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Resilient interactions between cyclists and drivers, and what does this mean for automated vehicles?

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A B S T R A C T

The road transport system is a complex sociotechnical system that relies on a number of formal and informal rules of the road to ensure safety and resilience. Interactions between vulnerable road users and drivers often includes informal communication channels that are tightly linked to social norms, user expectations and the environmental context. Automated vehicles have a challenge in being able to communicate and respond to these informal rules of the road, therefore additional technologies are required to better support vulnerable road users. This paper presents the informal rules that cyclists and drivers employ within a cyclist overtake manoeuvre, through qualitative data collected from focus groups and interviews with road users. These informal rules are classified into the key elements of resilience (monitor, detect, anticipate, respond and learn) to understand how they guide the resilient interactions between road users. Using a human factors approach, the Perceptual Cycle Model shows how information is communicated between different road users and created by the situational context. This is then used to inform how automation will alter the communication between cyclists and drivers, and what additional feedback mechanisms will be needed to support the systems resilience. Technologies that can support these feedback mechanisms are proposed as avenues for future development.

1. Introduction

The introduction of autonomous vehicles (AVs) to the road transport system must be reviewed with a sociotechnical systems approach (Auvinen and Tuominen, 2014; Banks et al., 2018a; Milakis, 2019) and one important aspect of the sociotechnical assessment of the road transport system is resilience (Mattsson and Jenelius, 2015). Resilience within transportation systems is vitally important to reduce disruption, maintain safe standards and ensure it meets the needs of its users. The field of resilience engineering aims to provide a proactive approach to safety within complex system, by reviewing the safety of the system as a whole, rather than reducing it to its individual components (Hollnagel, 2013). This aligns with contemporary human factors approaches that strive to move away from the term 'Human Error' as the cause of incidents and disruptions, and a move towards systemic approaches that can account for the system in its entirety (Dekker 2016; Shorrock, 2013; Read et al., 2021). By taking a proactive approach, resilience engineering aims to anticipate possible risks and system failures before they occur and design against them, rather than relying on the benefit of hindsight (Hollnagel, 2017). Furthermore, it understands that systems can be subject to positive variability as well as negative variability and that both of these forms of variability need to be considered when assessing the resilience of a system (Cornelissen et al., 2013; Read et al., 2021). Understanding that the performance of a system is subject to both good and bad forms of variability can assist in proactively supporting positive variability and restricting negative variability (Cornelissen et al., 2013).

Hollnagel (2013) outlined four key cornerstones of resilience: monitoring, anticipating, responding and learning. Systems that can effectively manage performance across these four key areas will have enhanced resilience. Transportation systems require resilience through the application of each of these cornerstones (Mattsson and Jenelius, 2015; Parnell et al., 2023). Road users must monitor the roadway, anticipate the actions of other road users, respond to the actions of others and learn the appropriate roadway behaviours. Parnell et al. (2023) applied the resillience cornerstones to autonomous vehicles and identified an additional cornerstone, 'detect', which was demonstrated to be particularly important when considering the interaction between automated systems and humans. The detect element refers to the detection (visual, audio or mechanical) of possible hazards in the environment, which is vitally imporatant within resillient interactions. In non-automated interaction the dection falls to the human senses and skill based behaviours to alert us to particular events. Interactions with automated systems will rely on detection events that will rely on sensor technologies. The appropriate design and accuracies of these technologies is important to ensuring resillience (Parnell et al., 2023).

This paper will apply these five cornerstones to review the resilience in the future interactions between cyclists and AVs. The importance of

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reviewing the interactions between AVs and vulnerable road users was highlighted in the AV collision with a cyclist who was crossing the path of vehicle, wherein poor communication resulted in the death of the cyclist (Merriman, et al., 2021). AVs will change the interactions between different road users, as well as the nature of these interactions and communication channels (Dey and Terken, 2017; Straub and Schaefer, 2019; Lee et al., 2021). For example, at Level 3 automation (SAE, 2021) and above, the driver may engage in non-driving related secondary tasks (e.g. reading) and at Level 5 automation (SAE, 2021), the driver may no longer be seated in the driving seat. As such, communication between the AV and the vulnerable road user, rather than between the driver and the vulnerable road user, becomes important. Yet, the methods through which AVs should communicate with other road users is yet to be determined (e.g. Brill et al., 2023). Within this paper we propose that the current interactions between cyclists and drivers should be used to guide the design of interfaces and communication methods for AV interactions, based on the mental models and expectations of road users. This takes a human factors and user-centered approach through collecting road user feedback and applying it to models of human behaviour.

A focus within this paper will be on the informal rules of the road which guide interactions between all road users and allow for cooperation (Björklund and Åberg, 2005; Latham and Nattrass, 2019). Informal rules are tightly linked to expectations, social norms and specific situational context (Björklund and Åberg, 2005). These informal rules are separate to the formal rules laid out in The Highway Code (in the UK and comparative rule books in other countries). Some informal rules may be unsafe behaviours that lead to negative variability within the roadway system, for example speeding, traveling too close to the vehicle in front and not driving with both hands on the wheel. Yet, there are also informal rules performed by road users that can be attributed to positive variability and enhanced resilience, for example using eye contact, hand gestures and road positioning to communicate intentions to other road users (Walker, 2007; Guéguen et al., 2015). These informal rules are matched to the set of circumstances experienced by all road users involved and therefore are similarly interpreted and applied through informal and formal communication channels (Latham and Nattrass, 2019). Björklund and Åberg (2005) showed that informal rules of the road influence the priority given to different types of road users at intersections.

Latham and Nattrass (2019) discuss the 'normative patterns of negotiation' that inform and structure how road users interact with each other. These normative patterns of negotiation refer to the common understanding between road users within a given scenario or situation. This common understanding enables formal rules to be interpreted with respect to the situation and there may be the need, in certain situations, for formal rules to be disregarded in favour of informal rules that better align with the current situation. While these are not formalised within The Highway Code, they do offer some form of resilience within the road transport system through enhanced communication strategies (Sucha et al., 2017; Dey and Terken, 2017). These communication strategies are particularly useful to interactions between vulnerable road users and drivers, who use a mixture of implicit (e.g. vehicle speed or distance) and explicit cues (e.g. horn, hand gestures, eye contact, shoulder checks, bell) to communicate with each other and enable safe interactions on the road (Hou, et al., 2020; Latham and Nattrass, 2019; Lee et al., 2021; Lundgren et al., 2017; Walker, 2005). These communication strategies are not available to AVs, therefore interactions between different road users must be reviewed to determine how AVs can best interact and communicate with different road users.

Previous work by Parnell et al. (2023) has reviewed resilience within the interaction between drivers and cyclists within an overtake scenario, looking at current overtaking behaviour and how this behaviour will adapt with the inclusion of automated vehicles, see Fig. 1 for a representation of the cyclist overtake scnerio that was used. For the purpose of this work Level 3 automation, as outline by the Society for

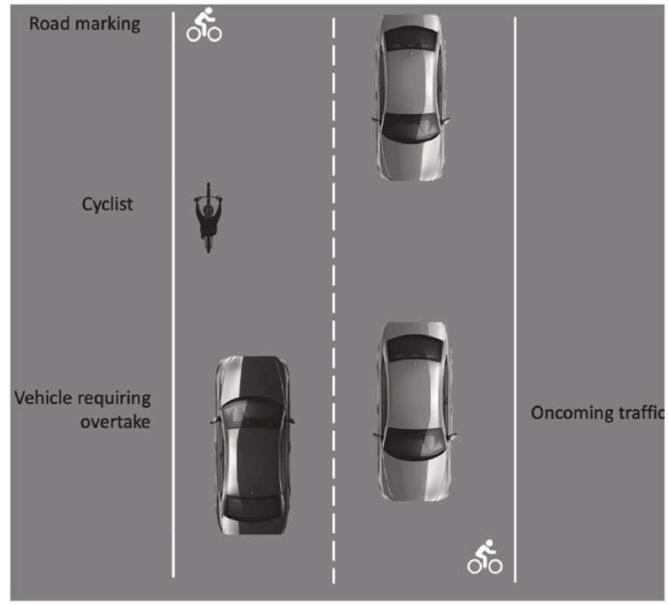


Fig. 1. Cyclist over take scneario from Parnell et al. (2023). The black vehicle on the left-hand side of the road is to overtake the cyclist ahead.

Automotive Engineers (2021) was considered. This was due to the need to capture the near-mid term introduction of AVs, which will still require some driver supervision. Many experts still consider Level 4 and 5 automation to be a long way off (Tabone et al., 2021). Parnell et al. (2023) used human factors methods to map the individual tasks involved in manual and automated vehicle overtake scenarios, whilst also accounting for the opportunities for failures to occur. This revealed that AVs will increase the complexity of the overtaking scenario, stressing the need for the sociotechnical systems approach, however, they also showed that if automation is implemented effectively, it can bring the opportunity to enhace resillience within the road transport system (Parnell et al., 2023). This is owed to increased connectivity between elements in the system and increased diversity in the failure prevention options.

Parnell et al. (2023) used desktop based methods, including Operator Event Sequence Diagrams and the Systemic Human Error Reduction and Prediction Approach (SHERPA) to predict possible sources of error and failure resolution strategies. This approach reviewed 'best-practise' in cyclist-vehicle interactions as stated in The Highway Code and using input from road safety experts. Yet, the complex nature of road transport systems suggests that there is a significant varibility and adaption occurs within driver-cyclist interactions, in contrast to the formal rules of the road (e.g. Walker, 2007). Therefore, this work aims to understand drivers and cyclists self-reported behaviour during a cyclist overtake scenario, to understand how resilience is currently embedded within non-automated cyclist overtake manoeuvres. Self-reported behaviour from drivers and cyclists will explore the 'patterns of negotation' that need to be considered in the introduction of AVs (Latham and Nattrass, 2019). This aims to capture the positive and negative variability within the cyclist-driver interactions that currently exist within the road transport system, with a focus on the informal rules of the road that are applied in contrast to the formal Highway Code. This will then be built upon to capture how cyclists and drivers envision automated vehicles to interact, and what information or communications they would like to receive from the AV. This requires taking a human factors approach that incorporates together concepts of resillience and sociotechnical systems theory.

