Resilience Engineering on the road: Using Operator Event Sequence Diagrams and system failure analysis to enhance cyclist and vehicle interactions

Abstract

Future visions of transport systems include both a drive towards automated vehicles and the need for sustainable, active, modes of travel. The combination of these requirements needs careful consideration to ensure the integration of automated vehicles does not compromise vulnerable road users. Transport networks need to be resilient to automation integration, which requires foresight of possible challenges in their interaction with other road users. Focusing on a cyclist overtake scenario, the application of operator event sequence diagrams and a predictive systems failure method provide a novel way to analyse resilience. The approach offers the opportunity to review how automation can be positively integrated into road transportation to overcome the shortfalls of the current system by targeting organisational, procedural, equipment and training measures.

Keywords: Resilience, automated driving, OESDs, SHERPA, cycling, active travel

1. Introduction

Transportation systems continually evolve in response to the societal and technological developments that shape and define them (Lyons, 2013). This continues to the present day and beyond with the current developments in automated technologies becoming increasingly integrated to our roadways, seaways, railways and airways. Yet, the transport industry currently faces growing sustainability challenges, as concerns over climate change heighten. Transportation is the biggest contributor to greenhouse gases in the US and UK (Environmental Protection Agency, 2020; Department for Transport, 2021). A shift in the types of transport we use and the way in which we use them is needed if we are to slow down (or even reverse) climate change.

Future visions of our roadways depict autonomous connected transport networks, as well as increased active travel options (e.g., Innovate UK, 2021). The complimentary nature of the two is, however, yet to be fully understood. Cycling is growing in popularity as a mode of transport, with evidence to suggest a cultural shift away from the reliance on cars towards more sustainable travel modes (Pucher & Buehler, 2017). Developments in e-bikes and bike sharing platforms are set to make cycling a more attractive mode of travel to more people (Pucher & Buehler, 2017). Yet, there is also the suggestion that developments in automated vehicles (AVs) and shared car programs will limit active travel, with AVs becoming a more popular alternative in the journeys typically undertaken by bike (Booth et al, 2019). There are still many unknowns regarding the interactions of automated vehicles with other road users, both in the event of fully automated vehicles and in the transition period that precedes it, where different levels of automation and human interaction will be required (Society for Automotive Engineers, 2021). Our current transports systems already provoke issues in the interaction between active transport users, such as cyclists, and private vehicle owners (Bil et al, 2010; Chaurand & Delhomme, 2013; Dozza et al, 2016; Lamb et al, 2020).

Concerns over how the integration of automation and an increased uptake in active travel modes are now being reviewed (Botello et al, 2019; Latham et al, 2019; Pettigrew et al, 2020; Thompson et al, 2020). Interviews with subject matter experts, including academics, stakeholders, and industrial sectors (Tabone et al, 2021; Pettgrew et al, 2020; Botello et al, 2019), have highlighted that fully automated vehicles are still a long way off. Yet, future infrastructure design needs to be considered now as infrastructure change is long and costly. Experts also suggest that governments will be the regulators of AVs which is likely to lead to some variability in how automobiles and cyclist cohabit the roadway, depending on the prioritisation of modes across local and national authorities (Botello et al, 2019). Communication between vehicles and other road users is also highlighted as a key area for review, to understand how AVs will interact and communicate with other road users (Stanton et al, 2020), as well as how they will be perceived and understood (Tabone et al, 2021; Pettgrew et al, 2020; Banks et al, 2014).

Latham et al (2019) applied an ethnographic approach to highlight the importance of formal and informal rules of the road that current road users utilise, such as hand gestures and eye contact. They raise concerns around how these informal rules will be replaced by AVs. This emphasises the need to understand the tendencies of society in the development of AVs due to the large number of moral dilemmas and decisions that they will need to resolve, which may overshadow their perceived benefits (Lathem et al, 2019). Research that has incorporated insight from the computer science discipline has also shown how adaption and emergent behaviour may lead to new sources of error (Thompson et al, 2020; Millard-Ball, 2018). For example, the enhanced safety benefits of automated vehicles may lead to more risk-taking behaviour by cyclist (Thompson et al, 2020). Adaption of behaviour in response to new technologies is well evidenced in the automotive domain since the introduction of Automated Cruise Control (Rudin-Brown & Parker, 2004; Young & Stanton, 2007). Therefore, systems need to be designed so that they can facilitate adaption in a safe and reliable way (Read et al, 2015). The ability of a system to adapt to perform in new ways in response to new technologies determines its resilience.

1.1 Research Aim

In order to understand the possible future issues within the interactions between autonomous vehicles and vulnerable road users a predictive approach is required that can review the possible emergent behaviours. The aim of this research is to develop a predictive method that is able to assess resilience within the interactions between autonomous vehicles and cyclist. A literature review is conducted to review the current methodologies available and how they can be applied to this problem space, before the method is applied to a case study scenario.

2. Resilience Engineering Approach

Hoffman and Hancock (2017) define resilience as the "*systemic capacity to change as a result of circumstances that push the system beyond the boundaries of its competence envelope*" (p565-566). They differentiate this from adaptivity on the basis that resilience involves some form of change, away from the original processes to establish a new state of stability. Whereas adaptivity involves finding stability within the original parameters. The introduction of autonomous vehicles into our road transport systems provides the need for resilience in the face of changing interactions between roads users and the technologies that will alter the tasks and processes required of human operators (Banks et al, 2014; Hancock et al, 2019).

Resilience engineering is a field of safety research that aims to provide a more proactive approach to safety than those that align it with errors and failings of individuals within a system (Hollnagel et al, 2011; Read et al, 2021). There are calls within the Human Factors (HF) domain to move away from the term 'Human Error' (Dekker, 2011; Shorrock, 2013; Salmon et al, 2017; Read et al 2021), with the suggestion that it is slowing the pace of safety improvement (Read et al, 2021). Instead, a movement towards a systems perspective is advocated which takes the system as the unit of analysis, rather than its comprising elements. These analyses should review the conditions and interaction between components in their normal functioning to understand how variability in system performance may lead to system failure (Dekker, 2011; Hollnagel, 2014; Salmon et al, 2016; Read et al, 2021). This means not relying on the benefit of hindsight but proactively reviewing system functioning to support any positive variability and reduce negative variability (Read et al, 2021). Resilience engineering encourages the anticipation of possible risks and system failures before they happen, to create foresight, rather than account for where safety was neglected after an event has occurred (Hollnagel, 2017). This approach encourages proactivity through considering four key aspects to resilience: monitoring, anticipating, responding and learning (Hollnagel et al, 2011). We need to be able to monitor the system, anticipate possible threats, respond to critical events that may arise and learn from them to prevent them happening again. Recent publications with the journal of Applied Ergonomics highlight the importance of reviewing resilience within the discipline in relation to disaster management (Son et al, 2020) and unpredictable events (Cook & Long, 2020), as well as the importance of being able to work predictively to prevent adversity (Arcuri et al, 2021).

Foresight of the challenges and risks of integrating autonomous vehicles into current road transport systems offers the opportunity to enhance the resilience of the system with the new technologies, rather than cause it a detriment. Yet, there are limited methods and measures to account for system resilience (Hoffman & Hancock, 2017).

The Functional Resonance Analysis Method (FRAM; Hollnagel, 2017) is based on the concept that success and failures within systems have the essentially the same underlying processes. Taking insight from socio-technical systems theory, it suggests that the variations in normal everyday performance between interacting elements can lead to emergent events that can lead to both success or failure, dependant on the direction of the variability. Grabbe et al (2020) applied FRAM to automated vehicle overtakes and suggested that the model could account for some of the variabilities and uncertainties of automating driving tasks, yet the analysis itself was highly complex and time consuming, with concern that it could not account for the interaction with vulnerable road users in addition to automated driving (Grabbe et al, 2020). The complexity of the method has called into question the applicability to real world events (Stanton et al, 2019). FRAM also accounts for performance at the task level and does not map out the interactions between systemic influences such as governance and regulation (Stanton et al, 2019).

This paper proposes utilising alternative human factors methods in combination in order to model system resilience through assessing the interactions between actors. Human factors already have a number of validated and renowned methods that can be used to predict possible hazards and systems failures, as well as predicting possible systems interactions. The Systemic Human Error Reduction and Prediction Approach (SHERPA; Embrey, 1986) has been a prevalent error prediction method this is known to be a reliable and valid method of study (Barber & Stanton, 1996; Stanton & Stevenage, 1998; Hughes et al, 2015). Originally designed with a focus on ‘human error’, the analysis reviews all tasks comprising an activity and identifies their opportunity for ‘error’ against the SHERPA taxonomy (Embrey, 1986). Developments of this method (e.g., Stanton, 2004) have allowed it to move beyond a simplistic ‘error’ analysis to identify how the interaction between different tasks and actors can facilitate error recovery, as well as where system recovery is not possible and failures arise. Reviewing these ‘errors’ as potential system failures also allow for resilience engineering interventions to be identified and proposed (Parnell et al, 2021). These interventions can, and should, look towards the wider systemic influences. Using the SHERPA in combination with a method that can map the interactions between systems actors can enable insight into how the system enables resilience to possible failures, or conversely how they facilitate them. In a similar vain to FRAM this focuses on how failures can occur through ‘normal’ systems performance. The difference in this approach is a more prominent focus on the interactions between the different actors that are involved through using operator event sequence diagrams (OESDs). Furthermore, it allows for the difference in actors and their interactions to be compared within current systems as well as future automated systems.

An OESD is a useful tool in mapping system interactions, particularly in response to automated integration (Banks et al, 2014; Harris et al, 2015; Stanton et al, 2021a;) with validity (Stanton et al, 2021b). OESDs present the allocation of functions to human actors and non-human actors equally, to show the distributed performance of the systems in achieving its goal (Hutchins, 1995; Soensen et al, 2011; Stanton et al, 2021b). This makes them particularly useful in mapping out how autonomous vehicles may interact with the driver and other road users (Banks et al, 2014; Stanton et al, 2021a).

