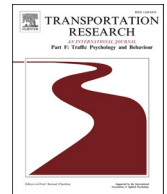




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“That’s a bit of a tight squeeze!”: A thematic analysis of narrow passage driving interactions using the Perceptual Cycle model

Peter Youssef^{*}, Ben Waterson, Katherine L. Plant

Transportation Research Group, University of Southampton, Southampton, United Kingdom

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ABSTRACT

The ability to accurately represent driver behaviours in microscopic traffic models and for autonomous vehicles to discern human driving behaviours is reliant on having a deep understanding of the behaviour that is being modelled. In spite of this, the decision-making processes undertaken during narrow passage interactions, a high risk and relatively unregulated situation in which a road narrowing means that two opposing vehicles cannot pass through at the same time, remain under investigated. To rectify this limitation, an on-road “think aloud” study was conducted with participants in the UK and supplemented by a video-cued retrospective interview using a shortened version of the Schema World Action Research Method. 175 decision points were then analysed using Neisser’s Perceptual Cycle Model, which highlights the relationships between the information perceived from the narrow passage environment, a driver’s schema, and the actions taken. It was found that drivers conduct four key assessments, including evaluating their interaction partner’s intention and the suitability of give way gaps on both sides of the road, when deciding what actions to take during a narrow passage interaction. These results provide a clearer understanding of how driver behaviour is influenced by different contextual/situational factors in a safety critical driving situation and helps ensure that future mathematical models better reflect driver decision-making during narrow passage interactions. This, in turn, can be used to ensure that autonomous vehicles are able to safely interact with human drivers at narrow passages and that microscopic traffic models are able to produce more accurate outputs.

1. Introduction

Autonomous vehicles (AVs) and microscopic traffic models are amongst the most important innovations in road transportation (Lindorfer et al., 2018; Shabanpour et al., 2018). The potential of AVs to help achieve government goals related to traffic safety, emissions and mobility has led to over \$100bn being invested in the technology in the last decade (Shetty et al., 2021), whilst microscopic traffic models have been used to aid transport analysts with operational and planning challenges (Zhong et al., 2016).

Despite the benefits of these technologies, they still face challenges. One of the biggest challenges facing these technologies is the modelling of road interactions, situations in which at least two road users intend to occupy the same space at the same time, thereby creating a space-sharing conflict (Markkula et al., 2020). To accurately model road interactions, it is vital to have a deep understanding of the human processes that are being represented. Without this insight, AVs may struggle to gain the trust of their human users (Beggiato & Krems, 2013; Flemisch et al., 2008; Sun et al., 2020) and may have an understanding of road situations that is

^{*} Corresponding author at: Transportation Research Group, University of Southampton, SO17 1BJ, United Kingdom.

E-mail address: psy1g16@soton.ac.uk (P. Youssef).

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incompatible with that of their human interaction partner(s), which may result in collisions (Salmon et al., 2013). In the context of microscopic traffic models, the incomplete comprehension of a behavioural phenomenon may result in the over and/or underestimation of outputs used by transport practitioners (Liu, 2011; Troutbeck & Kako, 1999). Despite the importance of having clear cognizance of the behaviour that is being modelled, the factors that affect these interactions have often been neglected by modellers (Saifuzzaman & Zheng, 2014; Sharma et al., 2018).

1.1. Cooperative road interactions

This need to understand the factors that affect driving behaviours is particularly relevant in the context of cooperative road interactions, and as such increased attention has been given to these interactions from those seeking to develop AVs (Stoll et al., 2020) and microscopic traffic models (Aakre & Aakre, 2017). Cooperative road interactions are situations in which two or more vehicles are engaged in a space-sharing conflict (Markkula et al., 2020) and are required to work together to “manage the interference to facilitate the individual activities and/or the common task” (Hoc, 2001, p. 515). To achieve this, drivers utilise both formal traffic regulations and informal traffic rules (widely understood rules derived from social convention (Cialdini & Trost, 1998)) to ensure that they have the compatible understanding required to avoid a collision (Salmon et al., 2014).