The current (non-automated) decision-making processes, actions and interactions with the environment that occur in a current driver-cyclist overtake will be captured through focus groups and interviews with cyclists and drivers. Qualitiative analysis will allow for in-depth insights into the procedures and thought processes that drivers and cyclists have during cyclist overtake maneuvers such at that presented in Fig. 1. Focus groups with a mix of drivers and cyclists will enable discussions on the different perspectives of this scenario, how they interpret each others actions and any patterns of negotiation. The interactions from the non-automated driver-cyclist overtake will be assessed to understand how AVs may alter the interactions with cyclists in this scenario, and drivers and cyclists will be asked what information needs to be communicated between the AV and the cyclist to ensure that the system remains resilient. The utility of digital technologies to support this communication will then be reviewed. The Perceptual Cycle Model (PCM: Neisser, 1976) will be used to frame the analysis, this is a naturalistic decision making model that enables decisions to be reviewed within the broader context of the environment that the actors are situated within, as well as reviewing the resulting actions and elents that arise from the decision. More detail of this method is given in the method section below.

2. Method

Data was collected from two in-person focus groups and five online interviews, with a total of 14 participants (7 male, 6 female, 1 non-binary). The methods for these two activities are presented below. Ethical approval was gained by the University's Faculty Ethics Committee (Ergo: 79904).

2.1. Participants

The first focus group consisted of one male cyclist, one female driver and two participants who were both cyclists and drivers (1 male, 1 female). The second focus group consisted of one female driver and four participants that did both (3 male, 1 non-binary). Five online interviews were conducted with two cyclists (1 male, 1 female), two drivers (1 male, 1 female) and one female who did both. Of the participants who did both, two drove more (1 male, 1 non-binary), two cycled more (1 female, 1 male) and three cycled and drove for the same amount of time (2 male, 1 female). Full demographic information is shown in Table 1. All participants received £10 cash (in-person) or voucher (online) as renumeration for taking part.

2.2. Materials

During the focus groups and interviews a powerpoint presentation was presented with some background information on the study aswell as the questions that were posed during the focus group. The questions posed in the focus groups and interviews were semi-structured, so the questions were used as the starting point, however additional questions were asked depending on the discussions and responces from participants.

The structure of the questions fell into two phases. The first phase of the focus groups and interviews asked participants about their current driver-cyclist overtake experiences. They were asked to talk through an overtake experience (from their respective road user status), detailing their thoughts, actions and information cues that they used. Participants were presented with a video that represented the scenario given in Fig. 1. The video was used to be more engaging and prompt the participants to think about their own experiences. The researcher prompted participants throughout, where appropritate, on the methods that they use to communicate with other road users, environmental factors (e.g. weather, hills, bends) and other road user characteristics which may influnce their trust and decision-making in overtake scenarios. The second phase of the focus groups and interviews asked participants about their thoughts and recommendations for a future AVs interactions during a similar overtake scenario. They were asked about how a AV should communicate with a cyclist during an overtake, including the information (if any) that they would want it to provide, the modality for this information and the location (on the AV or the bicycle). They were reminded that the scenario was hypothetical, there was no right or wrong answers and to think open-mindedly without being limited to what is currently available.

2.3. Procedure

The study was advertised by the authors through social media, the organisations intranet and fliers. Participants who expressed an interest to take part were sent an online demographics questionnaire which asked about their age, gender, ethnicity, current employment status, area within which they currently live and whether they identify as a driver, cyclist or cyclist and driver. They were then asked to sign up to an in-person focus group or an individual online interview session. Flexibility in scheduling the participants was given to enable a broad range of participants to take part in the study. All the interviews were run online with the participant and researcher, using the video conferencing platform Microsoft Teams. Both focus groups were run in-person with all participants sitting in the same room as the researcher. The researcher led the participants through the questions and guided the conversation to remain related to the research questions.

The focus groups each lasted 1.5–2 h and the interviews lasted around 1 h for each participant. To ensure consistancy between both activities, Microsoft Teams was used to record the audio data from the focus groups and interviews. The recordings were transcribed by the researcher before being deleted to remove identifying characteristics.

Table 1
Participant Demographic data.

Demographics		Cyclists		Drivers		Cyclists and Drivers	
		N		N		N	
Gender	Males	2		1		4	
	Females	1		3		2	
	Non-Binary	0		0		1	
Ethnicity	White	3		2		7	
	Asian	0		1		0	
	Mixed	0		1		0	
Current Employment Status	Student	0		1		0	
	Part-Time	0		0		1	
	Full-Time	3		2		6	
	Retired	0		1		0	
Area Currently Live	Urban	3		2		6	
	Rural	0		2		1	
		M	**SD**	**M**	**SD**	**M**	**SD**
Age (years)		44.00	7.81	35.75	18.25	44.43	14.08

2.4. Data analysis

The recorded focus groups and interviews were transcribed and analysed by the research team. The reports were then analysis using the PCM framework.

2.4.1. The Perceptual Cycle Model (PCM)

The PCM is a naturalistic decision making model that enables decisions to be reviewed within the broader context of the environment that the actors are situated within, as well as reviewing the resulting actions and events that arise from the decision. It has been applied to the raod transport domain to review interactions between different road users from a sociotechnical systems approach (e.g. Revell et al., 2020; Banks et al., 2018b; Liu et al., 2023). The model has three key elements: 'Schema', 'Action' and 'World' which are reciprocal and influence each other in a cyclical manner (see Fig. 2). Schemas are an individual's cognitive map of the world which are structured from past similar experiences and learnt information (Bartlett, 1995). These schemas are triggered by information in the environment and affect how the individual interprets the environment, their anticipated interactions and their expectations. Actions are the repertoire of possible actions. The schemas direct the actions that the individual performs to respond to the information in the environment. The World element of the PCM represents the events and information that are available in the environment. This information triggers an existing schema and can also modify and update the schema following the individual's experience. This updated schema will then influence the individual's subsequent interactions with the environment and the process continues.

The PCM can capture the world environment of a given scenario and suggest how it is interpreted by the respective road users to inform their actions and decision making. Two individuals can be mapped onto the same PCM to show how the users interact across a specific scenario (e.g. Parnell et al., 2021). Therefore it is proposed that it can capture the 'patterns of negotiation' discussed by Latham and Nattrass (2019), through showing how road users' interactions are deeply connected to the set of circumstances in the world environment that they are situated within. Furthermore, the different phases of an event can be captured on the PCM to show the development of a decision-making process (e.g. Plant and Stanton, 2015; Parnell et al., 2021). Therefore, the driver and the cyclist can be presented on the same PCM as well as their interactions across the monitor, detect, anticipate, respond and learn phases of resilient interactions.

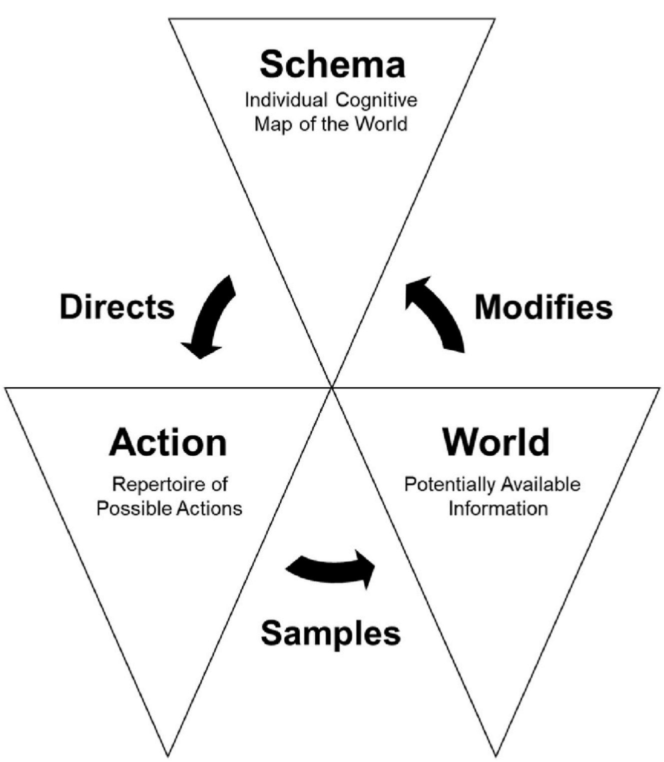


Fig. 2. Representation of the PCM, adapted from Neisser (1976).

The first phase of the analysis focused on the driver overtake without automation. The tasks identified from the Highway Code and mapped out in Parnell et al. (2023), with road safety experts and human factors professionals, were used to develop this PCM. The mappings to the cornerstones of resilience as identified in Parnell et al. (2023) were used. This acted as the baseline of best-practise to compare the participants self-reported behaviour against. Following this, deductive coding was run on the transcripts from the interviews and focus groups. The Schema World Action elements of the PCM were used as the initial coding framework before they were then mapped onto the phases of the overtake in line with the resillience cornerstones (monitor, detect, anticipate, respond, learn). The coded transcripts were then compared to the PCM developed from the Highway Code and Parnell et al. (2023). This was done individually for drivers and cyclists to establish a PCM for driver performance and a PCM for cyclist behaviour. The data from participants that were both cyclists and drivers were split across the instances when they discussed each of the two transport modes (during the data collect these road users were asked to make it clear which form of transport there were discussing when answering the questions).