This paper proposes combining, for the first time, a SHERPA with OESDs to map out the interactions between cyclists and road vehicle to proactively identify the opportunity for systems failures and the key interactions that result in such failures, as well as show how resilient remedial measures can be implemented to prevent failures. Application of predictive approaches to OESDs offers the opportunity to review possible disruptions in a systematic manner by reviewing how different scenarios may play out across all relevant actors within a system. It can show how failures from one interaction may impact on later interactions and also where alternative interactions may be able to overcome the failures. We review where interventions can provide new interactions between actors and artefacts that can enhance overall system resilience. To do this it will first seek to understand how current interactions between cyclists and non-automated vehicle to understand the failure points within the current road transport systems. These failure points will then be reviewed to with respect to the possible interactions between autonomous vehicle technology and cyclists to identify where the introduction of automation within road vehicles offers the potential to improve interactions between the two road user groups.

2. Method

2.1 Analysts

A total of three road safety and cycling safety professionals were involved in the development of the Hierarchical Task Analysis (HTA) which formed the basis of the OESDs. The task hierarchy from this analysis was then reviewed by three Human Factors professionals who also had experience with road safety. Three separate researchers were involved in producing the OESDs (and conducting the SHERPA analysis). The primary researcher initially outlined the OESD before it was reviewed by the two other researchers, each with a combined number of over 50 year’s experience in Human Factors (8, 10 and 40+ years respectively) and significant experience in the OESD and SHERPA methodologies.

The review process involved clarifications and elaborations of the OESDs as well as some discussion on the error classifications and remedial measures proposed in the SHERPA.

2.2 Scenario

A vehicle overtakes a cyclist on a two-way road in an inter-urban area, depicted in Figure 1. The road is a shared between the driver and the cyclist, the road markings show that the road forms part of a cycle way, with the cycle figure printed on the road (shown in white). However, there is no separate designated cycle lane. This means there is limited room for a vehicle to overtake at the same time as another vehicle passes in the opposite direction so the driver of the vehicle must ensure that traffic in the opposite direction is clear. The road ahead is straight, crossing into the opposing traffic lane is permitted (dashed centre lane). This scenario does not present a major disruption, rather it focuses on a normal event which occurs frequently on our roadways. Our analysis is interested in reviewing how normal deviations in behaviour may lead to adversity and/or highlight key areas of resilience.

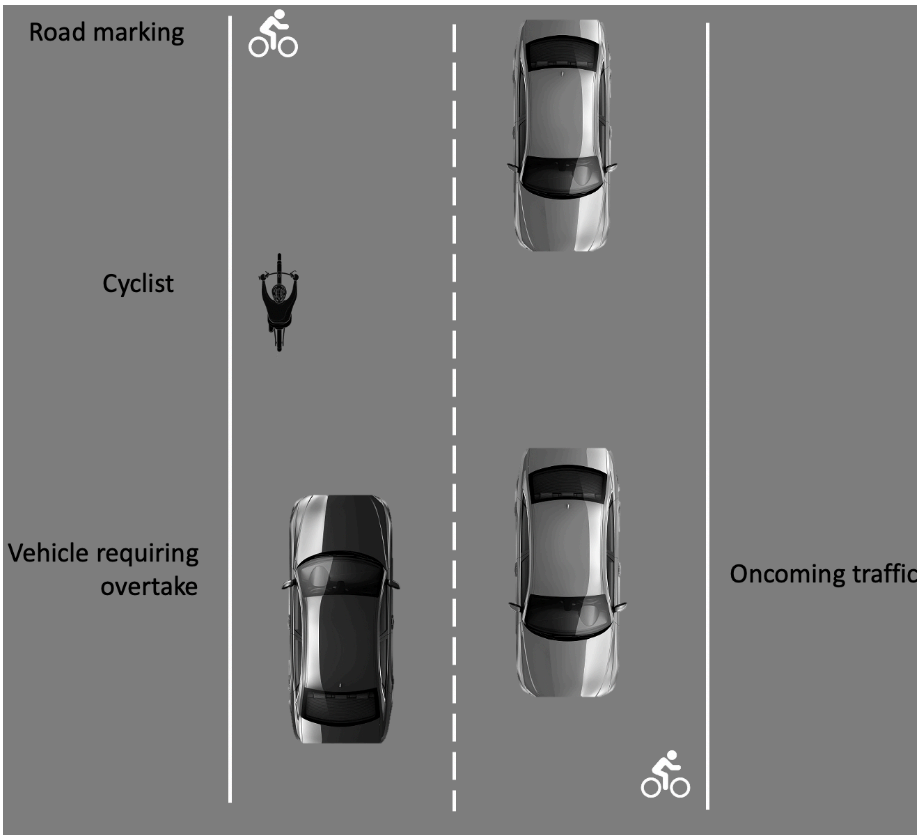

Figure 1. Cyclist overtake scenario. The black car is to overtake the cyclist in the left-hand lane

In this original scenario, which will from now on be referred to as the ‘manual’ scenario, the vehicle has Level 0 automation (SAE, 2021). A comparison between this manual scenario and a future scenario including vehicle automation will be used. For the automated scenario, this work intends to focus on the near to mid-term introduction of automated vehicles at Levels 3 automation (SAE, 2021) which will still require the driver to have a supervisory role. Level 4 or 5 automation (SAE, 2021) is still considered by many experts to be a long way off (Tabone et al, 2021). Therefore, this work will focus on the more pending issues surrounding the interaction with cyclists and automated vehicles where the driver still interacts in a supervisory role. The focus is on the types of general technology that are predicted to be available at this level, but we avoid focusing on specific manufacturers which would limit the applicability of the outputs.

2.3 Task Hierarchy

A HTA is a method that maps out all of the tasks and sub-tasks that comprise an activity with a tabular plan that shows how each of the tasks are conducted in relation to each other, see Stanton (2006) and Annett (2003) for more information on this method. A HTA (Stanton, 2006; Stanton et al, 2013) of a manual cyclist overtake was conducted within the CRoss-modal Intervention to Improve Cyclist Awareness Levels (CRITICAL) project in collaboration with The Road Safety Trust. This project aimed to inform road safety training that included both cyclist and driver perspectives. They collected data from both road user groups on how they approach different scenarios on the road, including a cyclist overtake scenario. This work involved road safety professionals performing cyclist overtakes in a real-world road environment while verbalising their thought processes. This is known as a verbal protocol method which capture the contents of an individuals' working memory through their verbal reports in relation to the context and decisions that they are making (Ericsson & Simon, 1993). The outputs of this were used to generate the task hierarchy. This was then validated by expert drivers and cyclists by comparing the outputs to the verbal protocols that were recorded by the experts when they were performing the overtake. The final task hierarchy comprises of a total of 66 tasks and 7 goals which were used to inform the OESD for the manual cyclist overtake scenario. The complete task hierarchy can be found in Appendix A. This hierarchy presents the tasks involved following best practises, as guided by the highway code. Not all overtakes are performed the same and the analysis conducted within this work seeks to review the variability that may occur.

2.4 Operator Event Sequence Diagram

A OESD is used to map out the different actors within their own 'swim lane' and present the tasks that each actor is responsible for conducting. The interrelation and dependence between each of the tasks are mapped with arrows between the tasks. The diagram of the different interacting tasks is the output of the method, providing a visualisation of the interactions between all actors in conducting a task. They have been used effectively in mapping driver and vehicle interactions as well as identifying the role of vehicle automation (Banks et al, 2014; Stanton et al, 2021a, b). A OESD of the manual cyclist overtake scenario was constructed from the tasks identified in the task hierarchy. The main operators include the driver of the vehicle, the vehicle, the cyclist and the road infrastructure. The standardised symbols used in OESD created were used, see Figure 2. The scenario was separated into the pillars of resilience proposed by Hollnagel et al, (2011).

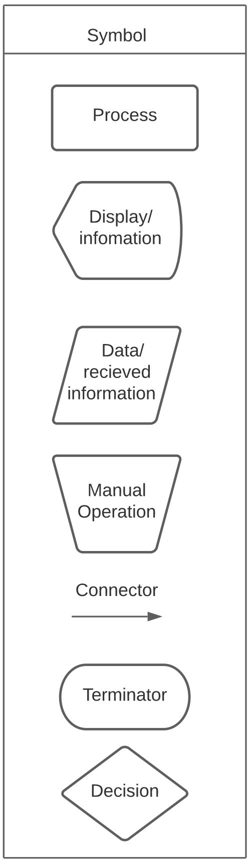

Figure 2. OESD standardised symbols

2.5 SHERPA

SHERPA is an error analysis tool developed by Embrey (1986). It provides an error taxonomy of the different types of errors that can occur within the functioning of a system.

This taxonomy is applied to the task that are required within the everyday functioning of the systems to understand where opportunity for failure can occur. It is a predictive manner therefore the analysts apply the taxonomy predictively by identifying all possibilities for failure. See Harris et al (2005) for further explanation and example application. A SHERPA was conducted to review the opportunity for failure in the tasks and interactions of the operators. Failures were coded in accordance with the SHERPA failure taxonomy. These were classified by the analysts (see Section 2.1) who each independently applied the SHERPA taxonomy before discussing their results together to agree on the final set of possible errors. The possible failure recovery events and the likelihood and criticality of the failures were classified in accordance with the methodology as stated in Stanton (2004). This involved a discussion between the expert human factors analysts until agreement was reached. For the manual scenario, the likelihood of the failures were classified in accordance with the historic statistics available on the contributory factors related to pedal cyclists incidents in the UK (DfT, 2021). This included factors related to the cyclists, the driver and other vehicles. Low likelihood were categorised as those that never, or very rarely, occurred before and were therefore not included on the DfT (2014) top 10 causal factors list. Medium likelihood related to failures that had occurred in the past and had led to incident or injury and were therefore included on the DfT (2014) list. High likelihood was reserved for common and well-known failures that happened most of the time. For the automated scenario the classification assumed that automation was fully functioning and therefore considered failures relating to failure in the automated system to be low in likelihood. Medium likelihood failures were classified as those where a breakdown in the interaction between the automation and the driver, as this is considered to be as area of significant risk in the implementation of automated vehicles which means that there is opportunity for these types of failures to occur (e.g., Campbell et al, 2018; Gold et al, 2017; Pattinson et al, 2020).