It is theorised that there are two types of cooperative road situations: time-pressured dynamic situations and deadlock situations (Stoll et al., 2019). During time-pressured dynamic interactions, one interaction partner has priority over the other, and has limited time to give away their priority to their requesting interaction partner, e.g., a lane change (Stoll et al., 2020). Deadlock interactions, on the other hand, are lower-speed interactions in which drivers do not have priority and can not pass each other (Stoll et al., 2019). One example of a deadlock interaction are narrow passage interactions.

1.2. Narrow passage interactions

Narrow passage interactions occur when two (or more) vehicles travelling in opposite directions meet at a road narrowing, see Fig. 1. Often caused by parked vehicles or designed traffic calming measures, the narrowing is only wide enough to allow one vehicle to pass at a time, and, therefore, requires drivers to coordinate who passes through first. During the interaction, neither interaction partner has priority over or can pass the other. Due to the potential high risk of collisions (Gibbard et al., 2004; Bundesamt, 2023) and relatively unregulated nature (Miller et al., 2021; Rettenmaier et al., 2021), an increasing body of research has looked to understand the behaviours of drivers during the interaction.

One informal rule argued to govern narrow passage interactions is the “first-come, first-served” rule. In their observational study, Rettenmaier, Requena Witzig and Bengler (2020) noted that drivers that arrived first at a narrow passage generally left the narrow passage first, often choosing to maintain or increase their speed. This was found to complement the actions of vehicles arriving second at the road narrowing as they often chose to give way, typically by decelerating, thus suggesting an informal understanding of the situation. The speed manipulations observed in the study also further supported the findings of previous studies regarding the meanings of these actions/communications (Imbsweiler et al., 2017; Imbsweiler et al., 2018; Şahin Ippoliti et al., 2023; Strelau et al., 2024). Whilst the informal “first-come, first-served” rule has been supported by some studies (Miller et al., 2022), other studies have argued against such a rule (Quante et al., 2023) and have instead found that drivers passing through the narrowing second typically communicated their intent first (Schuler et al., 2022).

Rettenmaier, Requena Witzig and Bengler (2020) also found that drivers mostly communicated implicitly using their vehicle’s dynamics or trajectory, in line with other studies (Imbsweiler et al., 2016; Schuler et al., 2022). This was found despite suggestions as to the importance of explicit communications, communications that do not alter a vehicle’s dynamics or trajectory (e.g. flashing of headlights, hand gestures) (Bengler et al., 2020; Markkula et al., 2020; Miller et al., 2022), in ensuring successful narrow passage interactions (Imbsweiler et al., 2017; Imbsweiler et al., 2018; Imbsweiler et al., 2018; Strelau et al., 2024) and the preference of drivers for their use (Miller et al., 2023; Rettenmaier, Albers, et al., 2020).

In a series of driving simulator studies, Rettenmaier, Albers, and Bengler (2020), Rettenmaier, Dinkel, and Bengler (2021) & Rettenmaier and Bengler (2021) highlighted the importance of the lateral positioning of an interaction partner when deciphering their intention during a narrow passage interaction. The authors found that ‘pulling in’ was perceived as indicating an intention to give way at the narrow passage, with the opposite true when drivers remained central on the road. Indeed, it was found that safer and more efficient narrow passage interactions occurred when lateral offsets were used in conjunction with longitudinal movements of vehicles (Rettenmaier et al., 2021; Rettenmaier & Bengler, 2021), such that it has been argued that lateral manipulations are a vital communicative method (Li et al., 2024), given the increased saliency of a greater visual angle change of a vehicle. In agreement with

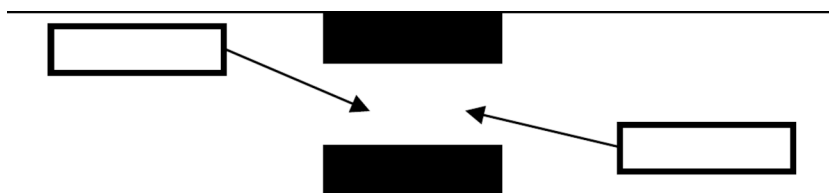


Fig. 1. Schematic of a narrow passage interaction.