The second phase of the interviews and focus groups discussed AVs and cyclist interactions with AVs within a AV-cyclist overtake. A PCM of the AV scenario was created, again using the tasks from Parnell et al. (2023) in the same way that the non-automated PCM was created. These tasks respresent the formal tasks of intended AV interactions, as identified by human factors experts. The discussions by participants about their perceptions, attitudes and intended interactions with AVs were contrasted to this PCM to review where further support may be needed to increase the resilience in the interactions between AVs and cyclist. Coding of the transcripts used the resillience cornerstones and schema, action, world codes in the same way as was done for the discussions on the non-automated overtake. A summary of this process is given in Fig. 3.

3. Results

The results are presented across the two phases of the study (as outlined in Fig. 3), the first phase present the results from the questions asked in realtion to current, non-automated, cyclist overtaking behaviour. The second phases presents the results from the questions that focused on automated vehicles and their interactions with cyclists in the future.

3.1. Non-automated overtaking behaviour

Using information detailed The Highway Code and a task assessment of a cyclist-driver interaction during an overtake from Parnell et al. (2023), a PCM of a non-automated, overtake scenario was developed, see Fig. 4. This shows the cognitive processing of the driver and the cyclist through their respective schema's, the actions that they take and the information that is utilised from the world. These tasks were identified by three road safety analysts and reviewed by three human factors experts. They suggest the safe interaction that should occur as outlined by the Highway Code and road safety best practise. However, it well known that road users do not always follow best practise and the formal and informal rules of the road may be substituted depending on the broader road context (Björklund and Åberg, 2005; Latham and Nattrass, 2019).

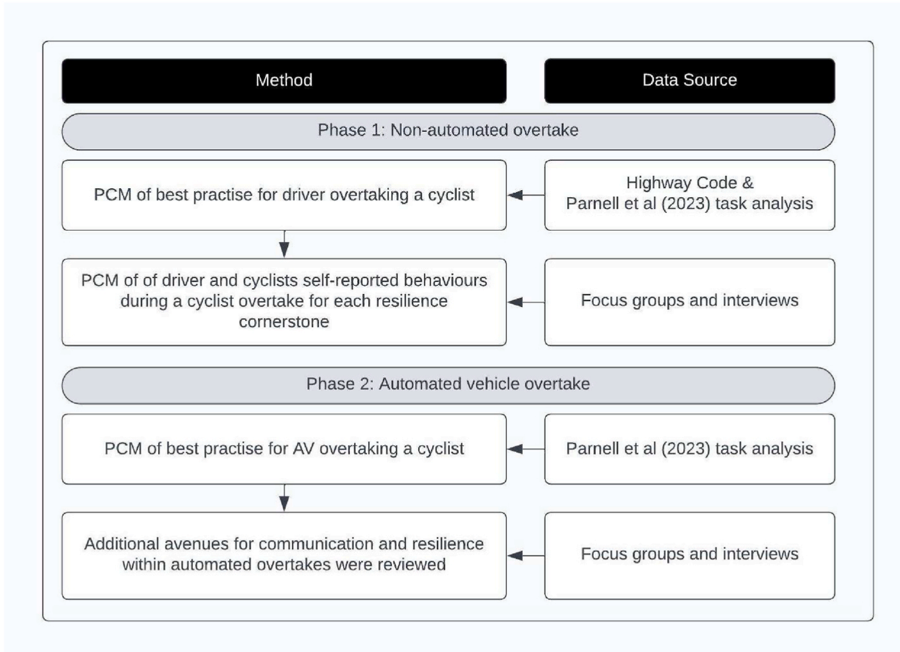


Fig. 3. Summary of the data anlysis processes in this study.

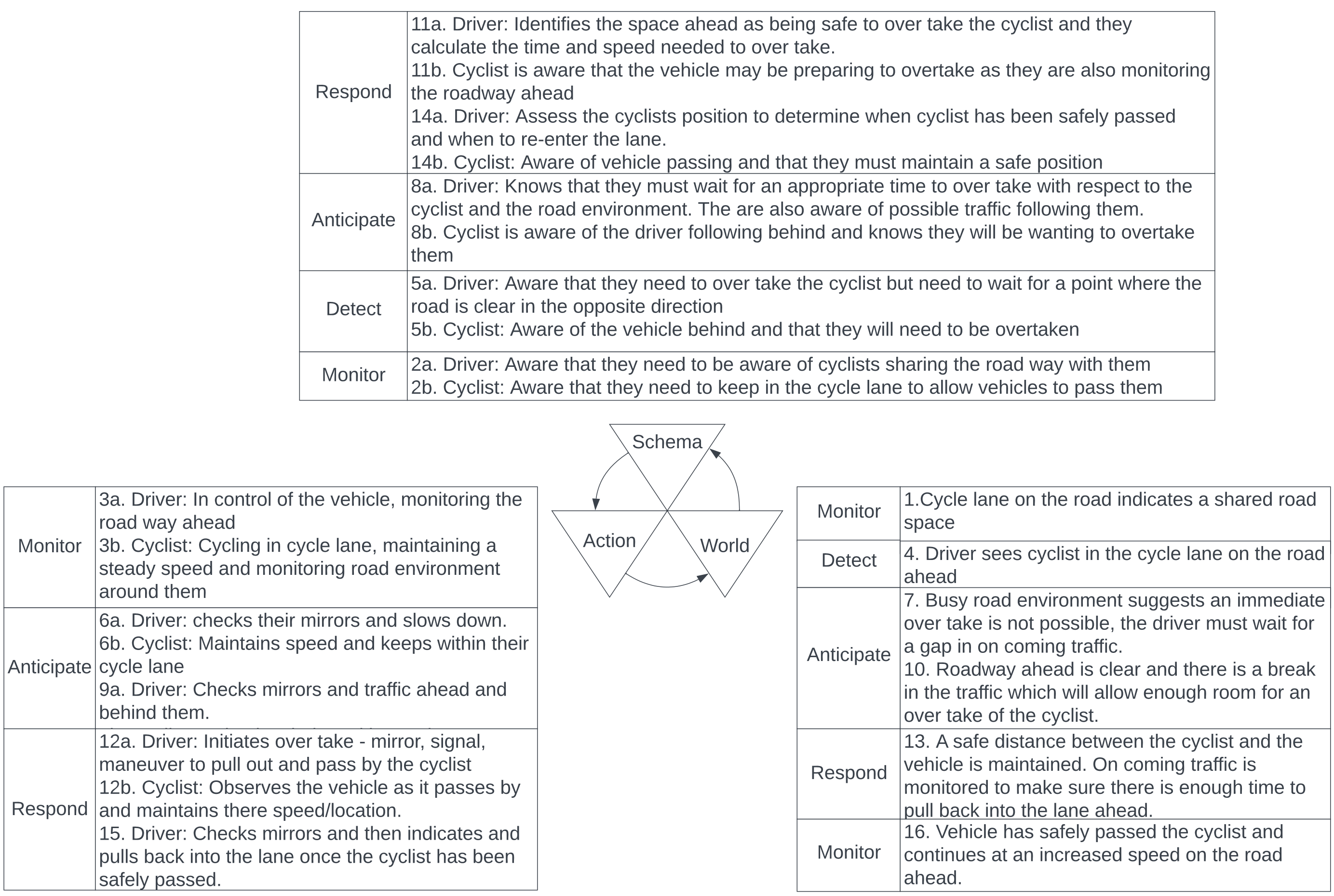


Fig. 4. PCM of a non-automated driver and a cyclist interacting during a cyclist overtake maneouvre with the phases of the resilience cornerstones, tasks taken from Parnell et al. (2023).

The reports from the drivers and the cyclists on their current, non-automated, overtaking behaviour in the focus groups and interviews were contrasted to the 'best practise' behaviour that was reported in Parnell et al. (2023) and used to create the PCM in Fig. 4. Through this process it was evident that there was some divergence and variability between what drivers and cyclist should do and what they actually do within the overtake scenario. This variability is mapped on the PCM across the different phases of the overtake as distinguished by the resilience cornerstones 'monitor', 'detect', 'anticipate', 'respond' and 'learn'. Four PCMs are constructed to illustrate each of these phases in the overtake (Figs. 5–8), with discussions on the learn cornerstone running across all other phases. The performance variability and informal rules of the road are discussed across the resillience cornerstones below.

3.1.1. Monitor

The monitor phase of the overtake refers to the period before the driver has encountered the cyclist and they are monitoring the road environment to ensure safe performance. The roadway in this scenario is a shared roadway with a cycle lane on the road, denoted with a painted line (see Fig. 1). The PCM of the monitor phase in Fig. 5 shows that the cycle lane provides the world information that informs the driver that there may be cyclists up ahead which they will need to monitor the road enviornment for. It also signifies to the cyclist where they should position themselves. A number of drivers from the participant sample stated that they felt reasured by the presence of the cycle lane as it clearly marks the space for the cyclist, e.g. '*I think if there's a dedicated cycle lane, I'd be more likely to overtake because there should be space for an overtake manoeuvre because that's what the cycle lane is designed for.'* (P1, Driver & Cyclist). However, the cyclists from the sample highlighted that these types of cycle lane on a shared road way do not provide enough space for the cyclist and vehicle to pass by one another e.g.*'when all they do is paint a cycle lane down the side of an existing road, I think they're not actually making any more space for the cyclist or car here. Uh and it certainly isn't an indication of how close you can be'* (P13, Cyclist). Instead, the cyclists claimed that the road markings would make it more acceptable for car drivers to drive closer to cyclists and pay them less attention on the road. One participant even went as far as to refer to them as '*murder strips'* (P6, Driver & Cyclist).

