to safer interactions. Similarly, Fournier et al. [49] found, in a vehicle driving simulator experiment, that drivers who are also frequent cyclists, paid more attention when driving towards cyclists. Furthermore, they also studied the impact of familiarity with different bicycle facilities on driving safety including, only bike lanes, bike lane with sharrow, and intersection treatments (merge lane and bike box). Drivers who are more familiar with bike boxes stopped further away from the bike box, and those who are more familiar with merge lanes performed the merging maneuver earlier.

The effect of infrastructure was further evaluated by Bella et al. [50], [51]. It was found that colored paved markings were more effective than other treatments (no treatment (base condition) and raised island) in leading drivers to decelerate for a crossing cyclist. Further, in a following study [52], they found that colored paving markings led to longer, smoother braking maneuvers by approaching drivers, indicating less aggressive and safer behaviors. Field data [59] highlighted a higher risk for cyclists when crossing roads with two-lanes per direction compared to roads with one-lane per direction. Furthermore, when using the same markings on two different road configurations it was found to be inappropriate since it failed to induce appropriate behavior on the part of the driver.

Duivenvoorden et al. [53] studied how the number of cyclists, cyclists' direction of approach, and cyclists' actions affect driver behavior, and found that speed-reducing measures (e.g., plateau or chicane) and encountering multiple cyclists led drivers to lower their driving speeds. Also in this study, although drivers had the right-of-way, their behavior was still influenced by the encountered cyclists.

Boda et al. [54], [55] investigated drivers' responses and discomfort experiences when a cyclist crosses their path at an unsignalized intersection on a test track and in a vehicle driving simulator experiment with a virtual replica of the test track. In both studies, detailed vehicle control inputs, including accelerator and brake pedal use, were recorded. The drivers were instructed to maintain their speed at 30 km/h or 50 km/h. The bicycle speed was designed at 10 or 20 km/h. Three different crossing configurations were tested:(1) If drivers keep the speed the bicycle passes before the vehicle entering the intersection; (2) If drivers keep the speed 50% of the car front would crash with the bicycle; (3) If drivers keep the speed the bicycle passes after the vehicle. The results showed that neither the vehicle speed nor the bicycle speed directly influenced drivers' response process. The moment the bicycle became visible (which depended on the vehicle speed, the bicycle speed, and the crossing configuration), and the crossing configuration alone had the largest effects on the driver response process. In addition, it was found that participants' discomfort depended on the remaining time from the moment that the cyclist appeared to the moment they reached the intersection. Interestingly, drivers had the same braking strategy in both the vehicle driving simulator and the test track experiment but with different gas padel behavior. This is because drivers could not experience the forces when braking in the driving simulator. These results could help improve the driver assistance systems by making them more adaptable to the needs of drivers.

3) Drivers' Safety Perceptions and Attitudes: ***Drivers' safety perceptions and attitudes*** also affect their interactions with cyclists. The literature on this topic is summarized in Table IV.

Researchers found that **driver's cycling experience** was an important factor in affecting safety perceptions and attitudes. Drivers with cycling experience tend to show safer behaviors [60], [61], while negative attitudes to cyclists and driver's anger emotion are linked to increased aggressive behavior towards cyclists [62], [63], [69]. Low risk perception among car drivers leads to more risky behavior (e.g., overtaking at higher speeds and with less lateral clearance), which in turn reduces the subjective safety of cyclists [64]. In addition to the impact of anger, Fruhen et al. [65] examined changes in driver behavior (overtaking lateral distance, aggressive behavior) and negative attitudes towards cyclists following the introduction of minimum overtaking distance laws. These laws appeared to be less effective and potentially counterproductive in addressing negative attitudes and related interaction behaviors in the short term. Still et al. [68] showed that cyclists have a more accurate understanding of cycling laws and advice, while drivers recognized cyclist vulnerability but did not always act accordingly. Social-psychological factors, including driver's motivation to "punish" cyclists [66] and traffic safety culture [67] are also factors affecting the interaction behavior.

To summarize this section, current research on the interaction between CVs and cyclists shows that drivers' yielding behavior at crossings and overtaking behavior are significantly affected by cyclists' related factors, the road environment, and driver related factors. However, knowledge gaps remain, considering the various factors determining the road environment conditions and the heterogeneity of road users. Nevertheless, the existing knowledge on CV–cyclist interactions can serve as a foundation for developing AV–cyclist interactions, given the relatively scarce research on the latter.

B. Interactions of CVs and Cyclists: Cyclists' Point of View

In this section, 16 papers on the interaction behavior between CVs and cyclists, from cyclists' point of view, were reviewed. Table V summarizes the relevant studies, and the subsequent paragraphs summarize the main findings related to the main themes identified: ***(1) overtaking behavior and (2) crossing behavior***

TABLE IV

KEY STUDIES ON DRIVER'S SAFETY PERCEPTIONS AND ATTITUDES

Method	Study	Sample size	Country	Main aim
Survey	Johnson *et al.* [60]	1984 respondents	Australia	Identify differences in drivers' interaction behavior with cyclists, as a function of their knowledge of cycling rules, cycling experience, and attitudes towards cyclists.
	Rubie *et al.* [61] (Video based survey)	331 respondents	Australia	Identifying the factors shaping drivers' perceived risk when interacting with cyclists and assessing the relationship between vehicle's speed and the perceived risk of cyclists and drivers.
	Fruhen *et al.* [62]	276 respondents	UK	Investigate attitudes and social norms in shaping drivers' aggressive behavior towards cyclists.
	Fruhen *et al.* [63]	308 respondents	UK	Investigate how drivers' attitudes toward cars, the environment, and cyclist distinctiveness influence their aggression toward cyclists.
	von Stülpnagel *et al.* [64] (Photo based survey)	21500 respondents	Germany	Assess the subjective safety of different road user groups (drivers and cyclists) associated with shared road situations
	Fruhen *et al.* [65] (Pre & post survey)	302/426 respondents	Australia	Examine the changes in driver behavior and negative attitudes towards cyclists following the introduction of a cyclist minimum overtaking distance law, and cyclist numbers on the roads.
	Piatkowski *et al.* [66]	17850 respondents	USA	Investigate the reason of aggressive driver–cyclist interactions.
	Ward *et al.* [67]	938 respondents	USA	Examine the influence of traffic safety culture on driver behaviors that affect safe interactions with cyclists.
	Still *et al.* [68]	90 cyclists & 41 drivers	USA	Explore the extent to which cyclists and drivers are aware of bicycle-specific laws and differences in their risk perceptions.
Vehicle driving simulator	Lafont *et al.* [69]	45 participants	-	Investigate the impact of driver anger on their behavior when interacting with cyclists

1) Overtaking Interactions: Thorslund et al. [70] showed that cyclists were more cautious when interacting with a truck compared to a car. They also found that the available vehicle-adjacent space influence cyclists' behavior more than the presence of a bicycle lane. However, von Stülpnagel et al. [71] revealed a mismatch between cyclists' perceived safety and actual vehicles' overtaking lateral distances. While cyclists tended to feel safer on 30 km/h roads with dedicated cycling infrastructure compared to roads without dedicated cycling infrastructure, the overtaking lateral distances were smaller on these roads compared to roads without dedicated cycling facilities, suggesting that cyclists' feeling of safety may be influenced more by road design cues than by actual vehicle behavior. Louro et al. [72] recorded vehicle overtaking field data and found that the shorter the lateral distance and the faster the speed of a motor vehicle overtaking a bicycle, the higher the discomfort the cyclist felt.

Several studies investigated the safety perception of cyclists when being overtaken by vehicles. Llorca et al. [73] showed that higher lateral separation is not always associated with lower perceived risk, while higher speeds always increased the perceived risk levels. Beck et al. [74] used a "panic button" on bicycle to track discomfort events. When the cyclist was overtaken by a truck, the adjusted odds of a button press event were more than three times higher than when the cyclist was overtaken by a sedan. This study further identified significant relationships between cyclists' subjective experiences and factors such as vehicle type and infrastructure characteristics.