the conclusions of Rettenmaier and others, [Miller, Leitner, Kraus & Baumann \(2022\)](#) also argued that the finding was partly because lateral offsets are part of the manoeuvre being carried out. On the other hand, when no lateral offsets are used drivers can only monitor the longitudinal movements of their interaction partner to predict their intention, which requires evaluating changes in the Time-to-Collision of the opposing vehicle (TTC_{OV}) ([Miller, Leitner, Kraus, & Baumann, 2022](#); [Miller, Leitner, Kraus, Lee, et al., 2022](#)), something that drivers struggle to do ([Kiefer et al., 2006](#)).

Reviewing recordings of learner drivers in Germany during narrow passage interactions, [Deppermann \(2019\)](#) argued that the resolution of these interactions is dependent on the positioning of the obstacles and the passing spaces, the speeds and locations of the vehicles, as well as the width of the road and the interaction partner vehicles. Together, Deppermann suggested that these pieces of information allow drivers to evaluate who should give way and how they should do so.

Using an exploratory survey study, [Youssef, Plant, and Waterson \(2024\)](#) extended the range of factors investigated in a narrow passage context. Notably, the study found that the vehicle type being interacted with and the presence of vehicles beyond the main interaction partners influenced the likelihood of giving way. The findings were hypothesised to be due to different mental models being activated when interacting with different vehicle types and different perceived costs of cooperation when interacting with different numbers of vehicles. The authors also identified the meanings of different explicit and implicit communications during narrow passage interactions in a UK context.

1.3. Limitations of previous work

Whilst the narrow passage literature addresses how drivers communicate with one another during interactions, the chronological relationship between what drivers perceive from the road environment, their understanding of this information and the decisions they subsequently make has not been investigated ([Miller et al., 2021](#)). In the context of developing models for AVs and microscopic traffic simulators this insight is crucial as it allows for an understanding of the decision-making processes that need to be replicated and the factors that influence these processes. Whilst [Deppermann \(2019\)](#) best addresses this limitation, the driving lesson origin of the recordings is potentially problematic as it is unclear as to whether the verbalisations analysed reflect an idealised process for learner drivers to navigate narrow passages or the decision-making processes undertaken by a typical driver. Further to this, there has been limited investigation of the factors affecting driver decision-making during narrow passage interactions, especially in on-road settings ([Youssef et al., 2024](#)). This is problematic given that the nature of a system is dependent on the interactions between its components