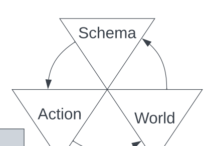
Cyclist also stated that they felt that drivers do not always pay attention to the road markings. However, there was an agreement between drivers and cyclists that many of the road markings for cycle lanes were confusing, with many appearing intermitantly which confused drivers on what they should do when the cycle lanes disappear e.g. *'where they put the cycle lanes in and then they just, they suddenly just stop, and I often think they stop in the worst places … that's really unhelpful as well because it's like, well, do you want us to overtake normally down the side of the cycle lane or do you actually still want us to go round'* (P11, Driver). For cyclist, when they are faced with confusing cycle lanes it can make them not want to use them and instead it can make them choose to cycle on the road, which they are aware can annoy drivers even more. The drivers in this sample were aware of the reasons why a cyclist may choose to not cycle in the cycle lane and gave examples of parked cars on the lane which may complicate the interaction between cyclists and drivers. However, an important factor mentioned by many cyclists was the potholes, drains and puddles on the road which influence their positioning and can cause them to come further out into the road e.g. *'I try and keep to my edge of the road reasonably, but I'm also aware that there are some absolutely massive potholes ….and I don't want to nip out and back in because that's gonna confuse the driver.'* (P4, Driver & Cyclist).

Therefore, there are a number of personal and environmental factors that can influence the events at the monitoring phase. There are a number of reasons why cycle lanes may not be used as expected and both cyclists and drivers are making assumptions about how one another use them. These assumptions are not included within The Highway Code, but come from personal experience and they may lead to cyclists abandoning the use of the cycle lane and contentious relations between drivers and cyclists.

3.1.2. Detect

The dection phase was added to the cornerstones by Parnell et al. (2023) when discussing future automated systems as these systems will need to detect events within the environment in order to anticipate, respond and learn from them. Within this scenario the detection phases

	Schema PCM Events	Participant reports
Monitor	**2a. Driver:** Aware that they need to be aware of cyclists sharing the road way with them	• Driver is aware that cyclists may not always use the cycle lanes
	2b. Cyclist: Aware that they need to keep in the cycle lane to allow vehicles to pass them	• Sometimes the cycle lane is not convenient so cyclists ride on the road.

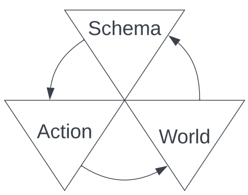


	Action PCM Events	Participant reports
Monitor	**3a. Driver**: In control of the vehicle, monitoring the road way ahead	
	3b. Cyclist: Cycling in cycle lane, maintaining a steady speed and monitoring road environment around them	• Cyclists move out of their cycle lane to avoid pot holes or drains • Cyclists do not check for vehicles behind them very regularly (when they are not aware of vehicles behind them)

	World PCM Events	Participant reports
Monitor	1.Cycle lane on the road indicates a shared road space	**Cyclists:** • The presence of a cycle lane does not mean there is enough room for the cyclist. The width of the lane may not be a safe distance for the cyclist but drivers assumes that it is. • Cycle lanes are intermittent and often confusing as they do not make it clear to the cyclist what they should do. • Cyclist feel that drivers often ignore the road markings • When there is a cycle lane it can make drivers feel more self entitled and less accepting of cyclists
		Drivers: • Cycle lanes suggests it is safe to overtake the cyclist. It is reassuring for the driver to know the cyclist has their space marked out. • Other drivers may park in the cycle lane and obscure it so the cyclist has to come all the way out and round. • Drivers are aware that cycle lanes are intermittent which can be confusing

Fig. 5. PCM of the monitor phase of the overtake with the driver and cyclists reported behaviours mapped on to the standardised events.

	Schema PCM Events	Participant reports
Detect	**5a. Driver:** Aware that they need to over take the cyclist but need to wait for a point where the road is clear in the opposite direction	• Drivers are very aware that they need to be cautious of oncoming traffic • Drivers feel conflicted in letting the cyclist know they are there. The don't want to spook them and but they want to let the cyclist know that they have seen them and they are safe • Drivers presume that the cyclist is aware of them from behind. They also assume that the cyclists know they will be over taken.
	5b. Cyclist: Aware of the vehicle behind and that they will need to be overtaken	• Cyclists listen for cars behind. Hearing a car is usually when they are first aware one is following them. • They can hear differences in vehicles size and speed. Lights help when it is dark. • Cyclists do not know that they have been seen by the driver • Cyclists can carry detection devices that alert them to drivers in their vicinity • Mirrors on the bike can help to determine if there is car behind without having to turn around



	World PCM Events	Participant reports
Detect	4. Driver sees cyclist in the cycle lane on the road ahead	**Drivers:** • Technology on the car can also detect cyclists on the road
		Cyclists: • Cyclists wear Hi-Viz to be seen more easily.

Fig. 6. PCM of the detect phase of the overtake with the driver and cyclists reported behaviours mapped on to the standardised events.

comes when the driver and cyclist first become aware of one another. Fig. 6 presents the detection events within the PCM which cover the movement from information in the world to the processing of the information by the schema of the driver and the cyclist. The driver detects the cyclist on the road which prompts them to acknowledge that they need to adjust their driving behaviour accordingly. The cyclist then becomes aware of the driver as the vehicle approaches them. The focus groups and interviews identified that there are different ways in which the detection phase can be enhanced, with technologies already available to both drivers and cyclists that can detect other road users e.g *'my new car's got [feature] that can see bicycles, which is very nice'* (P7, Driver and Cyclist) and *'I've got a little Garmin radar. So that detects things a couple of 100 m behind you … that was a game changer'* (P6, Driver and Cyclist). Some cyclists also had mirrors on their bikes to see approaching vehilces and others wore hi-viz to increase their chances of being detected. The main way that cyclist discussed detecting vehicles was through hearing them, and they tended to be able to make a number of assumptions of the vehicle by the sound that it made e.g. '*So usually I'd sort of be listening and trying to figure out … so you can usually hear cars going a little bit slower because they won't necessarily have changed gear*' (P1, Driver and Cyclist) and '*I do sometimes think well that sounds like I've got a big vehicle behind me or or somebody approaching me very fast behind me'* (P13, Cylist). The drivers stated that they made a number of assumptions about when the cyclists have detected them but they also felt that they do not need to let the cyclist know that they had noticed them e.g. *'I'm not sure they need to actually know that you're there. You just need to obviously be aware that they're there and maybe have that awareness of have they clocked you, but it's kind of down to you to overtake them safely.'* (P11, Driver). However, the cyclists also said that they often do not know that they have been seen by the driver e.g. *'I don't know if I've been seen. I don't know, I just have to hope.'* (P14, Driver and Cyclist).

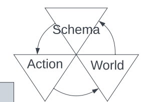
Therefore, at the detection phase there are a number of assumptions that are made about the other road user with regards to how aware they are of each others presence. Experience, physical cues and technologies can help with the detection of other road users, but there are limited ways of knowing that other road users have detected detected your presence on the road. Drivers make the assumption that the cyclist knows that they are there but they also don't want to spook the cyclist by making this explictly known to the cyclist e.g. by using their horn. Cyclist place a lot of trust in the drivers to detect them and to adapt their behaviour accordingly, they feel quite helpless in enabling drivers to be made aware of them.

3.1.3. Anticipate

The anticipation phase of the scenario occurs once the cyclist has been detected by the driver and the driver is determining the best time to overtake the cyclist while following them at a safe speed, see Fig. 7. The driver checks their mirrors quite frequently to make sure that they are aware of their environment. The feedback from drivers in this study revealed a number of factors that influence when and where drivers will choose to over take cyclists, and also feedback from cyclists on how comfortable they feel when being overtaken. The driver will adjust their behaviour to environmental factors that effect how the cyclist is traveling on the road, including weather e.g. *'so like really wet and windy or something, you can see like the cyclist is moving around more, you're going to give them more space'* (P11, Driver) and the road infrastructure. Hills and junctions were particularly mentioned as times when overtaking would become more tricky and they would hold off e.g. *'I wouldn't overtake on a hill or a bend. I'd like wait'* (P10, Driver). Cyclist were aware of similar areas where they would not like to be overtaken e.g. *'that is a particular dislike of mine is being being overtaken on a bend'* (P2, Cyclist).