López et al. [75] found that cyclists at the front and rear of a group reported the highest perceived risk while being overtaken by vehicles. Parallel riding and flying overtaking strategy (higher overtaking speed compared to accelerative overtaking) will cause higher perceived and objective risks due to reduced lateral clearance and increased speed. The perceived risk of cyclists is highest when the lateral distance is less than 1.5 meters. To study the susceptibility of cyclists to being overtaken by vehicles on street routes without bicycle lanes, Seriani et al. [76] found that non-experienced cyclists are much more affected by the overtaking vehicles than experienced cyclists. While, [77] showed that frequent cyclists showed more frequent cautious behavior, suggesting that they felt or detected dangers more than infrequent cyclists.

2) Crossing Interactions: Kovacsova et al. [78] used non-interactive animated video clips to investigate how do cyclists' eye movements and their crossing judgments differ between car approaching scenarios at uncontrolled four-way intersections. They found that cyclists spent more time looking at the approaching vehicles than to the rest of the visual scene and directed their gaze towards the vehicle that posed higher hazard. Traffic complexity resulted in dividing their attention between the two approaching vehicles and gazing at the right vehicle at a higher frequency. Kovácsová et al. [79] showed that perceived higher vehicle speed and acceleration were related to correct predictions that drivers would not let cyclists cross first. Incorrect predictions were related to believing that the vehicle's speed was slow or that the vehicle was slowing down, and reporting that the cyclist had the right-of-way. The findings on cyclists' predictions of risks can be used in the development of bicycle support systems. Al-Taie et al. [80] found that in controlled traffic situations (i.e., with traffic lights and clear rules), cyclists paid attention to road markings

TABLE V

KEY STUDIES ON CV-CYCLIST INTERACTIONS FROM CYCLIST'S POINT OF VIEW

Method	Study	Sample size	Country	Main aim
Overtaking interactions				
Video experiment	Oshiro *et al.* [45]	20 participants	Japan	Clarify the appropriate number and pattern of communication between drivers and cyclists in overtaking interactions.
Photo-based survey	von Stülpnagel *et al.* [71]	385 participants	Germany	Assess cyclists' expectations concerning the overtaking safety of cars overtaking them at different speed limits and cycling infrastructure.
Naturalistic data	López *et al.* [75]	10 participants	Spain	Analyze the objective and subjective risk of overtaking maneuvers of cyclists' groups.
	Louro *et al.* [72]	2032 interactions	Brazil	Analyze the impact of the vehicle's overtaking lateral distance and speed on cyclist's comfort
Field experiment	Beck *et al.* [74]	217 participants	Australia	Explore the relationship between cyclists' subjective experiences and the lateral overtaking distance of vehicles.
	Seriani *et al.* [76]	17 participants	Chile	Study the sensitivity of cyclists who are overtaken by a vehicle on a street route without cycling lanes.
Naturalistic data & Interviews	Llorca *et al.* [73]	2928 interactions	Spain	Compare the effect of lateral clearance and overtaking vehicle speed with a cyclists' subjective and relative risk perception.
Crossing interactions				
Video experiment & eye tracking	Kovacsova *et al.* [78]	36 participants	Netherlands	Analyze cyclists' eye movements and crossing judgments while approaching an intersection at different speeds.
Naturalistic data & Field observation	Al-Taie *et al.* [80]	12/414 participants	UK	Investigate how cyclist-driver communication and cyclist gaze behavior differ between various traffic situations in crossing maneuvers.
Bicycle Simulator	Mohammadi *et al.* [84]	25 participants, 9 interactions	Sweden	Investigate how cyclists interact with vehicles under different times to arrival and visibility of the approaching vehicle and evaluate the factors influencing braking time and yielding decisions.
	Thorslund *et al.* [70]	33 participants	Sweden	Study how infrastructure and vehicle properties affect cyclist decision-making and behavior when crossing intersections.
Photo based Survey	Kovácsová *et al.* [79]	1030 participants	Netherlands/ Northern America/ Australia	Understand how accurate cyclists are in predicting a driver's right-of-way violation, which cues contribute to cyclists' predictions and their self-reported slowing-down behavior.
Naturalistic data	Ackermann *et al.* [82]	11 cyclists, 69 interactions	Germany	Investigate parameters affecting cyclist-vehicle interaction in non- to less-regulated traffic situations
	Zangenehpour *et al.* [81]	90 hours	Canada	Investigate the safety impacts of cycle tracks at intersections, where interacting with turning vehicles
Mixed types of interactions				
Survey	Still *et al.* [68]	90 cyclists and 41 drivers	USA	Explore the extent to which cyclists and drivers are aware of bicycle-specific laws and the different risk perceptions of cyclists and drivers.
Video experiment	Lehtonen *et al.* [77]	38 participants 65 videos	Finland	Investigate the risk perception of cyclists in a city environment.

Among these studies, [45] was campus environment, [78] in a suburban environment, and [73, 75] on a rural road, while the remaining studies focused on urban road. [68] already reviewed in subsection (3), A.

and traffic signs without much interaction with the vehicles. However, in uncontrolled traffic environments, cyclists used hand gestures and shoulder checks.

Zangenehpour et al. [81] studied three conditions from video data: (1) cyclists continuing straight and right-turning vehicles without a bicycle track, (2) same interaction but with a bicycle track on the right, and (3) left-turning vehicles with a bicycle track on the left. It was found that the intersections with bicycle tracks reduced dangerous interactions, especially when the cyclist group was larger and fewer vehicles were turning.

To gain a deeper understanding of the parameters that influence cyclist-vehicle interactions in non- or less regulated traffic situations Ackermann et al. [82] reanalyzed a dataset from a previous study [83] and found that the most common

TABLE VI
KEY STUDIES ON AV-CYCLIST INTERACTIONS FROM AV PASSENGER POINT OF VIEW

Method	Study	Sample size	Country	Road	Main aim
Interaction's strategy					
Literature review	Stanciu *et al.* [85]	-	-	-	Synthesize existing research on interpersonal communication between drivers and cyclists and highlight implications and challenges for AV and cyclists.
Field experiment (AV Shuttle bus)	De Ceunynck *et al.* [86]	61 interactions	Norway	Urban road	Observe and analyze real-world interactions between automated shuttles and cyclists, identifying potentially risky behaviors and interaction patterns.
Human-machine interface					
Design	Bengler *et al.* [89]	-	-	-	Propose a framework for HMIs AV, describing different HMI types, their influencing factors and interrelations.
	Fraboni *et al.* [87]	-	-	-	Develop an adaptive HMI design framework for AVs that addresses the needs of both elderly users and cyclists.
Vehicle-bicycle coupled simulators	Lindner *et al.* [88, 90]	16 pairs of participants (32)	Germany	Urban road	Investigate AV passengers' crossing decision types and duration at intersections.
Acceptance and expectations of AV's passengers					
Vehicle driving simulator	Usama *et al.* [93]	300 participants	Belgium	Rural road	Analyze how AV drivers, with aggressive or passive style, respond to ADAS during overtaking.
Field experiment & interview	Nordhoff *et al.* [94]	119 participants 62 test rides	Germany	Campus road	Investigate automated shuttle passengers perceived safety and acceptance when interacting with cyclists.
Video study, vehicle driving simulator	Stange *et al.* [7]	118 participants, 28 participants, 10 participants	Germany	Urban road	Investigate passengers preferred automated driving style and acceptable perceived risks when interacting with vulnerable road users at urban junctions.
Survey	Vondráčková *et al.* [91]	1065 respondents	Czech Republic	Share road	Evaluate the level of perceived fear of different people of interactions between AVs and cyclists.
Vehicle driving simulator & eye tracking	Fleskes *et al.* [92]	43 participants	USA	Urban road	Investigate how human drivers respond to a take-over when interacting with cyclists during a right-turn maneuver at intersections.

cyclist behavior in non-regulated areas (such as traffic calming areas or parking spaces), was to avoid the vehicle with constant cycling speed or slightly accelerating. It was worth noting that cyclists' speed seemed to not change regardless of vehicle traffic level. Mohammadi et al. [84] investigated in a bicycle simulator, how time to arrival, visibility, and visual attention influenced cyclists' yielding decisions and found that lower visibility and shorter difference in time-to-arrival led cyclists to yield more frequently and to brake earlier.