Criticality was rated on a binary scale, critical or non-critical. A critical failure was deemed to be one that can directly relate to a collision between the vehicle and the cyclist that could lead to serious injury or fatality. A remedy analysis also applied to initial SHERPA on the manual scenario to allow resilience engineering interventions to be determined and then classified under 4 main themes: equipment, organisational, training, procedures (Stanton, 2004). The remedy analysis took a forward-thinking approach, reviewing the proposed developments in automated vehicles and technological advancement, as suggested within the academic literature.

Results from the SHERPA were then mapped back on to the OESD to view the resilience of the current scenario, as well as presenting how resilience engineering interventions could be applied to enhance the system.

3. Results

3.1 Operator Event Sequence Diagram

The OESD in Figure 3 shows the interaction between the different operators throughout the scenario. Alongside evidence for the monitor, anticipate and respond pillars, an additional phase was identified; detect. This refers to the detection (visual, audio or mechanical) of possible hazards in the environment. Meanwhile the ‘learn’ pillar was not evidenced within the OESD, although training and experience form an essential component of the driving and cyclist behaviour which will inform performance. The inclusion of the learn pillar is discussed later.

The initial monitoring stage takes place before the driver initially sees the cyclist, yet both the driver and the cyclist are monitoring the road environment for any possible hazards or emerging events that they will have to manage. The road infrastructure informs the driver that there is a possibility of cyclists on the road and therefore they should be primed to monitor the road ahead. The cyclist will be in the cycle lane, but as this is still on the shared roadway, they will be aware of possible approaching vehicles from behind as well as in front. They will also be monitoring the roadway ahead for any potholes or possible hazards.

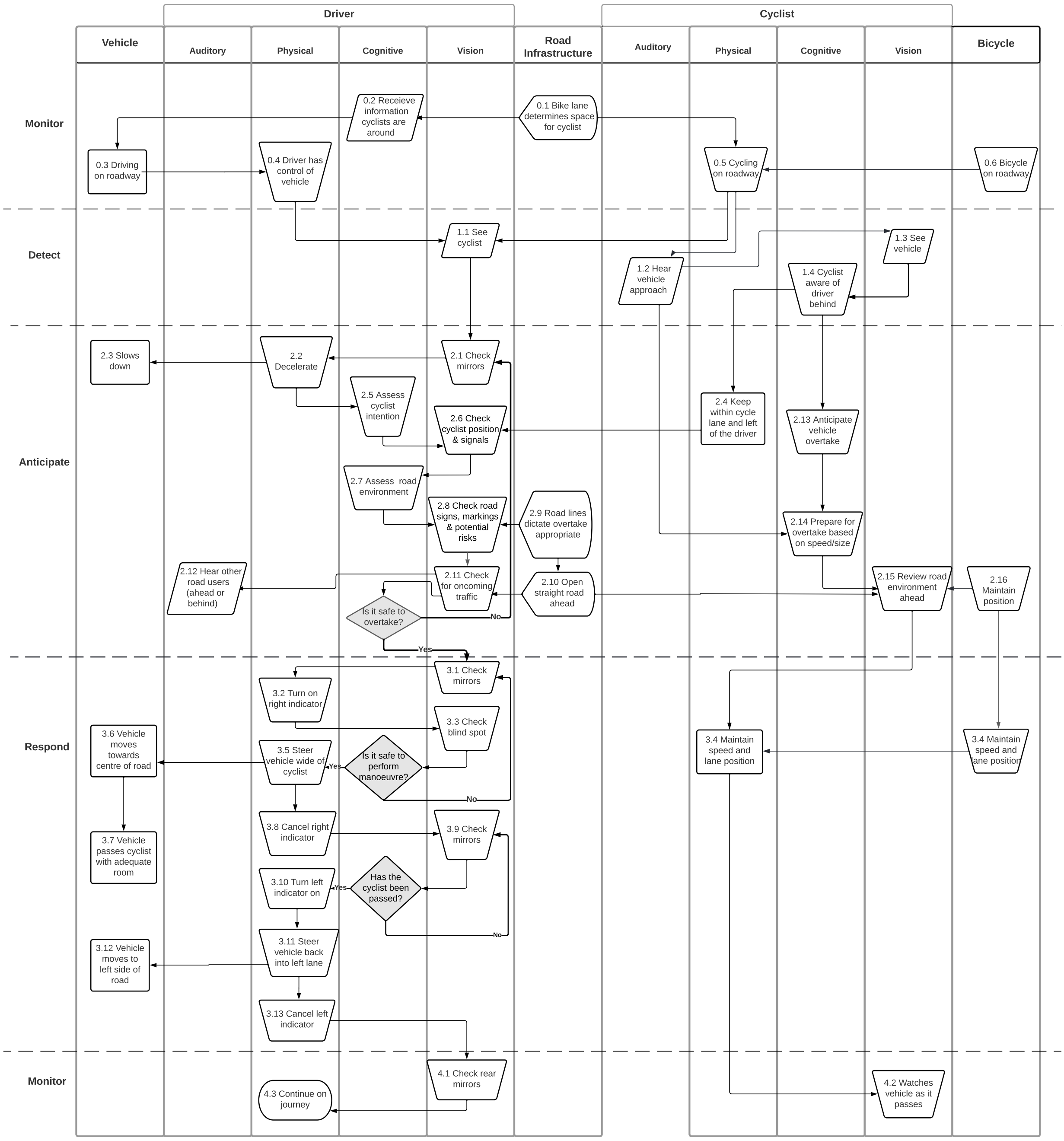

Figure 3. OESD of manual vehicle cyclist overtake

The detection phase is important as it includes the initial interaction between the driver and the cyclist as they first become aware of each other. For the driver, this is likely to be purely visual, seeing them on the road ahead. For the cyclist they will likely hear the vehicle first and then glance back to see the vehicle to assess its size and speed of travel.

Once the cyclist and the driver have detected one another they begin to anticipate the others response while also formulating their own responses. The cyclists maintain their speed and lane position. The driver of the vehicle assesses the cyclists speed and their intentions, as well as reviewing the road environment ahead to determine the feasibility of an overtake manoeuvre. The cyclist is also reviewing the road environment to assess for possible hazards such as potholes which may cause them to deviate from their current road position. The Anticipate phase accumulates in a decision made by the driver; “Is it safe to overtake?”. This decision is informed by all the information they have obtained through the previous events at this stage e.g., their mirrors, the road environment, lane markings. If the driver decides it is not safe, then they will continue to make checks until it is safe to do so. If they do deem it safe to overtake, they progress into the response stage.

The response phase captures the overtake manoeuvre itself. The cyclist must maintain their positioning while the driver checks their mirrors and blind spot to ensure there are no approaching vehicles. These checks also inform the decision of determining the safety of the manoeuvre and if the cyclist has been safely passed. The drivers handling of the scenario enables the overtake of the cyclist at a safe distance, while also indicating their intentions to the cyclist and other road users with their indicators.

Once the overtake is complete the vehicle and cyclist will resume their journeys, continuing to monitor the environment around them.

3.2 SHERPA

Table 1 presents the frequency of the different failures identified in the SHERPA, with a total of 44 possible failures from the manual overtake manoeuvre. The full SHERPA is detailed in Appendix B including a breakdown of all the failures, their severity, likelihood classification, the possible recovery opportunities, and future remedial measures options.

Table 1. SHERPA failure type and frequency from the of the manual cyclist overtake scenario

Failure categories	**Failure sub-categories**	**Failure frequency (n)**
Action	Operation mistimed (A2)	1
	Operation too much/too little (A4)	4
	Action omitted (A8)	5
	Total Action Failures	***10***
Checking	Check omitted (C1)	13
	Check incomplete (C2)	5
	Total Checking Failures	***18***
Selection	***Total Selection Failures***	***0***

Communication	Information not communicated (I1)	3
	Information communication incomplete (I3)	1
	Total Communication Failures	***4***
Retrieval	Information not obtained (R1)	3
	Wrong information obtained (R2)	3
	Information retrieval not complete (R3)	6
	Total Retrieval Failures	***12***
Total failures		**44**

Table 2 shows the frequency of events for each actor as well as the frequency of failures their criticality, and number of irrecoverable failures and therefore can result in total failure in the system.

Table 2. Frequency of SHERPA failures, their criticality and irrecoverable failures

Actor	**Total events**	**Failures**	**Critical**	**Irrecoverable Failures**
Driver	33	31	17	9
Vehicle	5	1	1	0
Cyclist	11	9	5	2
Road	3	3	2	1
Total	**52**	**44**	**25**	**12**

This shows that over half of the failures identified were critical in nature and therefore could lead to serious injury or fatality. While most of these critical failures had possible recovery events, twelve (27.3%) did not. There were no failures that were highly likely and no failures that were low in likelihood, as all were deemed by the researchers to have occurred in the past, but not to a high or common degree of frequency.