Drivers discussed the build up of traffic behind that may happen when they are anticipating an overtake. This can lead to a pressure to overtake the cyclist as soon as possible, e.g. '*you see the queue forming behind you and you know everyone else is waiting for you to do the overtake.'* (P11, Driver). Cyclists were also aware of this pressure and the stress that drivers may feel in having to slow down for them *'I know that it can be really annoying if you're a car to sort of be stuck behind a cyclist with no*

	Schema PCM Events	Participant reports
Anticipate	**8a. Driver:** Knows that they must wait for an appropriate time to over take with respect to the cyclist and the road environment. They are also aware of possible traffic following them.	• Drivers can feel pressure from traffic building up behind them. It makes them feel that they need to overtake the cyclist as soon as they can. • A driver may not feel confident in overtaking the cyclist which influences their overtake decision
	8b. Cyclist is aware of the driver following behind and knows that they will be wanting to overtake them	• Cyclists are aware that drivers may get annoyed with following them • Cyclists may be expecting to be overtaken and when it doesn't come they give support to the driver to let them know their intentions and when it is good to overtake • Cyclists try to make eye contact with the driver when looking back, to make sure that they have been seen. • Cyclists try to indicate to the drivers what their intentions are e.g. if turning



	Action PCM Events	Participant reports
Anticipate	**6a. Driver: c**hecks their mirrors and slows down.	• Drivers check their mirrors quite frequently if there is a lot of traffic behind and people are traveling close behind. • Drivers slow down behind the cyclist which they think lets the cyclist know that they are there and waiting for the right time to overtake
	6b. Cyclist: Maintains speed and keeps within their cycle lane	• Cyclists may move to the middle of the road on purpose to make sure the car gives them more space, knowing that it may also annoy the driver. • Once they initially hear the vehicle they then also do a visual check. But are cautious of not looking for too long as it can make them feel unstable.
	9a. Driver: Checks mirrors and traffic ahead and behind them.	• The driver is checking ahead to see if there are more cyclists or items ahead which may change their overtaking approach.
	9b. Cyclist: Maintains their position and expects an overtake	• Cyclist may change their speed to allow the car past, or speed up to maintain a speed that means the car doesn't need to overtake them • Cyclist move into the middle of the road to force the driver to go into the other lane when overtaking, forcing them to give the cyclist more space

	World PCM Events	Participant reports
Anticipate	7. Busy road environment suggests an immediate over take is not possible, the driver must wait for a gap in on coming traffic.	**Drivers:** • Weather conditions influence how much space drivers leave behind the cyclist • Hills will influence the drivers speed and position when following and overtaking • Upcoming junctions will also alter the decision to overtake
		Cyclists: • Cyclists are aware of the different road environments and where drivers should and should not over take them, e.g. at a junction, on a bend. They are also aware of the traffic conditions and how drivers may be feeling. • Cyclists check the vehicle type and also the driver behaviour - i.e. are they on their phone? • Cyclist don't like being overtaken in certain road environments
	10. Roadway ahead is clear and there is a break in the traffic which will allow enough room for an over take of the cyclist.	**Drivers:** • The safe space to overtake and the overtake distance depends of the drivers assessment of the cyclist. Their age, confidence and also the riding environment are considered.
		Cyclists: • Cyclist listening out for the vehicle to determine if it is revving to start an over take

Fig. 7. PCM of the anticipate phase of the overtake with the driver and cyclists reported behaviours mapped on to the standardised events.

option of overtaking.' (P9, Cyclist). Many cyclists reacted to this by trying to allow the driver to overtake where possible, even providing them with guidance e.g. *'if I'm feeling generous and I and and it looks like they're unconfident with with the overtaking, I'll signal left to show that I am gonna be imminently pulling off the road so they can start work on their overtake.'* (P13, Cyclist). However, where the cyclist may feel like they need more space they may also move out into the road way to ensure that the driver does not over take them until they have enough space.

Drivers and cyclists also stated that they undergo some information gathering on the other road users at this phase. Some cyclists spoke about trying to make eye contact with the driver while they are following them to make sure that they have been seen and also to note the vehicle type and the drivers behaviour e.g. '*I always sort of try and make eye contact with them because that way, you know there's just … I don't know what it is, there's some like inbuilt human interaction, isn't it? Where you know that they know.'* (P5, Driver and Cyclist) and *'So even in one glance you can see, are they, do they know I'm here, are they paying attention? You know, do I need to be additionally cautious?' (*P4, Driver and Cyclist). Meanwhile, the driver is also making assumptions about the cyclist based on their apparent competency, age and stability which they will use to decide when to overtake and how much space to give them e. g. *'I know if I'm driving, I'll be observing how confident I think the cyclist is … Just seeing if they're wobbling about, how straight they are cycling '* (P5, Driver and Cyclist) and *'if someone was in like proper kitted out gear, I would feel more confident overtaking them.'* (P10, Driver). The clothes that cyclist wear and what they are carrying give a cue to the driver as to how the cyclisit should be approached, with certain caution being given to children and older adults.

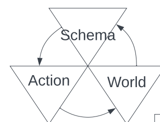
The anticipation phase therefore involves a number of assumptions that are made about other road users and the environmental conditions. An individuals perceptions of other types of road user will influence their own behaviour. Drivers reported behaving differently around different types of cyclists and being influenced heavily by environmental conditions. Cyclists like to be aware of the type of driver that they are encountering so that they can ensure they respond as safely as possible. These cues come from previous experience and personal expectations.

3.1.4. Respond

The response phase is the point at which the driver makes the overtake maneuvre, starting from the point where they identify the space to overtake and ending once the cyclist has been passed and the driver pulls back into their lane, as shown in Fig. 8. The original PCM in Fig. 4 highlighted that the driver would indicate before they pull out to go around the cyclist and then indicate again when they return to their lane after passing the cyclist. However, there were mixed reports from drivers as to whether or not they would indicate. Some drivers thought it could confuse other road users if they indicate e.g. *'I find that it's obvious enough that I'm overtaking and everyone else is gonna overtake … there's enough affordances in place that people know what's going on.'* (P14, Driver and Cyclist). However other drivers stated that indicating was important as it helps other drivers behind to know what is happening e.g. *'it helps sometimes when you've got other cars behind you, they can't see far enough ahead to see that there's a cyclist in the in the road. If you can see cars indicating it signals, if you like, that there's something that they're trying to avoid.'* (P3, Driver and Cyclist). Cyclists noted that they cannot see the indicator very easily and therefore they did not see that indicators were for their benefit.

For the most part, cyclists stated that they would try to make it easy for the driver to pass them, pulling in to allow them pass if needed. They stated that this was polite road etiquette, e.g. *'I think it's a matter of politeness especially if I can, if I can hear a big truck has been behind me very patiently waiting. I think he's done his part of the bargain, it's only fair that I do mine and get out the way when I can.'* (P4, Driver and Cyclist). The drivers also stated that they wanted to be cautious around the cyclist when they were passing, and they were also very mindful that the cyclist may swerve on the road. However, a number of drivers said that they accelerate past the cyclsit in order to get past them as soon as possible, but they were also aware of the noise that this would make and how it

	Schema PCM Events	Participant reports
Respond	**11a. Driver**: Identifies the space ahead as being safe to overtake the cyclist and they calculate the time and speed needed to overtake.	• Overtake distance varies depending on the type of cyclist being overtaken. • Overtake distance also depends on the road type
	11b. Cyclist is aware that the vehicle may be preparing to overtake as they are also monitoring the roadway ahead	• Cyclists may choose to move out of the way of the driver where the road allows it • Cyclists try to be polite when drivers have been politely waiting behind them. • Cyclists try to communicate to the driver when it is ok to overtake. • Cyclists cannot see the drivers indicators without looking behind, and it may not be safe to do so.
	14a. Driver: Assess the cyclists position to determine when cyclist has been safely passed and when to re-enter the lane.	• Drivers checks the position of the cyclist, but they do not know if the cyclist will stay straight. • The driver tries to complete the overtake as quickly as possible so that they can continue on their journey, but they are also mindful of the cyclist and their own engine noise.
	14b. Cyclist: Aware of vehicle passing and that they must maintain a safe position	• The only thing that cyclist can control when being overtaken is keeping their space. They don't look at the vehicle.



	Action PCM Events	Participant reports
Respond	**12a. Driver:** Initiates over take - mirror, signal, maneuver to pull out and pass by the cyclist	• Some drivers do not indicate to other road users when over taking, others always indicate. Some drivers think that indicating may be a confusing signal. • Drivers may try to make a gesture to the cyclist as they go past • Drivers hope that the cyclist can hear the indicator. But they are also aware that they cannot see it. They have limited ways to convey to the cyclist that they are overtaking. • Drivers hope that other road users will be understanding when they are overtaking
	12b. Cyclist: Observes the vehicle as it passes by and maintains there speed/location.	• Cyclists make sure they have space to avoid any pot holes in the road, so they move out in the road • Cyclists make sure they are in the most safe position to ensure they can protect themselves from any poor actions from the driver • Sometimes cyclist can receive abuse when they are being passed if the driver does not think that they should be there.
	15. Driver: Checks mirrors and then indicates and pulls back into the lane once the cyclist has been safely passed.	• Drivers feel the risk of another vehicle approaching • Car sensors can tell them when they have passed the cyclist • Drivers do not always indicate to come back in

	World PCM Events	Participant reports
Respond	13. A safe distance between the cyclist and the vehicle is maintained. Oncoming traffic is monitored to make sure there is enough time to pull back into the lane ahead.	**Drivers:** • Drivers are aware of the other cars and how far they can safely pull out around the cyclist **Cyclists:** • Cyclist do feel that they are given more space if carrying a load. They also feel that driver take into account their experience levels, where this is obvious.

Fig. 8. PCM of the respond phase of the overtake with the driver and cyclists reported behaviours mapped on to the standardised events.

could effect the cyclist e.g. '*I would absolutely stick my foot down and be at the speed limit from 10 miles an hour as quickly as possible. EV so it's quiet. Like I don't feel bad at all at doing it*' (P7, Driver and Cyclist) and '*probably again accelerate relatively hard. Knowing that it's a diesel and it makes a lot of noise, not foot flat … it is kind of like get around as quickly as possible, make sure it's safe and then pull in.*' (P6, Driver and Cyclist). Cyclist stated that they try to make themselves as safe as possbile when they are being overtaken and that they place a lot trust in the driver to give them enough space. Some cyclists noted that they did feel drivers gave them more space when they were traveling with panniers or if they look nervous.