Through the above identified studies, it was found that from a cyclist's perspective, cyclist-vehicle interactions are influenced by communication mode, vehicle lateral space, vehicle speed, and cyclist heterogeneity and visibility. In uncontrolled traffic environments, hand signals and shoulder checks are used more frequently for communication. Higher overtaking speeds consistently increased cyclists' perceived risk. Poor visibility and shorter time-to-arrival are associated with higher yielding decisions to vehicles and earlier braking. Therefore, lateral clearance and speed should be considered as design factors, with consideration of cyclist configurations, position on the road, and cyclists' experience, while recognizing the potential gap between perceived risk and objective risk.

C. Interactions of AVs and Cyclists: AVs' Point of View

This section considers the interactive behavior between AVs and cyclists from the viewpoint of AV's passengers. Following the inclusion criteria, 11 publications were found. Table VI summarizes the studies on this topic. Besides the paper by Stanciu et al. [85] which is a literature review paper about the communication mode between pedestrians/bicyclists and AVs, the remaining 10 papers address the following themes: ***(1) interaction's strategy (e.g., yielding or overtaking)*** [86], ***(2) human-machine interface (HMI)*** [87], [88], [89], and the impact of HMI on traffic safety [90], ***(3) Acceptance and expectations of AV's passengers*** [7], [91], [92]. The following paragraphs elaborate on the main findings of the studies found on these themes.

1) AV's Interaction Strategy: Regarding the **AV's interaction strategy**, from real-world traffic conditions with automated shuttles (Max speed:18 km/h), De Ceunynck et al. [86] found that in 38 of 61 interactions, the automated shuttle yielded correctly to the cyclist when the shuttle was turning right and a cyclist continued straight. While, in the remaining interactions, the shuttle did not yield and cut in front of the cyclist (violating the traffic rules). When riding in the same direction, cyclists overtook the automated shuttle (on the left-hand side) usually immediately (in 64%–77% of the interactions). Generally, the study found little evidence to suggest cyclists attempting to bully the defensive driving style of the automated shuttle. These findings cannot however be generalized to interactions with higher speeds of AVs.

2) Human-Machine Interfaces: ***HMI communication*** can support improving the safety of the interactions between

AVs and cyclists. There are many factors to consider when deploying AVs on public roads, such as the fact that cyclists are already used to interacting with human drivers, which makes the interaction between all components of the road transport system more complex. Stanciu et al. [85] concluded that human drivers used relative speed as a communication signal with cyclists (e.g., slowing down or speeding up to indicate intent to yield or pass first, respectively). For AVs to communicate with cyclists more effectively, the AV's driving behavior or style needs to be programmed accordingly to indicate the AV's intent correctly. This literature review study also highlighted the necessity to better understand when this communication fails, as foundation for future HMI and e-HMI designs. Further, Bengler et al. [89] presented an AVs' user-centered HMIs design for interactions with cyclists travelling in the same direction in urban traffic. They pointed out that HMI design could influence the interaction strategy and highlighted that considering both internal and external communication is important. Considering elderly users of AVs, Fraboni et al. [87] proposed that HMIs should be inclusive of elderly passengers using multimodal alarms (i.e., combination of visual, tactile, and auditory stimulations) instead of single-modal alarms.

To test the effect of an HMI on AV's passenger and investigate the interaction between AVs and cyclists, two studies using a coupled driving and cycling simulators were conducted by Lindner et al. [88], [90]. The first study's purpose was to validate the simulation setup, which was also rated by the participants positively, while in the second study the researchers investigated the interactions of AVs and cyclists at intersections. During these interactions, an external HMI (e-HMI) for cyclists showed the same information shown to the drivers via the HMI. When approaching a conflict point at an intersection, one of three possible interaction types was displayed on the HMI: (1) conventional traffic rules apply, (2) the AV deciding autonomously about the traffic rules, and (3) the AV-passenger deciding together. It was found that the HMI increases the perceived safety at these conflict points. However, from a total of 50 interactions, the AV passengers prioritized themselves in 43 cases (86%), and the cyclists in 7 cases (14%), even when told that yielding to cyclists would improve traffic efficiency. These results contradict the findings from the study on human drivers, who tend to yield to cyclists more often [58].

3) Acceptance and Expectations of AV's Passengers: The **acceptance and expectations of AV's passengers** are very important which directly influence trust, perceived safety, and help to better integrate AVs into existing traffic. Stange et al. [7] investigated passengers' preferred automated driving style at junctions with a stop sign in a human in the loop vehicle driving simulator. Most AV passengers preferred harmless interactions with cyclists (i.e., at the ideal braking's onset time), and accepted unpleasant, but not dangerous interactions at most (i.e., at the last acceptable braking onset time). The conclusions further proved that passengers' perception and evaluation of AV driving behavior should also be considered, to achieve a satisfying level of acceptance of AVs. Nordhoff et al. [94] reported that passengers feel safe due to lower speeds, while, some passengers pointed out that they would not feel comfortable driving at higher (car-like) speeds. This finding suggests the necessity to investigate perceived safety in relation to the AV driving style. Vondráčková et al. [91] found from a survey in Czech Republic that the level of fear of interactions with cyclists was higher in people who do not intend to use AVs than those who intend to use AVs, and the level of concern about the risk of AVs was positively associated with the fear of interactions with cyclists.

Fleskes et al. [92] showed from a vehicle driving simulator experiment that (1) the earlier a take-over request from level 3 AV was received, the longer the average time-to-collision, and therefore, the safer the interaction between the AV and the cyclist; (2) the introduction of a secondary task led to a decreased driver performance with respect to the time-to-collision and the time that it took a driver to first identify the cyclist on the roadway. From Usama et al. [93], it was found that passive drivers benefited most from ADAS than aggressive drivers, highlighting the need to adapt the design of ADAS features to driver age and style.

The current research on the interaction between AVs and cyclists from the AV's passenger point of view is relatively scarce, and still at its nascence level. Also, because human drivers or passengers do not yet have much experience with AVs. Therefore, there is a need for further studies on the impact of human factors of AV's passengers during interactions with cyclists, on different types of roads, different types of interactions, and considering the various potential influencing factors, those that are relevant for current interactions and those that are unique to AVs.

D. Interactions of AVs and Cyclists: Cyclists' Point of View

This sub-section focuses on AVs and cyclists' interactions from cyclists' point of view. Following the inclusion criteria, 28 publications were found, addressing the following themes: ***(1) cyclists' perceptions of AVs and how cyclists feel when sharing the road with AVs*** [10], [11], [91], [95], [96], [97], [98], [99], [100], [101], [102]; ***(2) cyclists' acceptance and recognition of AV's e-HMI or bicycle HMI*** [12], [15], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112]; and (3) ***the interaction behavior of cyclists with AVs*** [113], [114], [115], [116], [117].

1) Cyclists' Perceptions of AVs: To study ***cyclists' perceptions and feelings when interacting with AVs***, scholars conducted surveys [10], [91], [95], [97], [98], [99], [101], photo experiments [11], interviews [96] and bicycle simulator experiments [100]. Table VII summarizes the information of each study on this topic.