The SHERPA identified that the driver has more opportunity for failure (n=31) than the cyclist (n=9). Of the total number of failures that driver also had a higher percentage of failures that cannot be recovered from (driver 29.0%, cyclist 22.2%). All the recoverable failures resulting from cyclist events are dependent on the driver. The driver is reliant on themselves to recover from 4 failures and the cyclist to recover from 18 failures. Each of the detect, anticipate, respond and monitor phases in the OESD have the opportunity for critical failures. Of key concern are the critical failures which have no recovery events and therefore cannot be saved by other events further along the scenario. Many of the critical failure events without recovery that relate to the driver (n=4) involve their physical (n=2) or visual (n=2) capabilities within the scenario. These events include the driver checking their mirrors/blind spot and steering the vehicle around the cyclist. The other critical failures without recovery events relate to the road infrastructure (n=1) and the cyclist's physical actions (n=1). All of these critical, non-recoverable events were rated as medium likelihood.

The SHERPA failures and recovery events were mapped onto the OESD to provide a visual representation of the possibility for disruption within the scenario and how the actors and their actions are interconnected in recovery from these disruptions. Figure 4 shows the visual mapping of the SHERPA classifications to the OESD events.

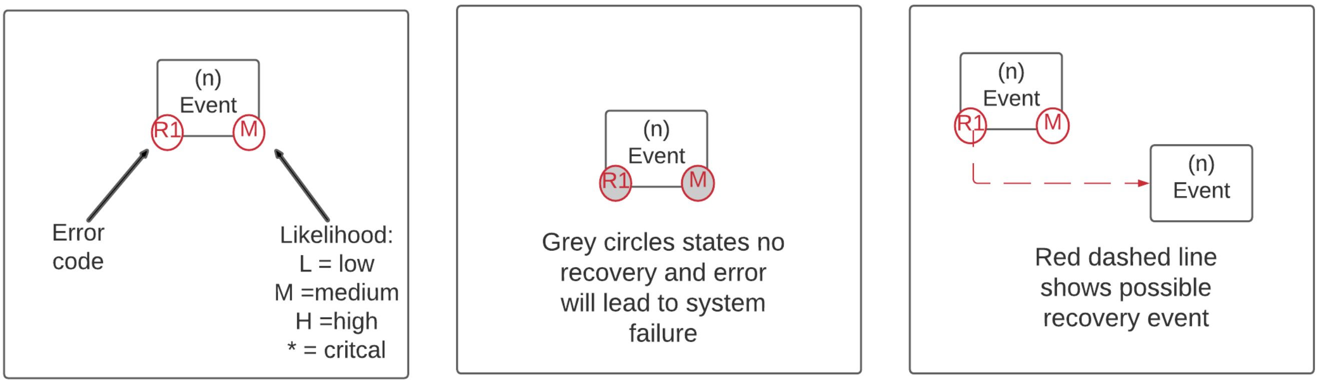

Figure 4. Key for mapping the SHERPA failures onto the OESD events

An example is provided in Figure 5. An 'information communication' (I1) failure on task 0.1 wherein the cycle lane is not clearly marked or obvious to the driver can be recovered by event 1.1, with the driver visually seeing the cyclist. However, the driver could fail to spot the cyclist, a 'check omitted' (C1) failure. This could be saved by the cyclist being aware of the driver (event 1.4), preparing them to adapt to the driver's behaviour. Yet, if the cyclist does not see anticipate the driver in behind them (Information retrieval failure, R1) then this failure can be recovered by the cyclist staying within their lane and out of the driver's way. If the cyclist's road position strays too far from the cycle lane (Action failure, A4) then this could not be recovered by other events within the system and it would lead to a system failure, with the possibility for a collision between the driver and the cyclist. Importantly this demonstrates that actors within themselves do not contribute to failures, but that it is the interaction between different events and actors within the system that enable failures to occur (or not occur). This highlights the importance of taking systems perspective when studying road safety and identify possible remedial measures.

Figure 5. Example visualisation of the SHERPA analysis on the OESD showing events leading up to a system failure. Non relevant events are greyed out for the purpose of the example.

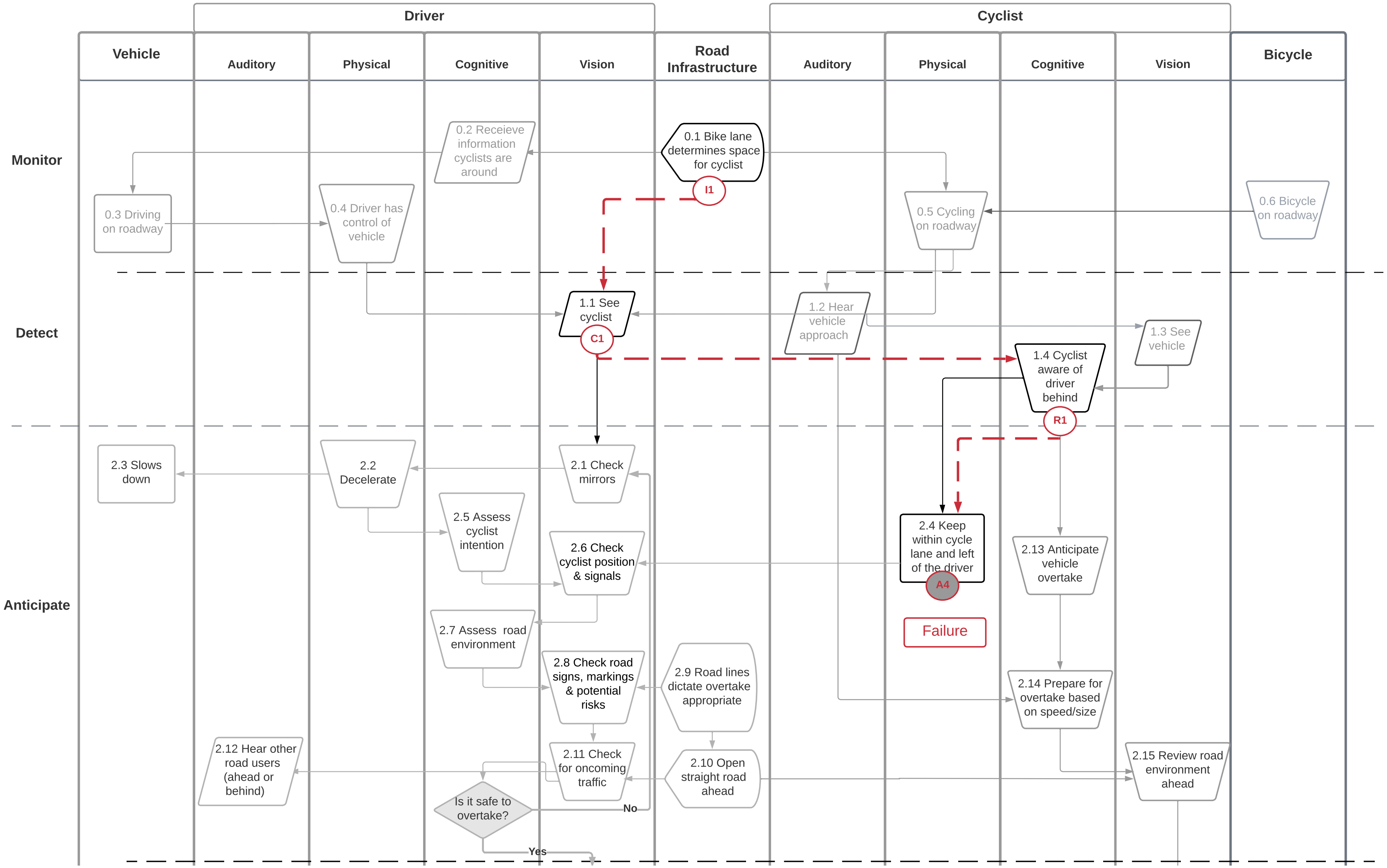

Figure 5. OESD with the SHERPA failures, criticality and recovery events indicated.

3.4 Automated OESD

SHERPA is advocated for its ability to allow the generation of remedial measures to the failures identified (Stanton et al, 2013; Parnell et al, 2020). The possible remedial measure to each possible failure is shown in the final two columns of the full SHERPA in Appendix B. The remedial measures were used to create a future version of the scenario which strives to overcome the failures identified in the initial cyclist overtake scenario. See Figure 6 for a snapshot of this OESD which presents the automated scenario, a more detailed version is provided in Appendix C. The new events that are present in Figure 6, but not Figure 4, are shown with a dashed box and the new connections are shown with a double line. The key elements of resilience are still included; monitor, detect, anticipate, respond and monitor. Events from the original OESD that are no longer required are shown in light grey.