Depending on the overtake and those involved some cyclists stated that they have received abuse from drivers when they were being over taken or experienced aggressive driving. This was particularly noted when cyclists are not using the dedicated cycle lanes e.g. *'And the fact that the driver could see that I wasn't using them but didn't get any further than thinking there's a cycle track there, why don't you use it? That made them more wound up and aggressive'* (P13, Driver and Cyclist). Yet, other drivers stated that they try to make polite gestures to the cyclist as they pass to say thank-you. Likewise the cyclist also like to thank the drivers for making a safe overtake when this occurs e.g. *'If someone's overtaking me really really well, carefully umm then I would give them a thumbs up. Because that gives them good feedback that they're driving well. And occasionally I do the opposite if someone's not driving well.'* (P3, Driver and Cyclist).

There is often communication between road users within the overtake scenario that falls outside of the standard and legal requirements of the roadway. The standard communication signals such as vehicle indicators are not uniformly used and many road users fear that they can lead to miscommunication during these sorts of maneuvres. Instead road users use eye contact and hand signals to communicate intentions and to indicate politeness.

3.1.5. Learn

Learn is the fith resillience cornerstone which captures the need to learn form previous behaviour and make improvements for the future. Learn is not represented in the same way as the other cornerstones on the PCM as it is encompassed by the Schema element of the PCM. A schema is the individuals cognitive map of the world, which is built through education and past experience. Driving on the roads in the UK requires a driving license that demonstrates that you have the sufficient capabilities to drive a vehicle and make safe assessments of the road environment. The process of learning to drive in the UK, and many countries glabally, includes both theoretical and practical assessment. This combines knowledge and experience to ensure an idivdual is competent to make safe assessments of the road environment and act appropriately. There is no such license requirement for cycling in the UK. The government has set out the National Standard for Cycle training (Department for Transport, 2018) but this is not mandated. A number of participants did draw on some of the education that they received at school on how to cycle on the roads during their responses to the questions. However, it was evident from the participant discussions that personal experience was the significant influencer over cyclists behaviour and their attitudes to other road users.

The cyclists and the drivers responses across the monitor, detect, anticipate and respose phases of the overtake scenario (in Figs. 5–8) show the complexity of the schema's held by drivers and cyclists. At the monitor phase, drivers have learnt that cyclist may not always use the cycle lanes as intended, showing an awareness that what happens in theory within the road environment differs from reality.

At the detection phase assumptions are made by cyclist that they have been detected by the driver and the driver assumes that the cyclist is aware that they are behind them, although there is no way to confirm this. Both road users make inferences from the world around them to determine that they have been detected.

During the anticipation phase there are a number of futher assumptions made by drivers on the type of cyclist which guides their overtaking behaviour. There is also the sense of pressure that they feel to not hold up the traffic. This is not taught within driver training but it comes from the social and cultural pressures that individuals hold. The cyclists were aware of a similar pressure to allow the drivers to pass which may cause them to pull over or slow down. This politeness is not taught but comes from personal experience and it varies across situations and individuals.

The response phase starts with the intiation of the overtake and includes the overtake maneuver. The driver is taught the best practise for overtaking other road users, as stated in The Highway Code (section 162-169). This states that drivers should use the mirrors-signal-manoeuvre behaviour when overtaking. Yet, the drivers in this sample showed some variability in whether they would use the indicator or not, with some participants stating that they thought it could be misleading to other road users. This shows that drivers do not always follow the taught rules of the road.

The responses from the participants demonstate the importance of the driver and the cyclists schema development in maintaining resillience within this overtake scenario. Past experinece and environmental cues inform schema development when driving and these play a significant role within this cyclist overtake scenario.

3.1.6. Participants that are both drivers and cyclists

The sample was comprised of drivers, cyclists and those who both drive and cycle. The statements made by participants who did both were categorised to either the driver or the cyclist reports, depending on what mode they were refering too (where this was clear from the transcripts). When reviewing the data there were comments made by this type of road user that suggested that their schema may differ to a user who only drives or only cycles. Those who cycle and drive could use their experience as one type of road user to inform their behaviour as another type or road user, e.g. "*Well as a driver, when I drive and see a cyclist … I will give them plenty of room because I'll feel like I want to protect them, as I would want a driver to protect me.*" (P5, Driver and Cyclist). The experience of being a cyclist led a number of participants to state that this would increase the space that they would give other cyclists when they were driving. They also suggested that other cyclists who did not drive may not be aware of how visible (or not visible) cyclists are to drivers e.g. "*I think they also have less idea of what it's like to be a driver and particularly if it's sort of dark or something. I think cyclists don't always realise how difficult it can be to see a cyclist if they've got no lights or anything.*" (P1, Driver and Cyclist). Hence, the awareness of more than one type of road users' perspective may assist in making more resilience interactions during the overtake scenario.

3.2. Overtaking cyclists with AVs

The second half of the interviews and focus groups asked respondants about their views on interacting with AVs during a cyclist overtake scenario. This included the information that cyclists and drivers would require from AVs and the broader road environment. Fig. 9 provides the PCM which captures the cyclist and AV interactions, as informed by the tasks set out in Parnell et al. (2023) for an AV overtake of a cyclist. This scenario involves Level 3 automation (SAE, 2021) which still requires the driver to have supervisory control, therefore the driver is requested to take over control when the vehicle encounters the cyclist, as

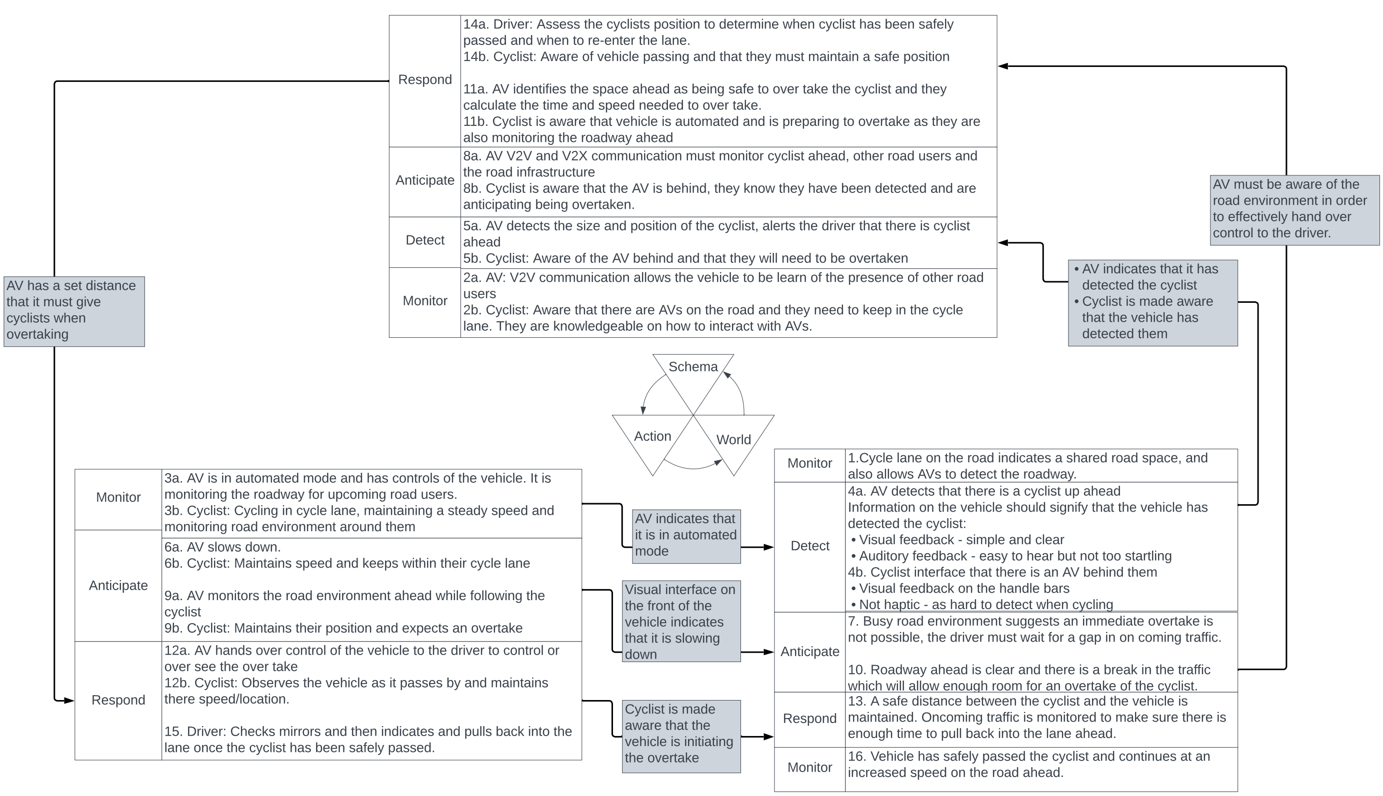


Fig. 9. PCM of a AV and a cyclist interacting during a cyclist overtake maneouvre across the phases of the resilience cornerstones. The grey boxes show the additional feedback mechanisms that are required to increase the resillience in the AV-cyclist interactions.

demonstrated in Parnell et al. (2023). The discussions with the cyclists and drivers in the focus groups and interviews revealved some feedback mechanisms that would assist with cyclist-AV interactions in this scenairo, these are shown the grey boxes in Fig. 9. They are also discussed below in relation to the resillience conerstones that they fall under.