Penmetsa et al. [99] and Das [97] found that participants with experience in interacting with AVs reported significantly higher expected safety benefits of AVs. This conclusion indicates that with an increasing cyclists' experiences of interacting with AVs their attitudes towards AVs become more positive. However, not all studies support a direct relationship between familiarity with AVs and more positive attitudes. In Vondráčková et al. [91], the authors reported that no significant relationships were found between the level of knowledge of AVs and the fear of interactions with AVs, and also between positive attitudes towards AVs and the willingness to use AVs. This inconsistency may be because of different traffic backgrounds, or due to the distinction between actual experience

TABLE VII
KEY STUDIES ON CYCLISTS' PERCEPTIONS AND FEELINGS WHEN INTERACTING WITH AVS

Method	Study	Sample size	Country	Road	Main aim
Survey	Pyrialakou *et al.* [10]	400 respondents	USA	Urban road	Analyze road users' (human drivers, cyclists, pedestrians) perceived safety when sharing the road with AVs, and the factors shaping these perceptions.
	Vondráčková *et al.* [91]	1065 respondents	Czech Republic	Urban road	Evaluate the level of perceived fear of different people of interactions between AVs and cyclists.
	Li, X *et al.* [95]	314 respondents	Australia	Urban road	Investigate factors influencing cyclists' receptivity towards sharing roads with AVs, and their behavioral intentions in interacting with AVs.
	Li, X *et al.* [98]	339 respondents	Australia	Shared road	Investigate how cyclists' risk profiles (e.g. drinking driving, fatigue) and individual characteristics influence the acceptance of sharing roads with AVs.
	Das [97]	795 respondents	USA	Shared road	Examine how cyclists perceive AV safety based on their understanding and experiences.
	Penmetsa *et al.* [99]	795 respondents	USA	Shared road	Evaluate whether interaction experiences with AVs influence perceptions.
	Pammer *et al.* [101]	522 participants	Australia	-	Explore cyclists' (and motorcyclists') trust in AVs versus human drivers, and how this relates to perceived safety.
Interview	Ngwu *et al.* [96]	6 groups (25 participants)	USA	Urban road	Explore teenage bicyclists' perceptions of AVs and their preferences for infrastructure and communication interface designs that support safe bicyclist-AV interactions.
Photo based survey	Hagenzieker *et al.* [11]	35 Participants 30 photos	Netherlands	Urban road	Investigate whether expectations and behavioral intentions of cyclists when interacting with AV differed from those with CV.
Bicycle simulator	Harkin *et al.* [100]	42 participants	Germany	Urban road	Examine how different vehicle driving dynamics and automation status affect cyclists' perceived safety, and intentions to cross.
Wizard-of-Oz study & post interviews	Berge *et al.* [102]	37 participants	Netherlands	Campus road	Examine whether cyclists can spontaneously detect driverless AV, how accurately they identify them when instructed, and what processes they use to do.

with AVs (as examined by Penmetsa et al. [99] and Das [97]) and mere knowledge of AVs (as in Vondráčková et al. [91]). Since the results are contradictory, more research is needed to understand the impact of local context on transportation in different countries. Hagenzieker et al. [11] pointed that participants in their experiment were no more confident about being noticed by AVs than manually driven cars, by letting participants judge bicycle-AV interactions from cyclists' point of view in a photo-experiment. Harkin et al. [100] found that early braking was the most advantageous strategy, while no yielding with acceleration led to increased risk expectations, but did not decrease perceived safety of cyclists or decrease the willingness to continue cycling through the intersection. They also found that automation state (i.e., automated or manual) had a limited impact on interactive behavior. Li et al. [95] pointed that older cyclists and male cyclists were less accepting of sharing the road with AVs than younger cyclists and female cyclists, respectively. Cyclists who had been involved in bicycle accidents were more positive towards AVs, and cyclists with higher propensity for risky behaviors are less likely to engage in intentional self-protective behavior when interacting with AVs. Pammer et al. [101] reached the same conclusion that cyclists generally have medium–low trust in both human drivers and AVs but perceive AVs as safer. This attitude was influenced by age and crash experience.

Further, Li et al. [98] pointed out that cyclists in lower risk group reported having higher intention to share roads with AVs than cyclists in higher risk group. However, the sample size of cyclists with high risk profile was relatively small, therefore, a larger sample size of the high-risk cyclist group is needed to further verify the findings. In addition to studying older cyclists' views on AVs [95], teenagers' views are also important [96]. Ngwu et al. [96] pointed that the teenage cyclists showed positive views of AVs, chose visual interfaces with familiar icons, and indicated their preference to have separate cycle-AV infrastructure on the road. Pyrialakou et al. [10] reported that cycling was considered the most dangerous activity compared to walking and driving near AVs. Berge et al. [102] reported from a Wizard-of-Oz study that cyclists were able to perceive the absence of a driver in an AV, especially when given the task of detecting the presence of a driver. The post interviews indicated that cyclists were curious about whether there was a driver, but felt safe, and reported a need to receive information about the AV's driving state, suggesting the necessity to develop e-HMI of AVs.

2) Cyclists' Acceptance and Recognition of AV's e-HMI or Bicycle HMI: ***HMIs for bicycles and e-HMI of AVs*** which serve as communication tools between AVs and cyclists, have attracted the attention of several researchers. Table VIII summarizes the information of each study on this topic.

Schrauth et al. [106] suggested that future developments of AVs should focus on the communication between AVs and cyclists (e.g. via e-HMI) to reduce uncertainties and promote trust. Berge et al. [12] highlighted overtaking and merging as

TABLE VIII

KEY STUDIES ON HMIS FOR BICYCLES AND E-HMI OF AVS

Method	Study	Sample size	Country	Road	Main aim
Literature review	Berge *et al.* [15]	-	-	-	Provides a synthesis of the current literature on communication technologies, systems, and devices available to cyclists.
Survey	Schrauth *et al.* [106]	5827 respondents	EU	-	Investigate cyclist's priori acceptance of conditionally AV and identify how trust influence acceptance.
Survey & Interview	Luger-Bazinger *et al.* [107]	889/19 respondents	Germany and Austria	Shared	Investigate bicyclists' attitudes and expectations towards AVs.
Interview	Berge *et al.* [104]	30 respondents	Norway and Netherlands	Urban	Identify cyclists' needs interacting with AV and explore on-bike HMI functionality and the implications of equipping cyclists with devices to communicate with AVs.
	Berge *et al.* [12]	8 participants	Netherlands and Norway	Urban/ rural	Generate representative and realistic test scenarios of cyclists' interaction with AV.
Photo based survey	Bazilinskyy *et al.* [108]	2000 participants and 180 photo	All the world	Urban/ rural	Examine the effects of blinded windows, vehicle approaching direction, distance to cyclists, e-HMIs, eye contact, and the environment visual complexity on cyclists' crossing decisions.
Video experiment	Vlakveld *et al.* [110]	1009 participants	Netherlands	Urban	Investigate how vehicle type (AVs, AVs with e-HMIs, and CVs), decision timing, and cyclists' trust in AVs influence their yielding behavior at intersections with right of way.
Design and Bicycle simulator	Hou *et al.* [103]	10 in design, 18 in BS	Canada	Urban	Explore and evaluate how different AV-cyclist communication interfaces affect cyclist confidence and interaction during lane merging scenarios.
Bicycle simulator	Kaß *et al.* [109]	20 participants	Germany	Urban	Investigate whether e-HMIs are useful in supporting safe and effective interactions.
Vehicle & Bicycle simulator, Survey	Ferenchak *et al.* [105]	10 participants, 310 trails	USA	Urban	Understand how AV communication strategies impact cyclists' perceptions.
Bicycle simulator & VR	Al-Taie *et al.* [111]	20 participants	UK	Urban	Evaluate three e-HMIs by comparing e-HMI versatility, acceptability, and usability and conclude with novel design guidelines for e-HMIs.
	Al-Taie *et al.* [112]	60 participants	UK/ Sweden/ Oman	Urban	Examine how cyclists' perceptions and behaviors toward interfaces conveying AV location and intentions, differ across cultures and traffic scenarios.

especially critical interactions. They emphasized that effective e-HMIs and attention to AV-specific behaviors are essential to improve cyclists' safety and trust. Further, Berge et al. [104] conducted semi-structured interviews and found that cyclists were hesitant to be outfitted with devices because they thought that the safety responsibility should lie with the AVs not cyclists. Kaß et al. [109] showed that cyclists' minimal velocity was higher with e-HMI than without, and that cyclists required a shorter time to cross the vehicle's trajectory during its braking maneuver with e-HMI compared to without e-HMI. Obviously, the e-HMI helped cyclists to interact safely with AVs. Also, Luger-Bazinger et al. [107] found that cyclists were open to e-HMI solutions, as long as these solutions can bring convenience and safety to cyclists. Bazilinskyy et al. [108] showed that the e-HMI and urgency level had a strong impact on the crossing decisions, whereas the complexity of the surroundings had no significant influence. Blinded windows caused participants to brake for the traditional vehicle, while driver eye contact encourages cyclists to continue cycling. In a follow-up experiment using the same method, the authors found that an e-HMI with 'GO' sign and blinded windows increased cyclists' detection ability of the vehicle's features. Furthermore, the participants preferred a segregated future infrastructure.