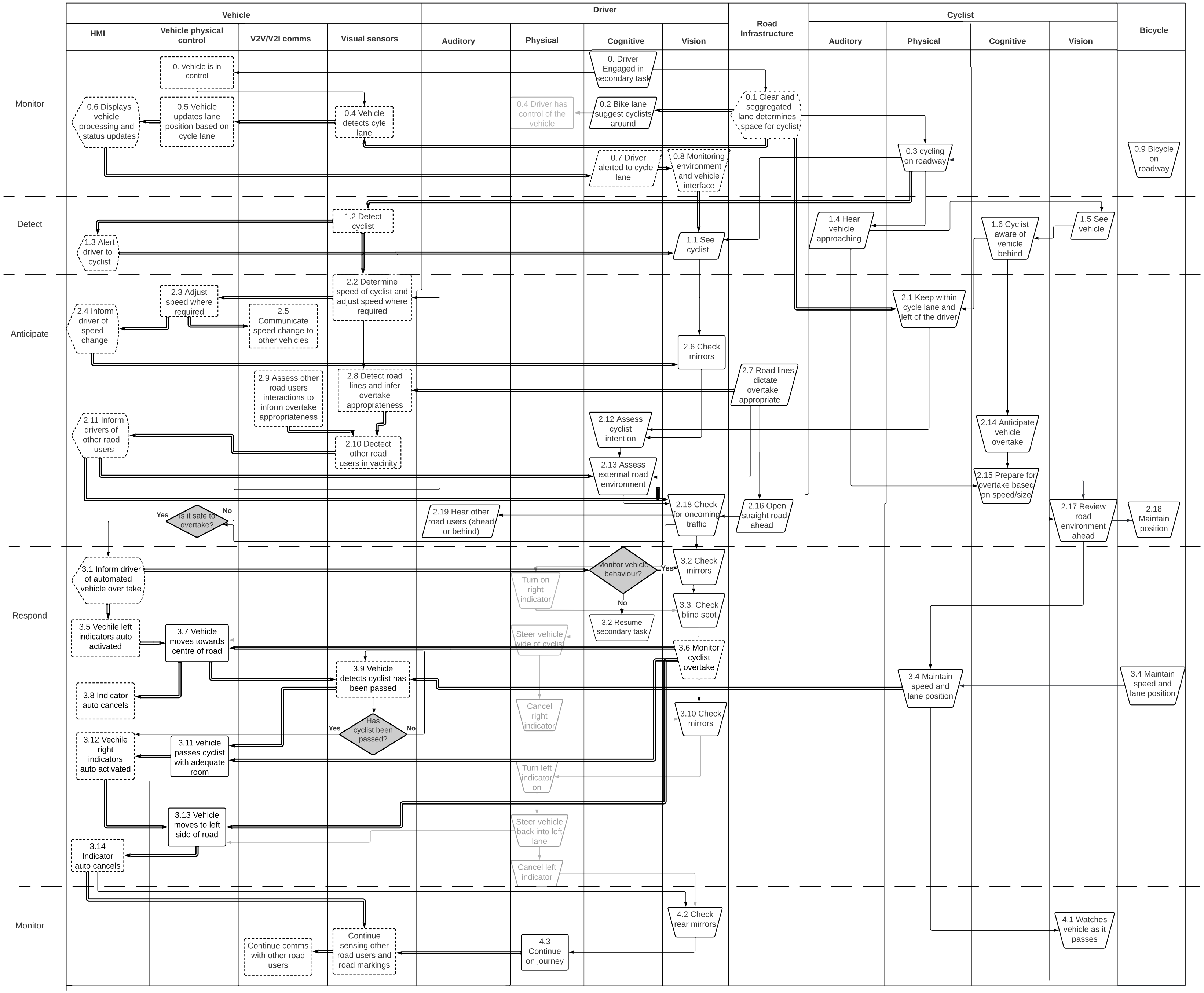
Vehicle
Driver
Road Infrastructure
Cyclist
Bicycle
HMI
Vehicle physical control
V2V/V2I comms
Visual sensors
Auditory
Physical
Cognitive
Vision
Auditory
Physical
Cognitive
Vision
Monitor
Detect
Anticipate
Respond
Monitor
0. Vehicle is in control
0. Driver Engaged in secondary task
0.1 Clear and seggregated lane determines space for cyclist
0.2 Bike lane suggest cyclists around
0.3 cycling on roadway
0.4 Driver has control of the vehicle
0.4 Vehicle detects cyle lane
0.5 Vehicle updates lane position based on cycle lane
0.6 Displays vehicle processing and status updates
0.7 Driver alerted to cycle lane
0.8 Monitoring environment and vehicle interface
0.9 Bicycle on roadway
1.1 See cyclist
1.2 Detect cyclist
1.3 Alert driver to cyclist
1.4 Hear vehicle approaching
1.5 See vehicle
1.6 Cyclist aware of vehicle behind
2.1 Keep within cycle lane and left of the driver
2.2 Determine speed of cyclist and adjust speed where required
2.3 Adjust speed where required
2.4 Inform driver of speed change
2.5 Communicate speed change to other vehicles
2.6 Check mirrors
2.7 Road lines dictate overtake appropriate
2.8 Detect road lines and infer overtake appropriateness
2.9 Assess other road users interactions to inform overtake appropriateness
2.10 Dectect other road users in vacinity
2.11 Inform drivers of other raod users
2.12 Assess cyclist intention
2.13 Assess external road environment
2.14 Anticipate vehicle overtake
2.15 Prepare for overtake based on speed/size
2.16 Open straight road ahead
2.17 Review road environment ahead
2.18 Check for oncoming traffic
2.18 Maintain position
2.19 Hear other road users (ahead or behind)
Is it safe to overtake?
Yes
No
3.1 Inform driver of automated vehicle over take
Monitor vehicle behaviour?
Yes
No
3.2 Check mirrors
3.2 Resume secondary task
3.3. Check blind spot
Turn on right indicator
Steer vehicle wide of cyclist
3.4 Maintain speed and lane position
3.4 Maintain speed and lane position
3.5 Vechile left indicators auto activated
3.6 Monitor cyclist overtake
3.7 Vehicle moves towards centre of road
3.8 Indicator auto cancels
3.9 Vehicle detects cyclist has been passed
Has cyclist been passed?
Yes
No
3.10 Check mirrors
Cancel right indicator
3.11 vehicle passes cyclist with adequate room
3.12 Vechile right indicators auto activated
Turn left indicator on
Steer vehicle back into left lane
3.13 Vehicle moves to left side of road
Cancel left indicator
3.14 Indicator auto cancels
4.1 Watches vehicle as it passes
4.2 Check rear mirrors
4.3 Continue on journey
Continue sensing other road users and road markings
Continue comms with other road users

Figure 6. OESD of automated vehicle overtake

The different phases of the event in relation to the pillars of resilience are discussed in turn.

3.4.1 Monitor

The scenario begins with the vehicle in control and the driver engaged in a secondary (non-driving) task. Event 0.1 in Figure 6 (i.e., clear and segregated lane defines space for cyclist in the road infrastructure) presents the first measure for enhanced resilience, infrastructure that clearly delineates between the different modes. This gives the cyclist the space they need while also clearly signalling to the driver, and the vehicle, that cyclists are present, and they therefore need to monitor the roadway for them. In the manual scenario it was only the driver that had to monitor for the cyclist, but future technologies could also detect cycle lanes on the road, updating the vehicles awareness (Stanton et al, 2017) of the road and altering their lane position accordingly. The vehicle can then communicate its intentions with the driver via the in-car Human Machine Interface, alerting the driver to the cycle lane and any upcoming cyclist. This is in line with the requirements of a SAE level 3 vehicle in this scenario. While automation brings changes to the drivers' activities and that of the vehicle, the cyclist maintains the same behaviours, albeit with improve infrastructure.

3.4.2 Detect

In the manual OESD in Figure 4, the driver was relied upon to see the cyclist and the cyclist would become aware of the driver by hearing them approaching and then possibly turning their head to see the vehicle which would inform their next actions. Figure 6 shows how the vehicle sensors can detect the cyclist on the road can facilitate another avenue for the detection of the cyclist. Via the in-car Human-Machine Interaction (HMI), the vehicle can also alert the driver to the cyclist. Increased options for detection will enhance the safety of the cyclist and their detection. Furthermore, the remedial analysis also suggested opportunity for external HMI (eHMI) on the vehicle itself or possibly via a bicycle interface that informs the cyclist that they have been detecting, giving the cyclist some reassurance (Stanton et al, 2020).

3.4.3 Anticipate

Within this phase the cyclist must continue to maintain their lane positioning and anticipate the vehicles approach and overtake, as they do in the manual condition. They are still vulnerable to the vehicle's actions. The vehicle is able to automate a large number of the tasks performed by the driver in the manual OESD through the sensor detection and automated speed control. If slowing down is required, the vehicle will communicate this through its brake lights to other drivers as well as being detecting in other automated vehicles detectors. It will also inform the driver via the in-vehicle HMI. The driver is still able to check the mirrors and build their situational assessment, as they would do in the manual scenario, but the vehicle is also building its assessment and is able to carry out the required actions to begin the overtake scenario. This includes reviewing the environment for on-coming vehicles via Vehicle to Vehicle (V2V) communication systems and inferring overtake appropriateness based on centre line detection and analysis. V2V communication relates to the wireless sharing of data between vehicles, including speed and location data. In this automated scenario the decision of 'is it safe to overtake?' is now made by the vehicle automation rather than the driver. If the vehicle decides it is not safe, then they continue to monitor using the vehicle sensors until it is deemed to be safe. The scenario then progresses to the respond stage.

Again, the cyclists' actions remain the same, reviewing the road environment ahead to check for upcoming vehicles which may inform them when the vehicle will overtake. They will also continue checking the road surface for possible potholes or hazards which may require them to change their lane position and could impact the vehicles overtake.

3.4.5. Respond

In the respond phase of Figure 6 the tasks that the driver once performed in the manual condition are shown to be performed by the vehicle, including the movement of the vehicle to the centre of the road to overtake the cyclist and the corresponding activation of the indicator lights. The vehicle initially informs the driver of the intention to overtake, and the driver then makes the decision to monitor the manoeuvre or to continue with their secondary task. The driver can continue to watch and check the mirrors to monitor the vehicles actions, they can also override vehicle automation where appropriate. The previous tasks of the driver turning the indicators on and off are greyed out to show the transference of these tasks to the automated vehicle. Furthermore, the decision that the cyclist has been passed and the vehicle can move back into the lane is now made by the vehicle, rather than the driver. The vehicle uses its sensors to detect the presence of the cyclist and its distance from them. The cyclist's actions remain unchanged, they must maintain their speed and lane position to allow the vehicle to safely pass. The SHERPA identified this to be a critical event in the manual OESD as it was a recovery event for many previous failings made by the driver. Within this OESD, both the driver and the vehicle are able to detect and monitor the cyclist's activity which could reduce the likelihood of a collision.

3.4.6. Monitor

The final monitoring stage includes the driver checking their mirrors as they continue on their journey after the overtake. The driver may then opt to engage in another task as the vehicle takes over the active monitoring task using its sensors and V2V/V2I communications. The cyclist continues to monitor the vehicle as it overtakes to ensure that it does so without posing any risk to them, as well as determining if other following vehicles are also overtaking them. They will then continue to monitor the environment ahead as well and listen out for vehicles from behind.