3.2.1. Monitor

Within the initial monitoring phase, Parnell et al. (2023) state that the AV will be initially able to detect the cycle lane which will notify the vehicle that there is the possibility of encountering a cyclist. Participants stated that this feature should only be available in more urban areas where there are clear cycle lanes. This was reflective of the concerns that participants had with the poor quality of the current infrastructure and the confusion that can be felt by both cyclists and driver when the cycle lanes are not clearly marked or are inadequately designed. A key element within this is the development of effective vehicle to vehicle (V2V) communication and also vehicle to infrastructure communication (V2I) which will allow different AVs to be aware of each other and the upcoming road environment. Participants within the interviews and focus groups also suggested possible platforms for vehicles to communicate with bicycles or cyclists so that the AV can be aware of upcoming cyclists on the road, including a vehicle to bike communication channel (V2B). This would require some form of device to be attached to the bicycle or held by the cyclist. Some participants were in favour of this, yet others felt that this could be problematic e.g. '*it would take away a lot of the advantages of being on a bike in the first place*' (P13, Cyclist) in terms of having to maintain it and monitor it. The general consensus was that the onus should be on the AV detecting the cyclist and that any interface for the cyclist should be optional. If this is not the case then participants stated that *'it either has to be something very cheap or something integrated that the government has to take control of and deal with the economic impact and cycle impact*' (P14, Driver and Cyclist).

3.2.2. Detect

The detection phase of the overtake scenario involved a number of discussions about whether the cyclist should be made aware of the AV and if the cyclists needed to know if the vehicle is automated. The AV should be able to detect the cyclist using the V2B communication and sensors on the vehicle when they are in closer proximity to the cyclist. Participants suggested two ways in which the vehicle and the cyclist could be made aware of each other, either the vehicle has an interface to communicate to the cyclist that they have been detected, or the cyclist has an interface that informs them of the AV's presence.

For the first option, there was two modes through which this communication was suggested. The majority of participants stated that the feedback should be auditory so that the cyclist does not have to look away from the road. Some participants suggested that this could be spoken feedback, or a solitary beep-like sound. One participant stated that it would be useful if the sound got louder as the vehicle got closer to the cyclist. Alongside these discussions was the issue of electric vehicles which cannot be as easily heard by cyclists, auditory feedback would therefore assist in these cases. However, participants were also aware of the complexity of placing auditory feedback on the vehicle, with noisey road environments, headphones, hearing loss and the local area having a limiting effect. The other feedback mode that was suggested was a visual interface on the vehicle that would inform cyclists that they had been detected. It was stated that this would need to be very simple and clear, being visiable across the range of different environmental light conditions. They stated that this should not be distracting and that the cyclist should be able to easily see it when glancing back.

The alternative option, with V2B communication, is that the cyclist has an interface on their bicycle that informs that there is an AV approaching. One focus group suggested that this could be on the handle bars of the bicycle, while another participant stated it could be on the phones of cyclist. A number of participants highlighted that any haptic feedback would not be easily registered by the cyclists due to the nature of cycling on the road, yet visual information could be detected.

3.2.3. Anticipate

Within the anticipate phase the appraoch outlined within Parnell et al. (2023) is that the AV would slow down after detecting the cyclist up ahead and notify the driver that there was a cyclist on the road ahead, via an in-vehicle interface. The driver would then takeover control and navigate around the cyclist. Participants stated that it would be useful for the cyclist to know that the AV is slowing down by looking at the front of the vehicle, currently the brake lights are at the back of the vehicle. With AVs, the cyclist may need more information about the vehicles intentions in order to trust it (Saleh et al., 2017). Therefore providing more real-time information on the AVs behaviour may be beneficial to the cyclist as it may allow them to adjust their behaviour accordingly. It has been identified that the driving patterns of AVs may not meet the expectations of drivers or perform in the same way that manually driven vehicles do (Revell et al., 2020), therefore more obviously displayed information on the status of the AV could be useful.

The driver in the AV will need to be made aware of the presence of the cyclist with ample time to be able to process the information in the road environment around them and make an informed response. There has been numerous studies on this handover behaviour and what information is required by the driver during handover situtions, e.g. Eriksson and Stanton (2017); Walch et al. (2017); Clark et al., 2019; Stanton et al. (2022). This study does not aim to add to this literature but it demostrates where this process falls within the cyclist-driver interactions in this given scenario and how it relates to the resillence of the system. The prescense of an interface within the vehicle that hands over control back to the driver feeds into the PCM process of integrating the infromation in the world to the schema of the individual. This schema must be sufficiently developed in order to process the information and the environment to make a judgement on how to safely overtake the cyclist.

3.2.4. Respond

The response phase involves the processes through which the overtake manuever is inititated and carried out. Participants discussed the utility of the AV in having a mechanism through which to set a safe minimum distance to pass the cyclist at, which would prevent vehicles from passing too close to the cyclist. Participants stated that the safe distance of 1.5 m stated with the UK Highway Code would be a good distance to assign to this, yet participants were also aware of the variability that different road users may need depending on their experience, age and if they were carring extra items. Therefore, some participants discussed the possibility of the vehicle being able to detect the type of cyclist and adjusting the overtaking distance appropriately, however they were aware of the complexity of this.

The cyclists experience of the response of the vehicle and the driver to initiate the overtake phase was discussed. A number of participants stated that they would like to know when the vehicle was inititating the overtake as they could then adjust their behaviour accordingly. They stated that this could be communicated through an auditory signal, either a spoken indicator that the vehicle is overtaking, or a sound that that increased in volume as the vehicle approached.

3.2.5. Learn

As with the non-automated scenario presented in section 3.1.5, the learn phase relates to the schema element of the PCM. The non-autmated scenario highlighted the variance between the learnt rules of the road as stipulated within The Highway code and the personal experience and environmental factors that influence how road users behave in the real world which provides some resilience to the driver-vehicle interactions. With the integration of AVs, the schema element of the PCM comprises part vehicle schema and part driver schema. Developments in automation that will allow V2V/V2X/V2B communication will enable the vehicle to have its own version of a schema of the road environment. Yet,

Table 2
Proposed technologies to provide increased resilience in the interactions between AVs and cyclists.

	Resilience mechanisms	Feedback	Proposed Technology
1.	Monitor (Action) → Detect (World)	The vehicle informs the cyclists that it is automated and if the automation activated or not.	e-HMI on the vehicle (visual) and/or e-HMI on the bicycle (visual) Connected Vehicle Architecture
2.	Detect (World) → Detect (Schema)	The vehicle informs the cyclists that it has detected them.	e-HMI on the vehicle (visual or auditory) and/or Bicycle/Cyclist device (visual or auditory)
3.	Anticipate (Action) → Anticipate (World)	The vehicle informs other road users in front that it is slowing down (or conversely speeding up).	e-HMI on the vehicle (visual)
4.	Anticipate (World) → Respond (Schema)	The vehicle informs the driver that there is cyclist ahead and what their required actions are.	Internal HMI inside the vehicle (visual or auditory or haptic)
5.	Respond (Schema) → Respond (Action)	The vehicle knows the correct distance to overtake the cyclist.	In-vehicle automated system
6.	Respond (World) → Respond (Schema)	The cyclist is informed that they will be overtaken imminently.	e-HMI on the vehicle (visual or auditory) and/or Bicycle/Cyclist device (visual or auditory)

within this Level 3 scenario the driver will still need to have some supervisory control and will need to takeover control of the vehicle when triggered by the cyclist. For successful performance, the vehicle and the driver will need to have a shared schema (Revell et al., 2020). This is referred to Distributed Cognition, whereby the cognitive components of a system are attributed to different parts of a complexly intergated system (Hutchins, 1995). It is a concept that has been applied to assess the integration of automated vehicles into our roadway systems (e.g. Banks and Stanton, 2017; Banks et al., 2018a). The methods used within this paper have established the drivers and cyclists schemas for the cyclist overtake scenario, including areas of variability and resillience. The recommendations presented in Fig. 9 suggest te development of interfaces where information can be transferred between road users to increase their awareness of each other to build a shared schema. The value of internal interfaces within the vehicle to increase the handover between the vehicle and the driver has been documented in the literature (Eriksson and Stanton, 2017; Walch et al., 2017; Clark et al., 2019; Stanton et al., 2022). Yet, this paper has also demostrated the potential value of external HMI to improve how AVs communicate with other road users, particularly vulnerable road users.

There is also information not detailed on the PCM in Fig. 9 which will be required, including possible training for cyclists on how to interact and behave around automated vehicles, as well as training for users of automated vehicles (e.g. Merriman et al., 2023). This will help to establish the schema of cyclists and drivers for vehicle automation.

4. Discussion

This paper presents the analysis of focus groups and interviews with fifteen road users who classified themselves as cyclists, drivers or cyclists and drivers. The aim of the paper was to review the variability in road users' behaviour during a cyclist overtake scenario, in comparison to the formal rules of the road. A comparison to the best practise for this scenario as detailed in Parnell et al. (2023), informed by road safety and human factors experts, was used to understand where variability occurs and the informal rules of the road that are employed. The overtake scenario was split into the resilience cornerstones: monitor, detect, anticipate, respond and learn (Hollnagel, 2013; Parnell et al., 2023). Analysis of these cornerstones has shown how informal rules of the road are employed to provided additional communication strategies between road users and show where road users make assumptions about other road users based on their own schema for the situation. Applying these phases to the interactions that AVs and cyclists will have on the road has identified where additional feedback mechanisms are needed to improve resilience in the interactions between the vehicle and the cyclist, in a proactive manner. Developments in digital technologies should focus on providing tools that can enhance these feedback mechanisms and ensure interactions between automated systems and road users are resilient.