To evaluate and better design autonomous driving-bicycle interfaces, Hou et al. [103] first conducted an individual design session and created 32 interface designs. Most of the participants preferred visual interfaces and auditory cues when merging or approaching intersections or obstacles. Based on the results of the designing session, the authors prototyped interface designs and conducted a bicycle simulator (with VR headset) experiment. The authors found that AV-bicycle interfaces could improve rider confidence in lane merging scenarios, however, the authors pointed out the risks with over-reliance on interfaces. Ferenchak [105] identified that the existence of e-HMI improved the cyclists' perception. Participants preferred text-based e-HMI to non-text-based e-HMI. Perceptual acclimation effects were detected: comfort increased during testing, task load decreased, and trust and acceptance were more stable for all e-HMI configurations compared to no e-HMI configurations. Al-Taie et al. [111] found that cyclists preferred large, animated, color-coded e-HMIs that clearly show AV intentions, improving confidence and safety perception of cyclists. Vlakveld et al. [110] in

TABLE IX
KEY STUDIES ON INTERACTIVE BEHAVIOR TOWARDS AVs

Method	Study	Sample size	Country	Road	Main aim
Literature review	Vissers *et al.* [115]	-	Netherlands	-	Review existing knowledge on how cyclists interact with AV.
Naturalistic data (video analysis)	Pelikan *et al.* [116]	one year	Sweden	Campus	Investigate how an AV coordinates its interaction with cyclists and identify challenges in meeting cyclists' expectations of social interactions in traffic.
Video based VR study	Nuñez Velasco *et al.* [114]	47 participants	Netherlands	Urban road	Identify the main factors influencing cyclists' intentions to cross in front of AV versus CV and to assess the suitability of this method for studying cyclist behavior.
Controlled field experiment	Oskina *et al.* [113]	29 participants	Netherlands	Campus road	Investigate the safety of cyclists when they interact with an AV and compare it with their interaction with a CV.
Wizard-of-Oz study	Harkin *et al.* [117]	663 cyclists (51 interviewed)	Germany	Urban road	Investigate how vehicle automation influences the behavior and perceived safety of cyclists and pedestrians when interacting considering driving dynamics and demographic characteristics.

a high-quality video animation experiment concluded that participants intended more to yield to AVs, followed by conventional vehicles, and then to AVs with interface to cyclists. This conclusion also illustrated the importance of e-HMIs in improving cyclists' confidence in AVs. The authors also found that the less trust participants had in autonomous driving technology, the more likely they were to slow down or yield. Al-Taie et al. [124] investigated how cyclists' perceptions and behaviors toward interfaces differ across cultures. It was found that cyclists from different cultural backgrounds preferred the same interface that includes full information about AV location and AV intentions, but their understanding and acceptance of the interfaces was different. Cyclists from Sweden were more conservative and relied more on vehicle behavior and were skeptical of AV intentions even with an interface. Cyclists from Glasgow trusted the interface more but performed more shoulder checks than cyclists in Stockholm, and cyclists from Muscat were the most receptive to the interface, which may be because they were used to fast interactions with vehicles without bike facilities.

3) Interaction Behavior of Cyclists With AVs: Understanding **cyclists' interactions with AVs** is essential for ensuring the safety of both AVs and cyclists. Table IX summarizes the information of each study on this topic.

Velasco et al. [114] using 360° VR experiment indicated that the gap size and the right of way were the main factors to affect the crossing intentions while the vehicle type and vehicle speed did not have a significant effect. Harkin et al. [117] indicated that the automation status of the vehicle influenced cyclists' behavior. For example, when cyclists perceived the vehicle as automated, they tended to exhibit quicker crossing. Furthermore, vehicle dynamics (no matter AV or CV) as implicit communication, were particularly decisive for cyclists' behavior and seemed to influence their perceived safety. To investigate the safety of cyclists when interacting with AVs, Oskina et al. [113] considered four interaction scenarios in a controlled field test experiment: a manual or automated vehicle approaching from behind and following the cyclist, and a manual or automated vehicle approaching from behind and overtaking the cyclist. The results showed that the risks involved when an AV followed the cyclist were similar to when a manual vehicle followed the cyclist, while the risk levels of automated overtaking were higher than manual overtaking. The results also showed that longer interaction times led to an increased cycling speed and a decrease in the lateral distance of the cyclist to the curb. Therefore, the authors also recommended that the overtaking maneuver duration should not be too long, since the duration of interaction plays a significant role in the cyclists' perceived and objective risk. Pelikan [116] studied how cyclists interact with autonomous shuttle buses and showed that the shuttle buses investigated do not comply with cyclists' expectations of social coordination in traffic. On the other hand, cyclists might base their behavior on incorrect or unjustified expectations about the behavior of AVs [115]. Addressing this gap is critical because the successful integration of AVs into traffic systems depends on understanding how all road users (here the focus is on cyclists) react to AV's presence and the implications for their safety.

It can be concluded that there is increasing evidence that e-HMIs are appreciated by cyclists, however, further research is needed to gather evidence regarding their effectiveness in scenarios with different complexity levels. There is no consensus among different studies regarding cyclists' attitude and behavior towards AVs and AV-HMI, and that cyclists' attitude is greatly affected by age, cultural background, understanding, knowledge, and experience with AVs.

IV. ROAD INFRASTRUCTURE ADDRESSED IN VEHICLES AND-CYCLISTS' INTERACTIONS STUDIES

To structure the existing literature around the type of infrastructure considered in these studies, Table X categorizes the different studies according to the road environments investigated and follows the four angles adopted in this review. Percentages are calculated within each viewpoint (row-wise).

Table X reveals that most studies from CVs' point of view, were focused on overtaking behaviors on straight road sections (49% of studies) and mostly in rural areas (59%). This may be due to rural roads having fewer cycling facilities with more dangerous interactions as vehicles' speeds are higher. Research on shared roads (19%) has focused on drivers' attitudes and

TABLE X
CATEGORIZATION OF THE DIFFERENT STUDIES BY THE TYPE OF ROAD INFRASTRUCTURE CONSIDERED

Point of view of:	Roundabouts	Intersections	Shared road	Straight rural roads		Straight urban roads	
				With bicycle facility	No bicycle facility	With bicycle facility	No bicycle facility
Cyclists and CVs interactions							
CV	2(4%)	**13(28%)**	9(19%)	3(7%)	**10(22%)**	4(9%)	5(11%)
Cyclist	1(5%)	**6(32%)**	0	0	1(5%)	**5(26%)**	**6(32%)**
Cyclists and AVs interactions							
AV	0	**5(72%)**	1(14%)	0	1(14%)	0	0
Cyclist	1(5%)	**11(55%)**	3(15%)	1(5%)	1(5%)	1(5%)	2(10%)

TABLE XI
CATEGORIZATION OF THE DIFFERENT STUDIES BY THE RESEARCH METHOD APPLIED

Point of view of:	Naturalistic	Controlled outdoor	Vehicle driving simulator	Bicycle simulator	Video Animation	Survey Interview	Photo experiment
Cyclists and CVs interactions							
CV	**7(19%)**	2(6%)	**13(36%)**	1(3%)	2(6%)	**11**(30%)	0
Cyclist	**4(29%)**	**3(21%)**	2(14%)	2(14%)	2(14%)	1(7%)	0
Cyclists and AVs interactions							
AV	0	2(29%)	**3(43%)**	1(14%)	0	1(14%)	0
Cyclist	1(4%)	0	1(4%)	5(20%)	2(8%)	**14(56%)**	2(8%)

perceptions. There are fewer studies from a cyclist's perspective. Most of these are focused on overtaking behaviors in urban environment. Interestingly, it is found that AV-Cyclist studies focused more on interactions at intersections. Previous research shows that increased interaction at intersections poses challenges for AVs and cyclists. It is worth mentioning that because the infrastructure affects the interaction behavior between vehicles and cyclists, it is recommended that researchers should classify interaction behaviors by the road infrastructure and cycling facilities when comparing different research studies.

V. RESEARCH METHODS APPLIED TO STUDY VEHICLES AND CYCLISTS' INTERACTIONS

Table XI categorizes the literature based on the research methods applied in previous studies to understand which research methods were most used. Percentages are calculated within each viewpoint (row-wise).