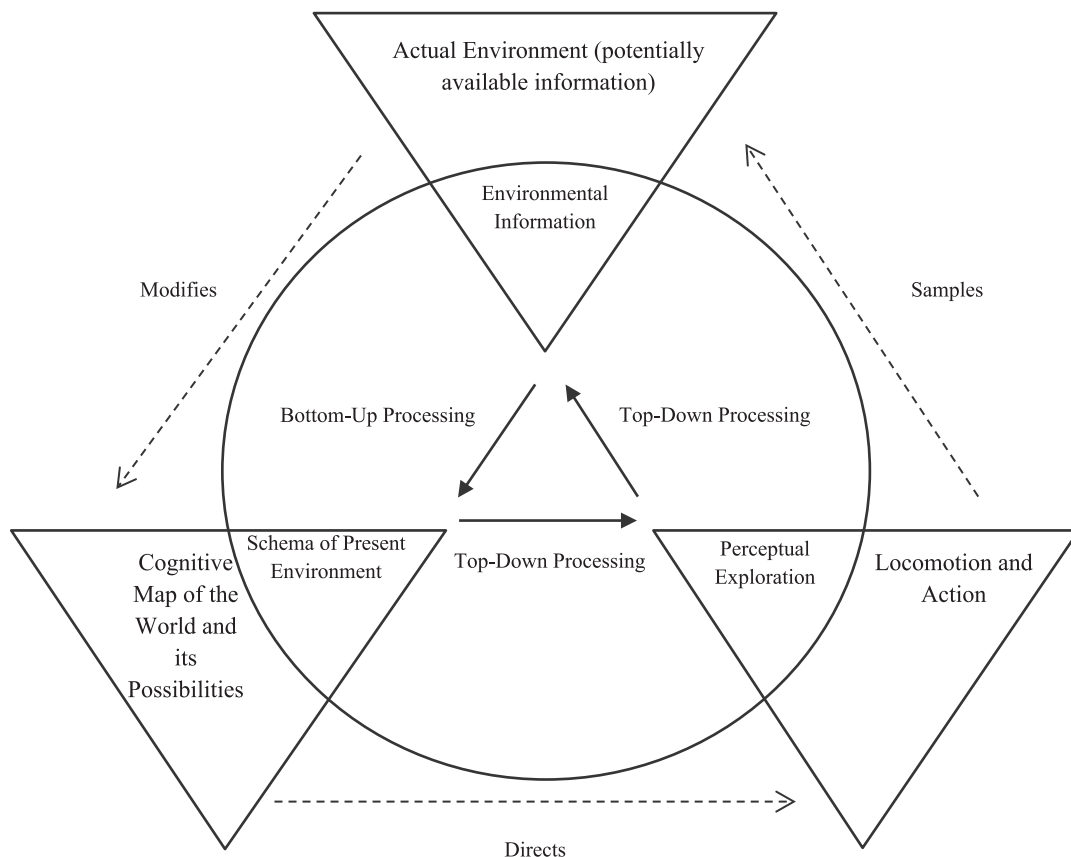
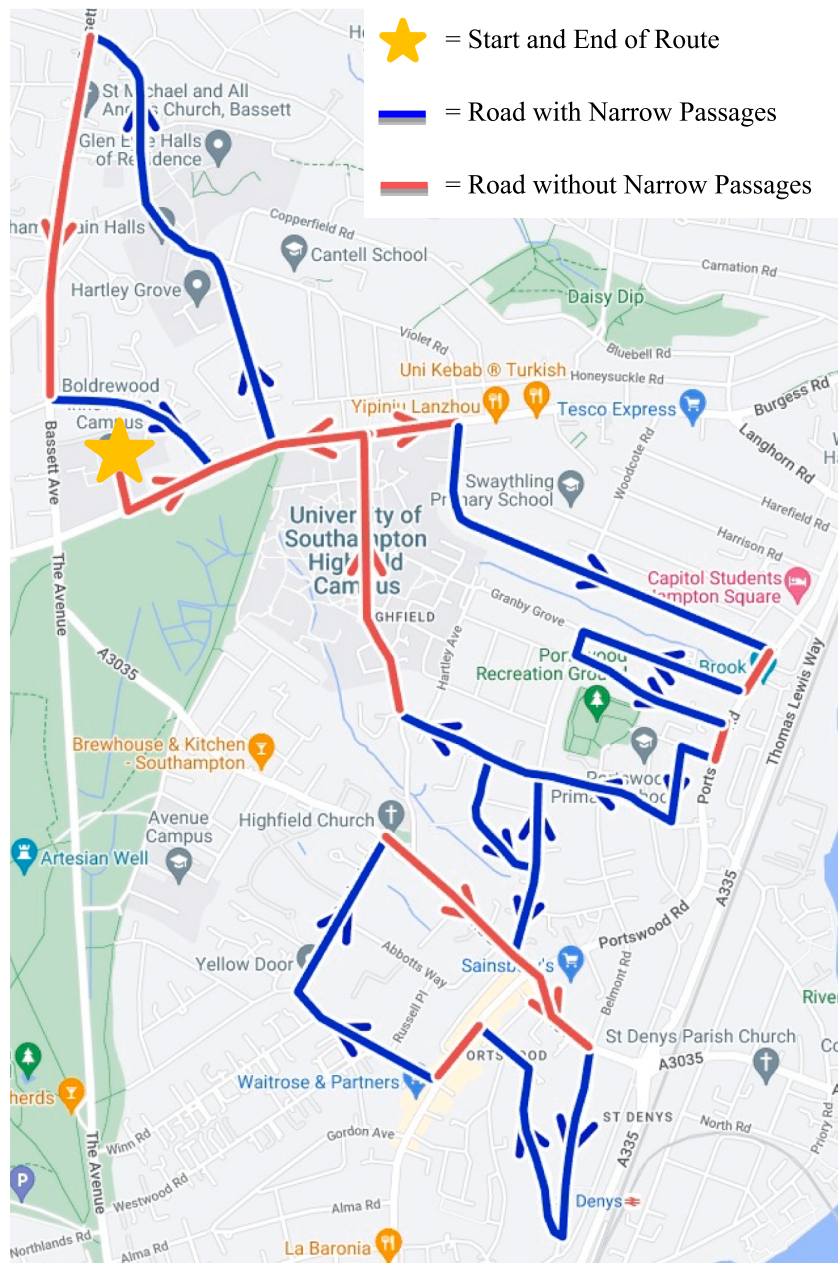