3.5 Automated SHERPA

A SHERPA was conducted on the events presented on the automated OESD in the same way that was done with the manual OESD. The full SHERPA is presented in Appendix D and the failure frequencies are shown in Table 3. As the likelihood of the failure is somewhat unknown due to them being envisioned failures, the reasoning for the classification is included against each failure within the SHERPA.

The automated scenario has more events in total, highlighting the complexity of the scenario with vehicle automation. There was also more opportunity for failure with a total of 58 failures identified in the SHERPA, however, a smaller proportion of these failures were critical (47.0%) and far fewer resulted in irrecoverable failures (12.1%). This suggests that the complexity with the system can provide more opportunity for recovery and ultimately that the automation can provide more resilience through the interactions between the different actors which can limit the opportunity for collision.

Table 3. Comparison between the frequency of failures, critical failures and irrecoverable failures between the manual and automated overtake scenario.

	Total events		**Failures**		**Critical Failures**		**Irrecoverable Failures**	
Actor	**Manual**	**Automated**	**Manual**	**Automated**	**Manual**	**Automated**	**Manual**	**Automated**
Driver	33	24	31	23	17	5	9	0
Vehicle	5	27	1	25	1	17	0	7
Cyclist	11	11	9	9	5	4	2	1
Road	3	3	3	1	2	1	1	0
Total	**52**	**65**	**44**	**58**	**25** (57%)	**27** (47%)	**12** (27%)	**7** (12%)

4. Discussion

This paper has presented the application of popular HF methods, OESD's and SHERPA, in combination to assess resilience in the interaction between cyclists and road vehicles. Vehicle automation holds the potential to push the road transport system '*beyond the boundaries of its competence envelope'* (Hoffman & Hancock, 2017, p565-566), if it is not integrated correctly. This is attested to in the analysis of the fatal collisions involving the first automated vehicles (see Banks et al 2019; Stanton et al, 2019). The manual OESDs (Figure 4) presented current interactions with manual vehicles, as informed by task hierarchy analysis conducted by experienced drivers and cyclists. The SHERPA detailed the numerous (n=44) failures that are possible in the cyclist overtake scenario which support the number of cyclist incidents and fatalities that are seen on the roads (Department for Transport, 2021b).

As autonomous vehicles develop, the prioritisation and integration of different transport modes on the roads needs to be carefully considered. Recent proposed changes to the highway code in the UK suggest including a 'Hierarchy of Users' whereby responsibility is based on level of risk that vehicles and individuals pose. Hence, vehicles would have more responsibility than cyclists as they pose a greater risk to the cyclist than the cyclist to the vehicle. However, such adjustments target the outcomes of incidents once they have already occurred, they do not proactively consider how roadways and vehicles could be designed to account for the comparative levels of risk. Future regulations need to be more proactive in the way in which different transport modes interact as automation threatens to pose significant legal, ethical and moral questions in the event of incident (e.g., Goodall, 2014; Schuelke-Leech et al, 2019; Rodríguez-Alcázar et al, 2020). This research is able to provide practical, methodological and theoretical contributions to the development of resilient road transport systems that cater for automated and vulnerable road users.

4.1 Practical contributions

The SHERPA in Appendix B provides resilience engineering interventions which can help to overcome the failures posed by the manual cyclist overtake scenario. These interventions measures were incorporated into the automated OESD in Figure 6. Many of these interventions echo similar considerations by others in the field, including the interviews with experts (Tabone et al, 2021; Pettgrew et al, 2020; Botello et al, 2019) and Lathem et al's (2019) ethnographic study. Yet, this is the first attempt to map them with validated HF methods. Each of the key areas for remedial measures are discussed in turn. These suggest where efforts should be focused but they also highlight the issues which are still prevalent will need to be carefully reviewed.

4.1.1. Organisational Measures

4.1.1.1 Infrastructure

The first events in the OESD in Figure 6 present the initial opportunity for enhanced resilience, with the utilisation of clearer and more segregated cycle lanes. Clearly indicated shared spaces with improved road infrastructure would allow road user an enhanced awareness of each other, allowing them to monitor for possible upcoming interactions. Yet, infrastructure change is costly. The implementation of such a measure would require significant organisational change and investment.

Ultimately it is governments who hold the power over road infrastructure and therefore they will be regulator of how automated and vulnerable road users interact with each other on the roads (Botello et al, 2019). The prioritisation of non-motorised transport modes is an outcome of the decisions made by governments, but it is important that these decisions are informed by the needs and tendencies of society (Lathem et al, 2019). Furthermore, while some see segregation of automated and vulnerable road users as the best way forward, others suggest that shared road use will be facilitated through connected roadways and advanced vehicle detections and sensor technologies (Botello et al, 2019). This paper argues that both will be needed to enhance resilience in the response to the integration of automation to our roadways and its interaction with vulnerable road users.

4.1.1.2 Connected roadways

There are various proposed ways in which roadways can become more connected; V2V, vehicle to infrastructure (V2I), vehicle to pedestrian (V2P), vehicle to bike (V2B), vehicle to anything (V2X). These connections aim to allow more resilience by providing more awareness of other road users and anticipate future interactions. Connected systems were presented within the anticipate phase of the scenario, allowing the vehicle to assess other road users' behaviour and communicate changes in speed to others.

Notably no communication was presented from the bicycle, however, smart phones could allow connected technologies to become a possibility, with signals communicating to the road infrastructure alerting other users to their presence or their needs. Cyclist could carry smart devices or have them inbuilt into their helmets which could enhance their detection as well as the distance that vehicles pass them (Pettgrew et al (2020). They could also communicate to the cyclist when a vehicle is approaching and what its intention is, such as: overtake, turn left or stay behind. This does, however, carry privacy concerns as all users will be monitored. Furthermore, cyclist may not be keen to have to buy and carry these devices with them with compliance possible ethical issues needed to be considered. The approach also needs to be inclusive, accounting for older or younger users who are less likely to use smart devices but whose priority on the road network must be maintained.

There is some concern surrounding the reliability and possibility for failures with this technology, therefore thorough testing and transparency is required. This analysis has shown how wireless communications can provide additional interactions between the different road user groups which can enhance the resilience. However, we should be careful not to fully replace other forms of communication in case of failure.

4.1.2. Equipment measures

4.1.2.1 Automated detection sensors

Automated vehicles will essentially be driven by sensors which build situation awareness by detecting roadway markings and other road users. The manual OESD in Figure 4 showed that detecting the cyclist was the first opportunity for a critical failure, if the driver failed to see the cyclist they were at serious risk. Further recovery was only possible if the cyclist could anticipant and adjust their lane positioning by getting out of the vehicle’s way. In the automated scenario the sensors gave added resilience by providing another way of detecting the cyclist.

Figure 6 shows the importance of the vehicles sensors throughout all phases of the overtake scenario. Within the detect and anticipate phase, the sensor provides the prime detection and assessment mechanism of the cyclist in preparation for the overtake. The driver monitors and checks for possible hazards. The accuracy of the sensors is paramount to the cyclist’s safety and therefore they need to be fully tested in their interaction with all vulnerable and non-motorised road users. There is, however, concern in the cycling community over the current accuracy of the sensors, particularly their ability to detect cyclists (Sandt & Owens, 2017). Despite testing in controlled environments, it is clear that automated vehicles have been introduced without full capability to accurately detect and respond to all possible interactions with other road users (e.g., Banks et al, 2019; Stanton et al, 2019). Connected systems may help with this by building situational awareness of road users in relation to each other and upcoming events (Stanton et al, 2017).

4.1.2.2 external HMI (eHMI)

A central part of the interaction between the vehicle and the cyclist is their detection and anticipation of each other's movements. eHMI proposes one way of providing clarity on the state and intentions of road users to allow a greater awareness for their current and future behaviours (Carmona et al, 2021). Vehicle indicators are one form of eHMI currently in use which provide the cyclist and other road users of the vehicles intentions during the overtake manoeuvre. More advanced eHMI could be developed within automated vehicles that could convey the automated status of the vehicle, such as: level of automation or the automated features that are activate and the vehicles intentions (Carmona et al, 2021; Zhang et al 2016; Stanton et al, 2020). These measures could be a relatively simple way of encouraging anticipation and distributed awareness for other road user interactions (Stanton et al, 2017). This would be particularly useful as vehicles with different levels of automation cohabit the same road space and therefore require different anticipatory behaviours.

4.1.3 Procedural measures

4.1.3.1 Overtaking distance

The distance that drivers give between the vehicle and the cyclists is an area of much contention (Lamb et al, 2020). Many governments have set minimum passing distance laws that set a specific safe overtake distance, which varies from 0.61m to 1.5m depending on country (Lamb et al, 2020). Yet, some evidence suggests that such laws do not make cyclists feel safer and instead it should be left to police officer discretion which is more homogenous with cyclists' safety perceptions (Lamb et al, 2020). When designing automated vehicles, the current laws and guidance will be encoded into the vehicles intelligence which will inform its decisions in situations such as overtaking a cyclist (Lathem et al, 2019). Using the current minimum passing distance will not be non-standard across countries, nor will it necessarily lead to the cyclist feeling safe, as safety is often dependant on the context and the characteristics of the cyclist themselves (Lamb et al, 2020). The informal rules of the road and the empathetic nature of drivers will be a large challenge in the integration of automated vehicles (Lathem et al, 2019). Yet, if automated vehicles improve on current interactions through larger passing distances and considerate road positioning, they offer much opportunity to enhance cyclist relations and encourage more into active modes of travel which has benefits for health and the environment (Pucher & Buehler, 2017).