As can be seen from Table XI the two most used methods for studying the perspective of CVs' point of view in CVs–Cyclists interactions, are naturalistic studies and driving simulators. The advantage of naturalistic studies is the level of realism, and the disadvantage is the low level of controllability. On the other hand, driving simulator experiments provide a higher level of controllability, but at the expense of ecological validity. These two methods were often used to study the lateral overtaking distance that CVs keep when overtaking cyclists. Studies on the safety perception and attitude of CV's driver and cyclists are usually conducted using video surveys, interviews, or regular surveys. From the perspective of AVs, it can be noticed that fewer studies were conducted, often using driving simulators, which is different from the most popular naturalistic method used in conventional vehicle research. This is expected, as AVs are not yet commonly deployed on the road, and driving simulators are an advantageous option due to safety and ethical concerns. Surveys [91] and interviews [94] were used to study the safety perception and attitude of AVs' passengers. From the perspective of cyclists, researchers focused on the comfort of cyclists and the acceptance of AVs, using mostly surveys and interviews. It is worth noting that only two studies [111], [112] used cycling simulator with VR were found. The introduction of VR in studies on interaction behavior will improve the experience in the simulator. Combining VR with a bicycle simulator, or even combining VR, bicycle simulator and vehicle driving simulator, will provide a new perspective for studying the interaction between AVs and cyclists.

VI. IDENTIFIED KNOWLEDGE GAPS

Interactions between CVs and cyclists have been relatively more explored compared with AVs-Cyclists, which can be also insightful for AVs-cyclists interaction research. In contrast, AV–cyclist interactions have been studied only to a limited extent and unsystematically.

From AV passengers' point of view, the factors impacting the interaction behavior (e.g., following, overtaking, crossing) and their perceived safety still need to be further studied. Firstly, cyclists are used to interacting with CVs rather than AVs by relying on implicit (i.e., vehicle dynamics) as well as explicit communication, such as giving hand signals, and eye contacts [94], especially in ambiguous situations where explicit communications were found to be of importance. Therefore, how AVs can utilize e-HMIs to replace the driver's role in CVs, giving corresponding feedback (e.g., yielding and giving priority) still needs to be further studied to achieve effective communication in various kinds of situations [85] and for diverse groups of cyclists. However, only a few studies investigated AV's e-HMI design focusing on cyclists [12], [109]. Especially on urban roads, cyclists' behavior changes quickly, and usually other road users can be in their vicinity, challenging scalability and generalizability. AVs must continuously adapt and interpret cyclists' cues and intentions to ensure safe interactions [89]. Secondly, there is still no consensus about the effect of HMI on AV's passengers. HMI design for AVs must consider not only external road users such as cyclists, but also the safety perception and comfort of its passengers. In turn, AV driving style may affect acceptance [7]. Although AVs' passengers (Level 4 +) do not participate in decision-making, they may be attentive to the road conditions, which will in turn affect their acceptance of AVs. However, there is only very limited research on the impact of AV's driving style on the safety perception, trust and acceptance of its passengers when interacting with cyclists. Therefore, research is needed to understand the preference of AV's passenger in terms of the AV driving style and its interactive behavior with cyclists in different conditions. Comparing passengers' safety perceptions, perceived comfort, and acceptance across multiple types of interactions, such as overtaking, yielding, or merging, would provide a more complete picture of passengers' perceptions. Furthermore, research regarding AVs - Cyclists' interactions in different weather and lighting conditions is lacking.

The introduction of AVs can improve cyclists' safety, however, there are still knowledge gaps regarding the impact of cyclists' perceptions and attitudes on their interaction with AVs. Firstly, **from cyclists' point of view**, there are still somewhat controversial findings regarding the relationship between the level of cyclists' knowledge about AVs and positive attitudes towards AVs. Thus, further exploration is needed regarding the factors that influence cyclists' safety and comfort perception when interacting with AVs. Moreover, research focusing on the communication between AVs and cyclists such as HMI on bicycles and e-HMI on AVs, despite the increasing attention of research efforts in the past few years, is still understudied. Some cyclists are hesitant to use AV's e-HMI or bicycle's HMI which bring much more responsibility and burden to them than before [104]. So, what factors affect the experience and acceptance of AV's e-HMI or bicycle's HMI, and how to design them, needs to be studied thoroughly.

In addition, **from both AVs' and cyclists' point of views**, no research so far, to the best of the authors' knowledge, has focused on the interactions on roundabouts. The interactive behavior on such road elements, which are commonly present on urban roads, needs to be explored.

At present, most research has obtained data using surveys, interviews, video/photo experiments and a few by using simulators or outdoor experiments. Therefore, there is a need for more driving and cycling simulator studies (with screen or VR headset) and controlled outdoor experiments to obtain more realistic data. It is worth noting that the realism of the experimental environment and the level of automation of the AV can affect participants' perceptions and behaviors. For example, studies using video or photo experiments often present simplified dynamics of the AV, which may not fully capture the complexity and uncertainty inherent in real-world interactions. Such simplifications may lead participants to have more positive attitudes toward AVs because they may overestimate system capabilities or assume ideal situations [11], [113]. In addition, the realism of the experimental setting can also affect participants' perception of interaction urgency and risk. Therefore, caution should be exercised when generalizing results from these methodologies because differences in experimental fidelity and AV features may systematically affect participants' perceptions and behaviors. Furthermore, ultimately, real-world data would be needed to validate the results from simulation experiments.

Overall, the interaction behavior between AVs and cyclists are still understudied. However, factors that could affect this interactive behavior have been identified from the literature review and are considered in the conceptual framework proposed in the following section.

VII. CONCEPTUAL FRAMEWORK & FUTURE RESEARCH DIRECTION

Based on the literature review and the research gaps identified in section VI, a conceptual framework has been developed and is presented in Fig. 2, and future research directions are proposed. The aim of this conceptual framework is to illustrate the various potential influencing factors of the interactions between AVs and cyclists. In this conceptual framework a solid line indicates that a factor is part of a category (e.g., weather is part of the environment category), a bold solid arrow indicates that a relation has been relatively well studied, while a relation that is understudied is indicated by a solid arrow, and those that are not yet or barely studied are indicated with dashed arrows. While existing studies have reported some associations among these factors, such as the influence of HMI on trust, the causal pathways and the directionality of these relationships remain largely unexplored. Consequently, this framework illustrates potential interactions rather than definitive causal links, which will require further empirical validation.

As conceptualized in Fig. 2, the interactions between cyclists and AVs are affected by four groups of factors including: the infrastructure, the environment, cyclists' factors, and AV's factors. Future research directions are structured in five sub-sections, following the four groups of factors in the conceptual framework, and a fifth sub-section regarding the research methodologies.

A. The Impact of Road Infrastructure on the AV–Cyclist Interaction Behavior

Infrastructure influences the interactions between AVs and cyclists (dashed arrow 1) through visibility (e.g., available sight distance), lateral space (e.g., facility type and possible oncoming traffic), intersection geometry (e.g., four-leg, Y-shaped, roundabout), and speed reduction measures (e.g., narrow traffic lanes). It also directly affects the cyclists and AV behavior (solid arrow 4 and dashed arrow 7, respectively). Further in the AV technology design, the infrastructure