Fig. 2. The Perceptual Cycle Model as proposed by [Neisser \(1976\)](#).

As such, this paper describes a study that investigates the decision-making processes of drivers during on-road narrow passage interactions, in an analysis and data collection process underpinned by the Perceptual Cycle Model (PCM) (Neisser, 1976), which has been used in range of different domains (e.g., aviation (Parnell et al., 2021; Plant & Stanton, 2017), maritime (Lynch et al., 2023) and road (Banks et al., 2018; Liu et al., 2023)).

Neisser's (1976) PCM, see Fig. 2, represents the cyclical and reciprocal relationship between the world environment, schema and actions taken, through a series of top-down (TD) and bottom-up (BU) processes (Plant & Stanton, 2016a). Initially, a person's schema



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(i.e., the mental patterns of thoughts and/or behaviours that help organise a person's knowledge and understanding of the world) is triggered by their world environment (i.e., externally available information). Through TD processing, the activated schema directs where the person looks for further information, as well as any other actions they take, thereby altering the information available to the perceiver in the environment. The new information perceived may, in turn, modify and update the person's schema, thus altering how the schema will direct future activities in a BU process, and thereby completing the feedback loop of the PCM.

Since perceived environmental stimuli do not hold a universal pre-determined meaning, it is vital to investigate the understanding of the situation held by the agents of interest (Dekker, 2014). Given that the PCM does not solely focus on the action outputs of a situation, but rather places an emphasis on the entirety of the decision-making process (Plant & Stanton, 2016a), the theoretical model has been employed in range of studies within the road domain. For example, the PCM has been used as both an analytical and data collection method in the investigation of the decision-making of vulnerable road users in low and middle-income countries, in which the casual relationship between what is perceived and the subsequent actions taken has been shown, and from which road design recommendations have been put forward (Debnath et al., 2021; Liu et al., 2023). Revell et al. (2020) employed the PCM to analyse the interaction between drivers and the in-vehicle systems of semi-autonomous vehicles and subsequently proposed seven considerations for safe autonomous vehicle design, whilst Das et al. (2024) used the PCM to analyse the causes of e-scooter collisions to make policy recommendations. Similarly, within road safety research the PCM has been used as an analytical framework to understand incidents at rail crossings (Salmon et al., 2013), as well as the circumstances of the fatal Tesla crash in 2016 (Banks et al., 2018). In both cases, the employment of the PCM allowed researchers to conclude that the cause of the studied collisions extended beyond “driver error”.

The increased use and the demonstrated ability of the PCM to offer contextual-based insights into operative decision-making has also led to the creation of the Schema World Action Research Method (SWARM) (Plant & Stanton, 2016a). The development of the SWARM sought to address the potential limitation of using methodologies developed for alternative theories in PCM analysis, by constructing a formalised data collection method specifically designed to elicit perceptual cycle information, as well as the interaction between the information perceived and the schema held by an agent, in both critical and non-critical scenarios (Plant & Stanton, 2016a). The resulting 95 prompts of the SWARM, which can be refined dependent on the analysis required (Plant & Stanton, 2016a), have been applied in a variety of contexts. For example, Parnell et al. (2023) employed the methodology to investigate the trust requirements of Unoccupied Aerial Vehicle (UAV) operators when piloting UAVs, whilst Banks et al. (2021) showed that the SWARM may be valuable in the design of technology when utilised early in product development lifecycles.