4.1.4 Training measures

Training that can increase the awareness for other road user behaviours can enable better integration between different modes, as reviewed in the CRITICAL project. There is currently no mandatory cyclist training which can lead to unsafe behaviours which drivers may find challenging. This can lead to stereotypes and animosity (e.g., English & Salmon, 2016). Training can encourage safe interactions and increase trust between different road users. Cyclists will likely need training in how automated vehicles will interact with them to understand how they will detect and respond to them. This will enable them to know how to react to automated vehicles safely. Vehicles that still require input from the driver in some capacity will also require the driver to have some level of training in how to respond and anticipate the vehicles interaction and what to do if anything untoward occurs. Standardised training can also help prevent any new sources of failure from occurring due to adaptation to new conditions (Thompson et al, 2020).

4.2 Methodological contributions

Mapping failures onto the OESD's provides a novel way of reviewing possible disruptions to the events in a given scenario as well as gaining an insight into how the system may adapt to recover from failures. The combination of the SHERPA and the OESD is useful in assessing the resilience of a system in its current functioning, as well as how the introduction of new measures can enhance system resilience. These methods are already well known with the human factors and ergonomics discipline and therefore this combined methodology is highly accessible, without the need to learn new approaches.

Mapping on the cornerstones of resilience identified by Hollnagel et al (2011) has identified where the different aspects of resilience need to be upheld. Notably this has identified the importance of detection in maintaining resilience in the given scenario. The cyclist detecting the vehicle and the vehicle detecting the cyclist are key events in the overtake scenario which influence the anticipation for action and the response of both actors. This is particularly pertinent to automated technologies that utilise sensors to interact with the world around them. Accurate detection will be a critical aspect of resilience in an automated world and therefore the authors propose this as a fifth cornerstone of resilience in addition to the four proposed by Hollnagel et al (2011).

The learning cornerstone was not stated within the OESDs, although it does present itself in the background, as it informs may of the events performed by the road users. Driving and cycling are learnt behaviours and interactions between the two road users develop over time, through formal teaching to pass a driving test but also through experiences. Salmon et al, (2014) highlight how previous experience of interactions with users across transport modes plays a large role in how they then perform in their future interactions with other road users. Over time this can lead to adaptations that are not foreseen and may impact on safety (Salmon et al, 2014; Thompson et al, 2020). Driver and general road safety training will need to be reviewed alongside the introduction of automation on the roadways and several challenges have already been identified (Merriman et al, 2021)

The introduction of automation brings another source of learning in the form of machine learning whereby algorithms are able to review large extensive sets and learn from it to inform decisions and assumptions about the world (Hancock, 2017; Hancock et al, 2019; Salmon et al, 2020). This is how automated vehicles will be trained to interact with the roadway and those within it. Overtime automation will also learn from previous experience through the generation of data and the sharing of that data to inform future behaviour.

This approach has focused on a specific cyclist over-take scenario. It should be noted that there are multiple other scenarios in which the interaction between automated vehicles and vulnerable road users needs to be reviewed and understood. However, applying the method to this scenario has demonstrated how the methodology can generate a significant number of recommendations that holistically target the wider sociotechnical systems that are responsible for successful automation integration in the road transport industry. The complexity of the road transport domain means that considering specific scenarios can be a useful way of understanding fundamental issues that may arise.

5. Conclusion

This is the first attempt to model resilience using OESD's by identifying opportunity for failure and their possible recovery options by applying the SHERPA to the event diagram itself. The analysis of the cyclist overtake scenario has shown that the driver and the cyclist are both heavily reliant on each other for recovering from each other's possible failings. The recovery from possible manual failures through automated features has shown how automation could be introduced to enhance resilience in the interactions between vehicles and cyclists. The methodology has allowed the "systemic capacity to change" (Hoffman & Hancock, 2017; p565-566) in a cyclist overtake scenario to be captured and analysed. This paper provides a new way of modelling resilience that builds on previously validated and valued HF methods. Applying them in new ways offers new opportunity for assessing resilience and enhancing the integration of autonomous systems. The practical contributions of this work target interventions that the government, regulators and resource providers need to focus on as automated vehicles become ever present on our roadways, in order to protect and facilitate the vulnerable, active transport users. However, it is clear that there is much to consider with the implementation of automated vehicles, with more complex interactions between all components of the road transport system.

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References

Annett, J. (2003). Hierarchical task analysis. *Handbook of cognitive task design, 2,* 17-35.

Arcuri, R., Bellas, H. C., de Souza Ferreira, D., Bulhões, B., Vidal, M. C. R., de Carvalho, P. V. R., ... & Hollnagel, E. (2022). On the brink of disruption: Applying Resilience Engineering to anticipate system performance under crisis. Applied Ergonomics, 99, 103632.

Baber, C., & Stanton, N. A. (1996). Human error identification techniques applied to public technology: predictions compared with observed use. *Applied Ergonomics, 27*(2), 119-131.

Banks, V. A., Stanton, N. A., & Harvey, C. (2014). Sub-systems on the road to vehicle automation: Hands and feet free but not 'mind' free driving. *Safety Science, 62,* 505-514.

Banks, V. A., Stanton, N. A., & Plant, K. L. (2019). Who is responsible for automated driving? A macro-level insight into automated driving in the United Kingdom using the Risk Management Framework and Social Network Analysis. *Applied Ergonomics, 81,* 102904.

Bil, M. Bilova, M., & Muller, I. (2010) Critical factors in fatal collisions of adult cyclists with automobiles. *Accident Analysis and Prevention, 42*(6), 1632-1636

Booth, L., Norman, R., & Pettigrew, S. (2019). The potential implications of autonomous vehicles for active transport. *Journal of Transport & Health, 15,* 100623.

Botello, B., Buehler, R., Hankey, S., Mondschein, A., & Jiang, Z. (2019). Planning for walking and cycling in an autonomous-vehicle future. *Transportation Research Interdisciplinary Perspectives, 1*, 100012.

Campbell, J. L., Brown, J. L., Graving, J. S., Richard, C. M., Lichty, M. G., Bacon, L. P., ... & Sanquist, T. (2018, August). *Human factors design guidance for level 2 and level 3 automated driving concepts* (Report No. DOT HS 812 555). Washington, DC: National Highway Traffic Safety Administration.

Carmona, J., Guindel, C., Garcia, F., & de la Escalera, A. (2021). eHMI: Review and Guidelines for Deployment on Autonomous Vehicles. *Sensors, 21*(9), 2912.

Chaurand, N., Delhomme, P. (2014) Cyclists and drivers in road interactions: a comparison of perceived crash risk. *Accident Analysis and Prevention, 50*, 1176-1184

Cook, R. I., & Long, B. A. (2021). Building and revising adaptive capacity sharing for technical incident response: A case of resilience engineering. Applied Ergonomics, 90, 103240.

Dekker, S. (2011). *Drift into Failure: From Hunting Broken Components to Understanding Complex Systems.* Surrey: Ashgate.

Department for Transport (2014). *Focus on Cycling in 'Reported Road Casualties Great Britain 2013* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/359311/rrcgb-2013.pdf [Accessed 21/09/2021]

Department for Transport (2021a) *Transport and Environment Statistics 2021* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/984685/transport-and-environment-statistics-2021.pdf Annual report [Accessed 21/09/2021]

Department for Transport (2021b). *Reported road casualties Great Britain, annual report: 2020.* https://www.gov.uk/government/statistics/reported-road-casualties-great-britain-annual-report-2020/reported-road-casualties-great-britain-annual-report-2020 [Accessed 07/20/2021]

Dozza, Marco, Ron Schindler, Giulio Bianchi-Piccinini, and Johan Karlsson. (2016) How do drivers overtake *Accident Analysis & Prevention, 88,* 29-36.

Ericsson, K. A., & Simon, H. A. (1993). *Protocol analysis: Verbal reports as data* (Rev.

ed.). Cambridge, MA: MIT Press. (First edition published 1983)

Embrey, D. E. (1986). SHERPA: A systematic human error reduction and prediction approach. In *Proceedings of the international topical meeting on advances in human factors in nuclear power systems.* 21-24. Knoxville, TN (USA).

English, P., & Salmon, P. (2016). New laws, road wars, courtesy and animosity: Cycling safety in Queensland newspapers. *Safety Science, 89,* 256-262.

Environmental Protection Agency (2020) *Sources of Greenhouse Gas Emissions* https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions [Accessed 21/09/2021]

Gold, C., Naujoks, F., Radlmayr, J., Bellem, H., & Jarosch, O. (2017, July). Testing scenarios for human factors research in level 3 automated vehicles. In *International Conference on Applied Human Factors and Ergonomics* (pp. 551-559). Springer, Cham.

Goodall, N. J. (2014). Machine ethics and automated vehicles. In *Road Vehicle Automation* (pp. 93-102). Springer, Cham.

Grabbe, N., Kellnberger, A., Aydin, B., & Bengler, K. (2020). Safety of automated driving: the need for a systems approach and application of the Functional Resonance Analysis Method. *Safety Science, 126*, 104665.

Hancock, P. A., Nourbakhsh, I., & Stewart, J. (2019). On the future of transportation in an era of automated and autonomous vehicles. *Proceedings of the National Academy of Sciences, 116*(16), 7684-7691.

Harris D, Stanton NA, Marshall A, Young MS, Demagalski J, Salmon P (2005) Using SHERPA to predict design-induced error on the flight deck. *Aerosp Sci Technol 9*(6):525–532

Harris D, Stanton NA, Starr A (2015) Spot the difference: Operational event sequence diagrams as a formal method for work allocation in the development of single-pilot operations for commercial aircraft. *Ergonomics, 58*(11):1773–1791

Hoffman, R. R., & Hancock, P. A. (2017). Measuring resilience. *Human Factors, 59*(4), 564-581.

Hollnagel, E. 2014. *Safety-I and Safety-II: The past and Future of Safety Management.* Farnham, UK: Ashgate.