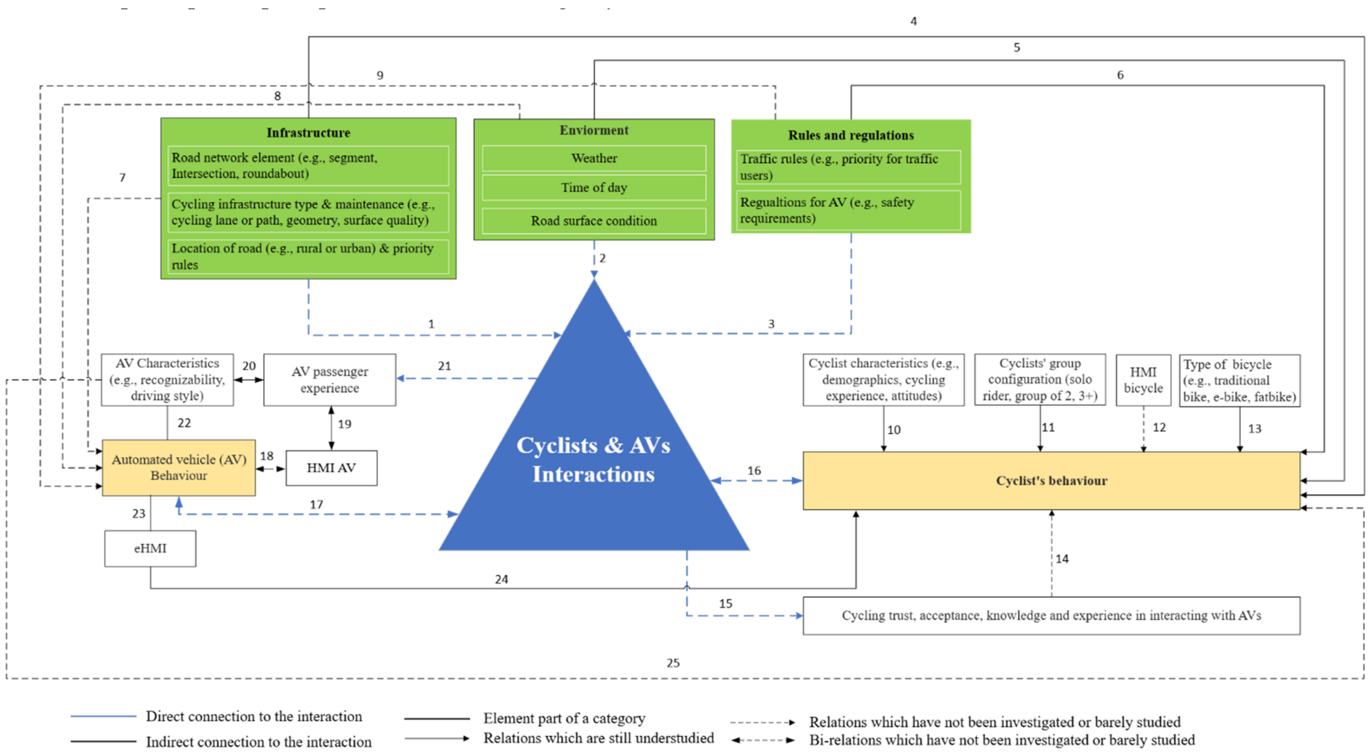

Fig. 2. Conceptual framework of interaction behavior between AVs and cyclists.

affects the AV behavior, such as the design of AV driving styles (e.g., taking earlier responses and more conservative driving in situations of unclear priority, and designing overtaking clearance).

For the research on AV-cyclist interaction behavior considering the road infrastructure, there is a lack of research on crossing interactions on roundabouts, and only a few studies focused on four-leg intersections, and Y-intersections (dashed arrow 1). Relevant research directions on crossing behavior at intersections/ roundabouts from the perspective of AVs' passengers include the design of the yielding behaviors of AVs at intersections/roundabouts taking into account traffic safety and the constraints of traffic laws and regulations, and to ensure the comfort and acceptance of AV passengers. Both yielding behavior and passenger comfort are closely related to the speed and acceleration of AVs, and the timing of response (e.g., from what distance the vehicle starts to respond). In addition, because there is little research on AV-cyclist interactions, the number of studies on overtaking behavior in urban and rural road conditions is also limited. Furthermore, the impact of different cycling infrastructures on AV - cyclist interaction on rural and urban roads also needs to be systematically studied. So, the research question which arises here is: how AVs interact with cyclists on different types of roads and different cycling facilities? For example, if AVs will be driving on roads with two-directional traffic (e.g., 30 km/h access roads in urban areas and 60 km/h access roads outside urban areas, which in the Netherlands are typically without a center line separating the two-directions), what impact will oncoming traffic have on the interaction behavior? Further, the overtaking strategy and lateral distance acceptance when overtaking cyclists from the perspective of AVs' passengers and cyclists need to be studied.

B. The Impact of Environment and Rules on the AV–Cyclist Interaction Behavior

Environmental factors (dashed arrows 2 and 8) could be challenging for AV's sensors, HMI, and e-HMI designs and visibility and might affect AVs interactions with cyclists. AVs equipped with multiple sensors are expected to have detection capabilities that exceed human drivers in low-visibility weather. Although multi-sensor AVs may exceed human drivers in detection under poor visibility, the resulting behaviors still need to be acceptable to AV passengers and understandable to cyclists. Therefore, will the interactive behaviors generated based on this capability be accepted by the AV's passengers? Further, whether the information shown by the e-HMI can be noticed by cyclists in fog or at night, and how they would adjust their behavior compared to when visibility is good during the day. In low-visibility settings, cyclists may miss e-HMI cues and rely more on implicit kinematic signals. AV passengers may prefer earlier responses and a more conservative driving style. So, how do we design the HMI so that AV's passengers can accept AV's driving style? In addition, when studying the environment, the lighting, weather, and visibility conditions should be described and their impact on yielding decisions, braking time, minimum approaching speed, perceived risk, and acceptance should be summarized so that the results of different studies can be compared. The impact of specific weather and visibility conditions on AV–cyclist interactions remain an open topic and warrants targeted investigation. What is the impact of different weather and visibility conditions on the AV-cyclist interactions?

Besides environmental factors, traffic rules and regulations (dashed arrows 3 and 9) for AV also influence AV behavior, for example, in how AV yields to cyclists. These traffic rules and regulations are likely to also affect cyclists' behavior, however, there is currently lack of knowledge of how future traffic rules and regulations for AVs would affect cyclists' behavior. Are traditional traffic rules sufficient to handle complex urban traffic environments between AVs and cyclists, and would the AVs be aware and strictly adhere to these rules? How do these rules and regulations' restrictions on AV behavior (e.g., strict priority, HMI/e-HMI message) affect the experience of passengers and cyclists (perceived safety, trust, and acceptance)? What impact will AV driving styles that break existing traffic rules have on the AV and cyclist experience?

C. The Impact of Cyclists' Factors on the AV–Cyclist Interaction Behavior

The cyclist's behavior will be affected by cyclists' characteristics (solid arrow 10), cyclists' group configuration (solid arrow 11), bicycle HMI (dashed arrow 12), type of bicycle (solid arrow 13) and cyclist's trust, acceptance, knowledge and experience interacting with AVs (dashed arrow 14). First, cyclists' interactions with vehicles vary depending on their age, gender, and experience, as well as on cycling culture and infrastructure across countries. Therefore, it is important to be cautious that findings from different regions with high cycling penetration and infrastructure, such as the Netherlands or Denmark, may not be directly applicable to regions with lower cycling penetration. Therefore, the findings should be interpreted based on the characteristics of the cyclists and the study location. In addition, after increasing the interaction experience, will cyclists trust AVs more or become more skeptical? Further, what impact will the interaction experience have on the cycling trust and experience (dashed arrow 15)? Will cyclists develop over-trust or mistrust behaviors for AVs overtime? Studies on CV-cyclists interactions found that for different cyclists' configurations, the overtaking behavior of a CV is mainly affected by whether it can invade the opposite lane. However, there is no research on how cyclists' configurations affect the interaction behavior of AVs and cyclists. To help AVs better identify the intentions of cyclists, some researchers have conducted preliminary research on bicycle HMI (dashed arrow 12). However, the use of bicycle HMI has aroused the disgust of cyclists, who believe that it has increased the burden of riding. Therefore, further exploration is needed to improve the design of bicycle HMI and how to drive AV to correctly recognize cyclist's gestures and overtaking intentions. Regarding the type of bicycle, different bicycle types (such as city bike, mountain bike, e-bike) have different performances and capabilities. From the perspective of cyclists, will it affect their interaction behavior with AVs?