As such, the use of the PCM as both a data collection and an analysis framework is deemed suitable to addressing the current limitations in the narrow passage literature, namely the lack of understanding of the casual and chronological relationship between what is perceived by drivers at narrow passages and the subsequent actions they take. Therefore, this paper uses the PCM to gain a deeper understanding regarding the relationships between what is perceived and understood by drivers in narrow passages and how this leads to their chosen actions, as well as how this may pertain to the development of reflective AV and microscopic traffic simulator models.

2. Method

This paper employed an on-road study in which participants drove around a pre-defined route, using their own car. All participants provided concurrent verbal reports throughout the drive, which was audially and visually recorded. These recordings formed the basis of the video-cued retrospective interviews, which were carried out to supplement the concurrent verbal reports to create a richer dataset (Ericsson & Simon, 1993), through the provision of additional inferences that may not have been verbalised whilst thinking-aloud whilst driving (Whyte et al., 2010) by investigating the knowledge of the participants (Bainbridge, 1979).

2.1. Study route

The route chosen for this study, see Fig. 3, started and ended at the University of Southampton's Boldrewood Innovation Campus car park. The route, approximately 7.3 miles (11.7 km) in length, required drivers to navigate urban, residential and university roads (20 and 30 mph speed limits) that were identified as areas likely to have narrow passage interactions occur. This was assessed through the researchers' prior experience of whether the road was likely to be narrowed (either via the road infrastructure or parked vehicles), and whether it was anticipated that the road would have the requisite traffic flow levels to ensure that interactions with other vehicles was probable. The chosen route also considered local bus routes to try and diversify the types of vehicles participants would interact with during the study.

2.2. Participant recruitment and sample characteristics

Following approval from the University of Southampton Ethics Committee (ethics ID: 71864), nine participants were recruited between April and May 2022 via the University's internal communications board and local social media groups. The inclusion criteria for this study required participants to be over the age of 18, have a full UK car driving licence and access to a car that they were insured to drive. The inclusion of a prerequisite of a full UK car driving licence sought to reduce the influence of other driving cultures, which vary by country and may result in differing formal and informal driving rules, on the results of the study.

Of the nine participants recruited in the study, six identified as male and three as female. The average age of the participants was 37.2 years (min = 24, max = 76, SD = 18.0) and almost all the participants (eight) reported that they had held their driving licence for at least 5 years. Seven participants stated that they drove a minimum of twice a week, whilst none reported holding an additional

professional driving licence.

2.3. Materials

A pre-study demographic questionnaire was completed on a tablet computer. The questionnaire recorded the participant's age, gender, the number of years they had held their driving licence, whether they held an additional professional driving licence, the make and model of the vehicle they were driving in the study and how often they drove in a typical week. A GoPro HERO5 camera with an internal microphone was used to record audio and video data throughout the study. To ensure that a view of the road environment was captured during the drives, the camera was mounted to the inside of the front windscreen of the participant's vehicle. This was done after checking with the participant that the camera did not obscure their view. All participants used their own vehicles, whilst a tablet computer was used for the think aloud training and the introduction to the test route. Following the on-road drive, participants watched back segments of their drive on a laptop computer, with the accompanying retrospective interview recorded both audially and visually using the GoPro HERO5 camera and its internal microphone.

2.4. Procedure

After reading the participant information sheet and signing the consent form, participants completed the 5-minute pre-study demographics questionnaire.