This work has utilised the PCM to provide a proactive analysis of cyclist-AV interactions to understand where digital technologies can be developed to increase the resilience of these interactions. The value of the PCM is in its ability to map the cognitive processes and cabilities of diferent end user to the broader road environment within which they are operating in, ensuring a sociotechnical systems approach (Plant and Stanton, 2012). Furthermore, it is developed using qualitative reports from road users to capture real world experiences. This insures that end-users are included within the design and development of new systems (Parnell et al., 2021). Qualitative research is vitally important in understanding how systems maintain resilience as the expereinces and behaviours of users can be explored in depth. It can also help to capture the social context within which behaviour occurs (Ungar, 2003), and the PCM is a useful tool to understand the relationship of behaviour to the broader context.

Through mapping the reslience cornerstones onto the PCM the different percpetual cycle processes that relate to the different aspects of resilience have been reviewed. Like the area of Resillience Engineering and the PCM methodology, this approach is not restricted to the AV domain and further work should seek to apply it across other domains and scenarios. It is through these structured user centered appraoches that human factors can have a strong impact on the design of future resilient systems.

4.1. Recommendations

Taking a human factors approach and utilising the PCM, the type of feedback mechanisms that would be beneficial to the cyclist overtake scneario were mapped onto the resilience cornerstones to show where additional technologies would be beneficial, see Fig. 9. Table 2 provides a summary of these proposed technologies and the form that they should take, as informed by the road users sampled within this research.

The first recommendation in Table 2 is the mechanism that enables monitoring of the road environment to lead to the effective detection of other road users. Monitoring of the roadway will be a key function of AVs, the sensor technology should enable the road markings to be detected and this will inform the positioning and direction of the vehicle on the roadway. Connected autonomous vehicle technology (CAV) will also enable AVs to communicate with other road users to determine their location and trajectory. This will help to increase the situational awareness of the AVs which will enhance the resilience of the system through effective monitoring capabilities. There are concerns that sensors on AVs are not currently accurate enough to detect cyclists (Sandt & Owens, 2017), which will limit the trust that cyclists have towards them. Discussions by the participants in this study suggested the opportunity for a device on the bicycle which would enable an AV to be able to detect their presence and also inform the cyclist of the AVs presence. This relates to the second recommendation in Table 2 which suggests a need for feedback to enable the detection of the cyclist in the world to update the cyclists' schema to let them know that they have been detected. Such a device would be beneficial in increasing the awareness of the two modes in a way which is currently not possible within the road transport system. Hagenzieker et al. (2020) showed that cyclists are less confident that they would be detected by an AV in contrast to a manually driven vehicle. In this study, when discussing the current interactions between manual drivers and cyclists, the participants stated that there were a lot of assumptions made by cyclists on where a vehicle may be, its intentions and if they have been detected. Likewise, the driver is also often unclear if the cyclist is aware of them and how they will react to being overtaken. The informal rules of the road and the use of implicit cues such as vehicle speed and location add an element of resilience to the system as they lead to assumptions and behaviours that prevent incidents and collisions. Yet, technological developments that can make the intentions of different types of road users explicit would be highly valuable to the introduction of AVs to the roadway system as AVs will not be as adept at reading these implicit cues.

Determining the form that such technologies should take poses a number of challenges which can invoke ethical issues of responsibility, policy requirements and safety. E-HMI are a communication tool that has been proposed to enhance future interactions between vulnerable road users and AVs (see Brill et al., 2023 for a review). The majority of this research has focussed on pedestrian interactions with AVs (e.g. Bazilinskyy et al., 2021; Brill et al., 2023; Eisma et al., 2021; Lee et al., 2022; Mahadevan et al., 2018; Rouchitsas and Alm, 2022). Pedestrians exhibit different behaviours to cyclists (e.g. Trefzger et al., 2018), therefore the interactions and forms of communication between AVs and these different types of vulnerable road users will have different requirements. As such, the e-HMI solutions that are needed for pedestrians may differ from the solutions that are needed for cyclists (Brill, et al., 2023; Hou et al., 2020). Additionally, the research that has looked at cyclists has mainly focussed on crossing (e.g. Bazilinskyy et al., 2023; Dey et al., 2021) or merging scenarios (e.g. Hou et al., 2020). Yet, it is important to also consider overtaking scenarios, as it was evident from this work that drivers and cyclist currently find they be anxiety inducing and dangerous.

One application for e-HMI that was suggested to be beneficial for the overtake scneario in this study is information on the front of the vehicle that informs those ahead that the vehicle is slowing down, or changing speed in general. This is the third recommendation in Table 2 and relates to the anticipation phase whereby the anticipated actions of others are made explicit within the world. Currently the brake lights at the rear of the vehicle are a useful indicator for road users behind. Research into frontal brake lights has shown that they do increase the identification of decelerations and they may be useful in indicating the vehicles intentions within automated vehicles (Petzoldt et al., 2018). Recent research has also shown that these are effective in children as well as adults (Bluhm et al., 2023). However, research into frontal brake lights has focused on pedestrians, the applications to cyclist interactions requires more research.

The fourth recommendation in Table 2, relates to the vehicle informing the driver that there is cyclist ahead that needs to be overtaken. This feedback mechanisms works through the anticipatory phase, taking the information in the world that there is cyclist ahead to update the drivers schema and their cognitive map of the road environment so that they can respond. The area of AV handovers has received a lot of research interest, with different modalities and interface concepts being designed and trialled (e.g. Eriksson and Stanton, 2017; Walch et al., 2017; Clark et al., 2019; Stanton et al., 2022). However, from the perspecitive of interactions with vulnerable road users the handover of control is an important factor in the trust that other road users will have towards AVs. Vlakveld et al. (2020) found that cyclist were more likely to yeild to vehicles at intersections when they knew that the vehicle was automated, suggesting that they were wary of interacting with it. When the AV displayed its intentions to the cyclists, they yeilded less freqeuntly, suggesting that that more information on the AVs intentions can increase trust by vulnerable road users (Vlakveld et al., 2020). Similarly, Parkin et al. (2023) found that AVs that gave way to cyclist were more trusted by participants than those that did not give way. They explained this increased trust to be due to the clarity in the AVs behaviour within complex situations and the participants expectation that AVs will be cautious. It therefore needs to be clear to cyclists what to expect from encounters with AVs, what the role of the driver will be and how they will be prioritised. Training on interactions with AVs will be a crucial area to maintaining system resilience.

This final two recommendations in Table 2 relate to the response phase of the overtake, wherein the overtake is initiated. The fifth recommendation requires the AV to have an awareness of the minimum required overtaking distance so that the vehicle and the driver are both aware of the 1.5minimum distance (as defined in the UK Highway code, but varies internationally, see Lamb et al., 2020). Similar to the lane keeping assist feature in vehicles, automated technology that can insure the minimum safe overtaking distance could work to ensure the vehicle does not pass too closely, even once control has been handed over to the driver. The sixth recommendation in Table 2 is a feature that notifies the cyclist that they are being overtaken. Within the participant discussions it was noted by cyclists that they used a number of implicit cues, such as engine noise, to inform them when they were going to be overtaken. E-HMI was suggested here to make it more explicit to cyclist when the overtake will start. Caution not to spook the cyclist was also noted by participants so the placement of an interface on the vehicle or the bicycle would need to be explored.

5. Limitations and future work

This study utilised qualitative data from a relatively small sample size of fourteen participants, although these were balanced by gender. It should be cautioned that these perspectives are not generalisable to the whole population and there are likley other informal rules and possible feedback mechanisms that have not been included. However, there is a lack of qualitative research into AV integration and especially with respect to vulnerable road users such as cyclists. Therefore, this research is an attempt to close this gap and provide more evidence for these types of interactions. Future work should seek to expand the sample size to review the generalisability of the results, with particular focus on different participant demographics such as gender and age which may influence the results. Another limitation is that this research focuses on Level 3 automation, in which the driver still has supervisory control of the vehicle. The level of automation is likely to change the requirements and need for the proposed technologies. Related to this, the work was focused on a relatively limited scneario on a shared roadway. The development and integration of AVs has suggested the need for dedicated lanes and infrastructure which is seggregated from vulnerable road users (Botello et al., 2019). However, discussion within this work highlighted that cyclists do not stick to cycle lanes where they see more efficient alternatives. Therefore we must consider possibilities for resillient interactions between the different transport modes.

The recommendations in Table 2 provide some insights into how new technologies can support the resilience of interactions between cyclists and AVs. While some research has already been conducted into some of the viability and utility of the technologies, more research is needed to understand their effectiveness and how they function across a range of different road contexts. The value of this paper is identifying how they relate to the perceptual cycle of the AV, the driver and the cyclist, and where they may be able to better support resilient interactions.

Further exploration into e-HMI for cyclists is needed, as there has been a greater focus on pedestrians, yet future e-HMI will need to enable effective communication with all other road user types. Ways of combining and building on these results with quantitative analysis could also be explored.

6. Conclusion

The integration of AVs to the road transport system requires taking a proactive approach to understanding how they will interact with other road users across a range of different contexts. This is particularly true with regards to vulnerable road users, who are already at a higher risk of being involved in incidents. A resilience engineering approach must be forward thinking and account for the broader sociotechnical context surrounding AV integration. This paper proposes a methodological approach underpinned by human factors to understand performance variability and the role of social context in resilient interactions, and assessing where technologies can play a role in enhancing the resilience of the system. With application to the road transport domain, this work has shown the current informal and formal rules of the road surrounding a cyclist overtake manoeuvre, as identified by end users. Furthermore, it uses this to show where automated systems will need extra support to ensure that resilience is maintained with the integration of AVs. A range of digital technologies that can support resilient interactions with vulnerable road users are presented in accordance with the key cornerstones of resilience (Hollnagel, 2013). Practitioners and technological developers should use this method to assess how their technology relates to the resilience of the system that they are designing for.

Data availability statement

Research data are not shared due to ethical and privacy restrictions.

Declaration of competing interest

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

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