Hollnagel E. , (2017) FRAM: the *Functional Resonance Accident Model Method: Modelling Complex Sociotechnical Systems. CRC Press.*

Hollnagel, E., Dédale, J.P., Woods, D., Wreathall J. (2011), *Resilience Engineering in Practice: A Guidebook*, Ashgate.

Hollnagel, E., Woods D.D., Leveson, N. (2017) *Resilience Engineering*. CRC Press, London UK.

Hughes, C. M., Baber, C., Bienkiewicz, M., Worthington, A., Hazell, A., & Hermsdörfer, J. (2015). The application of SHERPA (Systematic Human Error Reduction and Prediction Approach) in the development of compensatory cognitive rehabilitation strategies for stroke patients with left and right brain damage. *Ergonomics, 58*(1), 75-95.

Hutchins, E. (1995). *Cognition in the wild.* MIT Press.

Innovate UK (2021) *UK Transport Vision 2050: Investing in the future of mobility.* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1008833/IUK-050821-4293_Innovate_Future_Transport_A4Portrait.pdf [Accessed 21/09/2021].

Kirwan, B. & Ainsworth, L.K. (1992) *A guide to task analysis: the task analysis working group.* CRC Press, Boca Raton

Lamb, J. S., Walker, G. H., Fisher, V., Hulme, A., Salmon, P. M., & Stanton, N. A. (2020). Should we pass on minimum passing distance laws for cyclists? Comparing a tactical enforcement option and minimum passing distance laws using signal detection theory. *Transportation Research Part F: Traffic Psychology and Behaviour, 70*, 275-289.

Latham, A., & Nattrass, M. (2019). Autonomous vehicles, car-dominated environments, and cycling: Using an ethnography of infrastructure to reflect on the prospects of a new transportation technology. *Journal of Transport Geography, 81*, 102539.

Lyons, G. (2004). Transport and society. *Transport Reviews*, *24*(4), 485-509

Millard-Ball, A. (2018). Pedestrians, autonomous vehicles, and cities. *Journal of planning education and research, 38*(1), 6-12.

Merriman, S.E., Plant, K.L., Revell, K.M. and Stanton, N.A., 2021. Challenges for automated vehicle driver training: a thematic analysis from manual and automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 76*, pp.238-268.

Naikar, N., & Elix, B. (2016). Integrated system design: Promoting the capacity of sociotechnical systems for adaptation through extensions of cognitive work analysis. *Frontiers in Psychology, 7*, 962.

Parnell, K. J., Banks, V. A., Allison, C. K., Plant, K. L., Beecroft, P., & Stanton, N. A. (2021). Designing flight deck applications: combining insight from end-users and ergonomists. *Cognition, Technology & Work, 23*(2), 353-365.

Pattinson, J. A., Chen, H., & Basu, S. (2020). Legal issues in automated vehicles: critically considering the potential role of consent and interactive digital interfaces. *Humanities and Social Sciences Communications, 7*(1), 1-10.

Pettigrew, S., Nelson, J. D., & Norman, R. (2020). Autonomous vehicles and cycling: Policy implications and management issues. *Transportation research interdisciplinary perspectives, 7,* 100188.

Pucher, J., & Buehler, R. (2017). Cycling towards a more sustainable transport future. *Transport Reviews, 37*(6), 689-694.

Read, G. J., Salmon, P. M., Lenné, M. G., & Stanton, N. A. (2015). Designing sociotechnical systems with cognitive work analysis: putting theory back into practice. *Ergonomics, 58*(5), 822-851.

Read, G. J., Shorrock, S., Walker, G.H., & Salmon, P.M. (2021) State of science: evolving perspectives on 'human error', *Ergonomics, 64*:9, 1091-1114, DOI: 10.1080/00140139.2021.1953615

Rodríguez-Alcázar, J., Bermejo-Luque, L., & Molina-Pérez, A. (2020). Do Automated Vehicles Face Moral Dilemmas? A Plea for a Political Approach. *Philosophy & Technology*, 1-22.

Rudin-Brown, C.M. & Parker, H.A., (2004), Behavioural adaptation to Adaptive Cruise Control: Implications for preventive strategies. *Transportation Research Part F: Traffic Psychology and Behaviour, 7*, 59–76.

Salmon, P. M., Carden, T., & Hancock, P. A. (2021). Putting the humanity into inhuman systems: How human factors and ergonomics can be used to manage the risks associated with artificial general intelligence. *Human Factors and Ergonomics in Manufacturing & Service Industries, 31*(2), 223-236.

Salmon, P. M., Lenné, M. G. Walker, G. H., Stanton, N.A. and Filtness, A. (2014). "Exploring Schema-Driven Differences in Situation Awareness between Road Users: An on-Road Study of Driver, Cyclist and Motorcyclist Situation Awareness." *Ergonomics, 57* (2): 191–209. doi:10.1080/00140139.2013.867077

Salmon, P. M., Walker, G. H., Read, G. J., Goode, N. and Stanton, N. A. (2017). "Fitting Methods to Paradigms: Are Ergonomics Methods Fit for Systems Thinking?" *Ergonomics, 60* (2): 194–205. doi:10.1080/00140139.2015. 1103385.

Salmon, P. M., Walker, G. H., and Stanton, N. A. (2016). "Pilot Error versus Sociotechnical Systems Failure: A Distributed Situation Awareness Analysis of Air France 447." *Theoretical Issues in Ergonomics Science, 17* (1): 64–79. doi: 10.1080/1463922X.2015.1106618.

Sandt, L. & Owens, J.M. (2017). *Discussion Guide for Automated and Connected Vehicles, Pedestrians, and Bicyclists*. Pedestrian and Bicycle Information Center. Chapel Hill, NC

Schuelke-Leech, B. A., Jordan, S. R., & Barry, B. (2019). Regulating autonomy: An assessment of policy language for highly automated vehicles. *Review of Policy Research, 36*(4), 547-579.

Shorrock, S. T. (2013). "Human Error': The Handicap of Human Factors." *Hindsight, 18*: 32–37.

Society for Automotive Engineers (2021) *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles: J3016_202104.* SAE International DOI: https://doi.org/10.4271/J3016_202104

Son, C., Sasangohar, F., Neville, T., Peres, S. C., & Moon, J. (2020). Investigating resilience in emergency management: An integrative review of literature. *Applied ergonomics, 87,* 103114.

Sorensen, L. J., Stanton, N. A., & Banks, A. P. (2011). Back to SA school: contrasting three approaches to situation awareness in the cockpit. *Theoretical Issues in Ergonomics Science, 12*(6), 451-471.

Stanton, N., (2004). Systematic Human Error Reduction and Prediction Approach (SHERPA). In: N. Stanton, A. Hedge, K. Brookhuis, E. Salas and H. Hendrick, ed., *Handbook of Human Factors and Ergonomic Methods* 1st ed. Boca Raton: CRC Press, pp.368-378.

Stanton, N. A. (2006) Hierarchical task analysis: developments, applications and extensions. *Applied Ergonomics, 37*, 55-79.

Stanton, N. A., Brown, J. W., Revell, K. M., Kim, J., Richardson, J., Langdon, P., ... & Thompson, S. (2021a). OESDs in an on-road study of semi-automated vehicle to human driver handovers. *Cognition, Technology & Work*, 1-16.

Stanton, N. A., Brown, J., Revell, K. M., Langdon, P., Bradley, M., Politis, I., ... & Mouzakitis, A. (2021b). Validating Operator Event Sequence Diagrams: The case of an automated vehicle to human driver handovers. *Human Factors and Ergonomics in Manufacturing & Service Industries.*1-13. DOI: 10.1002/hfm.20887

Stanton, N.A., Eriksson, A., Banks, V.A. and Hancock, P.A., 2020. Turing in the driver's seat: Can people distinguish between automated and manually driven vehicles?. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *30*(6), pp.418-425.

Stanton, N. A., Salmon, P. M., Rafferty, L. A., Walker, G. H., Baber, C. and Jenkins, D. (2013) Human *Factors Methods: A Practical Guide for Engineering and Design* (second edition). Ashgate: Aldershot.

Stanton, N. A., Salmon, P. M., Walker, G. H., Salas, E. and Hancock, P. A. (2017) State-of-science: Situation awareness in individuals, teams and systems. *Ergonomics, 60* (4), 449-466.

Stanton, N. A., Salmon, P. M., Walker, G. H., & Stanton, M. (2019). Models and methods for collision analysis: a comparison study based on the Uber collision with a pedestrian. *Safety Science*, *120*, 117-128.

Stanton, N. A., & Stevenage, S. V. (1998). Learning to predict human error: issues of acceptability, reliability and validity. *Ergonomics, 41*(11), 1737-1756.

Tabone, W., De Winter, J., Ackermann, C., Bärgman, J., Baumann, M., Deb, S., ... & Stanton, N. A. (2021). Vulnerable road users and the coming wave of automated vehicles: Expert perspectives. *Transportation Research Interdisciplinary Perspectives, 9,* 100293.

Thompson, J., Read, G. J., Wijnands, J. S., & Salmon, P. M. (2020). The perils of perfect performance; considering the effects of introducing autonomous vehicles on rates of car vs cyclist conflict. *Ergonomics, 63*(8), 981-996.

Walker, Guy H., Neville A. Stanton, Paul M. Salmon, and Daniel P. Jenkins. (2008). A review of sociotechnical systems theory: a classic concept for new command and control paradigms. *Theoretical Issues in Ergonomics Science 9*(6) 479-499.

Young, M. S., & Stanton, N. A. (2007). Back to the future: Brake reaction times for manual and automated vehicles. *Ergonomics, 50*(1), 46-58.

Zhang, J., Vinkhuyzen, E., Cefkin, M. (2016) Evaluation of an Autonomous Vehicle External Communication System Concept: A Survey Study. In *Proceedings of the Advances in*

*Human Factors, Business Management, Training and Educatio*n, Florida, FL, USA, July; pp. 650–661.