D. The Impact of AV's Factors on the AV–Cyclist Interaction Behavior

Currently, there are few studies focusing on how AV behavior affects the interactions between AVs and cyclists (dashed double-arrow 17), and the feedback mechanism that could teach the AV to adapt its behavior to increase the safety of these interactions. Furthermore, there is limited research on the design of HMI AV (dashed double-arrow 18) adapting to different age of road users and the impact of HMI on AV's passenger (solid double-arrow 19). Regarding the impact of AV's passenger characteristics (solid line 22) on the AV passenger experience, there is still a lack of systematic research. Current studies indicate that AV's passenger's age and gender affect how AV's driving style is experienced (solid double-arrow 20). In addition, some researchers found that AV characteristics, such as blind windows, also affect the cyclist's behavior (dashed arrow 25). Hence, how do the AV characteristics and driving styles affect cyclists' interaction? And how does the difference between AV's driving style and its passenger's preferred driving style impact the interaction behavior with cyclists?

In addition, although there are several studies about the impact of e-HMI (solid line 23) on cyclists' behavior, there is still some controversy. What are the effects of e-HMI with different designs, different modalities, and different location on cyclists (solid arrow 24)? How to modify e-HMI to improve the acceptance and safety of cyclists? These are questions that still require further research.

E. Research Methodologies

So far, the research methods used for investigating AV-cyclist interaction behavior were mostly interviews, group discussions, and surveys. We argue that we need much more empirical data collected from simulators and field tests to reflect as realistically as possible the interactive behavior between AVs and cyclists. Specifically, for the analysis of interactive behaviors, such as the impact of different factors on the yielding or overtaking decisions, more driving simulator data or field data are recommended to be collected.

Real-world trials of new technologies are usually expensive, time-consuming, and most importantly potentially dangerous. Therefore, simulation provides a safe and controlled environment for testing interactions with novel technologies and data collection [118], however its fidelity and absolute validity is debatable [119], especially when the goal is to investigate two-way interactions between agents in real world environment [120]. Despite these limitations, simulation is still the most used approach for initial testing of new technologies. This is for ethical and safety reasons. However, as simulations cannot always reach absolute validity, it is essential that these new technologies get tested in real-world (controlled) environments and in real traffic conditions. Especially for observing two-way interactions, the impact of surrounding road environment and traffic, visibility and weather effects, and realistic dynamics between the two agents, which sometimes include explicit communication, such as eye-contact, real-world testing, in controlled environments and on public roads, is crucial. The main consideration when setting up such experiments is to guarantee the safety of the participants or road users involved in the testing, and getting ethical approval for the testing.

Ethical review procedures outline the standards for interactive behavioral research, a mandatory process for questionnaires, surveys, driving simulator studies, and real-world research. Furthermore, real-world experiments require clear safety management and careful standardization of conditions. Because lighting, weather, visibility, and surrounding traffic conditions can affect interactions but are only partially controllable, participant engagement time should be scheduled and recorded to ensure exposure falls within the pre-defined design range. If full control is not possible, these conditions should be maintained or reported consistently to ensure interpretability and comparability.

Therefore, it is recommended in testing of new technologies for safety reasons to follow a step-by-step approach: first testing the new technology in a simulation environment or a controlled real-world experiment testing, followed by testing on public roads. Beyond safety considerations, we also need to consider the consistency of the experimental setup in real-world, including lighting, weather, visibility, and surrounding traffic conditions.

VIII. CONCLUSION

Overall, the main contribution of this paper is the identification of the knowledge gaps, the proposed conceptual framework regarding the interaction behavior between AVs and cyclists, and the proposed future research directions. The conclusion of this paper is structured following the main research questions presented in the introduction section.

1) What Can We Learn From Current Interactions Between CVs/AVs and Cyclists?:

Existing studies on the interaction between CVs and cyclists have shown that infrastructure design, vehicle behavior and cyclist behavior are key factors affecting these interactions. In addition, traffic cultural background, traffic rules and regulations were also shown to significantly affect these interactions. For AV-cyclist interactive behavior, although current research is still limited, some key conclusions can be derived. First, there is evidence that cyclists have a positive attitude towards AV's e-HMI. It was also found that implicit communication (i.e., AV's dynamics) can also be used to communicate the intent of the vehicle to the cyclists. From the perspective of AVs' passengers, they tend to prefer AVs with conservative behavior (low speed or earlier yielding), but it was also found in one study [88] that AV passengers, unlike human drivers preferred, in driving simulator experiments, to let AVs pass first rather than cyclists at intersections. The results of these limited studies need to be considered while keeping in mind their limitations and the specifications of the AVs and how they have been modelled in these studies, which might limit the generalizability and scalability of the results.

2) Which Determinants Need to be Included in a Conceptual Framework to Investigate AVs–Cyclists Interactions, and How do These Determinants Relate to Each Other?:

The conceptual framework includes AV-related factors, such as AV characteristics, e-HMI, and AV passenger experience; cyclist-related factors, including riding experience, trust in automation, and expectations of AV behavior; infrastructure characteristics, such as road type, bicycle facilities, and intersection design; and environmental factors, including weather, visibility conditions, etc.

3) What Are the Remaining Knowledge Gaps and Future Research Directions Given the Proposed Conceptual Framework?:

Despite the growing research on AV-cyclist interactions, significant knowledge gaps remain. First, there is limited research on how AVs interact with cyclists in different road infrastructures (e.g., roundabouts, intersections, and access roads), especially in terms of overtaking and yielding strategies. Second, the impact of environmental conditions (including weather and visibility) on AVs–Cyclists interactions also require further research. Research on cyclist-related factors (e.g., group riding configuration, bicycle type, and experience with or trust in AVs) is limited and often is considered explorative. Similarly, the role of AV factors such as AV characteristics (e.g., blind windows, recognizability), and the design of e-HMI in cyclist safety and acceptance have not been systematically studied. Finally, there is an urgent need for more empirical research using field experiments, controlled outdoor experiments, simulator study and physiological measurement data to facilitate the generalization of conclusions to actual situations.

Future research should focus on addressing these research gaps. Among the five major research directions proposed, considering the experiments complexity, research on cyclist trust and HMI design may be more feasible in the short term because these topics can be explored through simulation or VR experiments. In contrast, weather-related factors, while important, may require larger-scale naturalistic data collection to study their impact on the performance of the AV sensing technology, and as a result on the AV behavior and interaction with cyclists. In addition, research on the impact of AV driving style on Cyclists–AVs interactions should also be accelerated. Experiments can be first conducted in driving and riding simulators, but caution should still be exercised when generalizing the conclusions to real-world results.

In conclusion, this literature review not only underscores the significant progress made in interaction behavior between AVs and cyclists but also highlights the need for continued research to fully address the complexities of the introduction of AVs into current traffic and their future interactions with cyclists.

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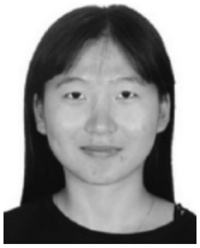

Jinyang Zhao received the B.S. degree in automation and the M.S. degree in control theory engineering from Jilin University, Changchun, China, in 2017 and 2020, respectively. She is currently pursuing the Ph.D. degree with the Department of Transport and Planning. Her current research focuses on the interaction behavior of AVs and cyclists and traffic safety.

Serge P. Hoogendoorn received the M.Sc. degree in applied mathematics and the Ph.D. degree in civil engineering from Delft University of Technology in 1995 and 1999, respectively. He is currently a Full Professor with Delft University of Technology, where he holds the chair position in traffic operations and management and is a Distinguished Professor in smart urban mobility. He has authored or co-authored over 280 articles. His research interests include traffic flow theory, traffic management, ITS, and active mode mobility. He is an IAC Member of ISTTT. He is a member of the TRB Traffic Flow Theory Committee. He was a recipient of the ERC Advanced Grant in 2014. He is the Chair of the TRB Crowd Modeling and Management Subcommittee. He is an Editor of *Journal of Advanced Transportation*, EJTL, and EJTIR.

Haneen Farah received the Ph.D. degree in transportation engineering from the Technion—Israel Institute of Technology. Before joining TU Delft, she was a Post-Doctoral Researcher with the KTH-Royal Institute of Technology, Stockholm, Sweden. She is currently an Associate Professor with the Department of Transport and Planning and the Co-Director of the Traffic and Transportation Safety Laboratory, Delft University of Technology. Her research interests include road infrastructure design, road user behavior, and traffic safety. She is also examining the implications of advances in vehicle technology and automation on the road infrastructure design and road user behavior in the framework of several national and international projects.