Once the participant had completed the questionnaire they were introduced to the study route and given a description of the concurrent think-aloud method, taken and adapted from [Ericsson and Simon \(1993\)](#), and a short two-minute video of “experts” performing the method whilst driving in urban and motorway environments was shown to the participants. Additionally, to help aid the production of constant verbalisations, through the provision of a verbalisation structure, the Perceptual Cycle Model was shown and explained to the participants. After any questions had been answered, participants were invited to practice providing concurrent verbalisations whilst completing simple tasks (e.g., solving simple maths problems) and were subsequently offered feedback. Once both the participant and the researcher felt confident that the participant was able to provide concurrent verbalisations, participants completed a short practice drive within the car park at the University of Southampton, whilst verbalising their thoughts. This was done to confirm to the researcher that the participant was able to provide concurrent verbalisations whilst driving and to help the participant gain familiarity with verbalising their thoughts whilst driving. This training took on average 25 minutes to complete.

Following training, participants completed the 30-minute study drive whilst accompanied by a researcher sat in the passenger seat. The researcher was present to provide directions to the participant when needed and to remind the participant to “keep talking” when long pauses without verbalisations occurred. No other communication was made between the researcher and the participant.

After completing the study route, participants were invited to take a short comfort break whilst the researcher downloaded the recording of their drive. Participants were then shown clips of interest (i.e., where narrow passage interactions occurred, which had been noted by the researcher during the drive) and were asked questions about their decision-making in the scenarios. This retrospective interview followed a semi-structured format and used a shortened version of the Schema World Action Research Method (SWARM) ([Plant & Stanton, 2016a](#)), see [Table 1](#), according to the needs of the study. The SWARM was utilised in this study as it was designed and has been shown to elicit perceptual cycle information used in decision-making ([Banks et al., 2021](#); [Parnell et al., 2023](#)). The use of the SWARM in this study, therefore, ensures that the concurrent and retrospective methods employed in this study are both theoretically underpinned by the Perceptual Cycle Model, thus allowing for consistency in the analysis of driver decision-making during narrow passage interactions across the two datasets. In total, the video-cued retrospective interview segment of the study lasted approximately 30 minutes.

Table 1
Retrospective interview questions, taken and adapted from SWARM ([Plant & Stanton, 2016a](#)).

Question Type	Question
Schema	• Did your trained experiences help you/ have any influence on any expectations you had? • Did you use past experiences to help you in this situation/did it help form any expectations? • Were you ever in doubt as to what to do?
Action	• How did information you were looking for/received influence you? • Did you communicate with anyone (how, who to and what did you communicate?)? • How did you assess, evaluate and interpret the situation? • What were you looking for?
World	• What other options did you have? Why did you not pick them? • What information did you use from the natural environment and what did this tell you/did it influence you? • What information was communicated to you from the other vehicle? What did it mean, did it influence you and is there more information you would have wanted? • How did location influence your decision making? • Was there any information missing? How would this have influenced you?
Basis of Choice	• Do you think you could come up with a structure of considerations, which would enable someone to make the same decision?

2.5. Transcription and coding

To ensure consistency and understanding of the verbalisations, all verbalisations were transcribed verbatim by the same person. This resulted in a dataset of approximately 45,000 words, which was broken down into segments of a sentence or less, with each segment representing an idea or thought. The thematic analysis undertaken was both deductive and inductive in nature. Initially, a

Table 2

Higher level coding scheme with definitions and examples.

SAW Theme	High Level Theme	Definition	Example
Action	Situation Monitoring and Assessment	Any action related to observing and/or interpreting the surrounding environment, whether that be internal (i.e., looking at the speedometer and evaluating their speed) or external (i.e., looking at their environmental surroundings, for example looking for give way gaps and evaluating their suitability).	“Just looking for where the parked vehicles are” or “Looking for a gap to go into, but I can’t see any big enough for me to fit into”.
	Narrow Passage Actions	Statements related to any actions the participant takes in narrow passage environments beyond monitoring and assessment actions. As per the literature, this category includes actions such as the lateral and longitudinal movements of the vehicle, as well as the use of communications such as flashing headlights, hand gestures and eye contact.	“Just accelerating slowly” or “Just give a quick flash of my lights”.
Schema	Narrow Passage Behavioural Schema	Schema related to any expectations formed from actions taken by either interaction partner in narrow passage environments.	“Pulling in means they are yielding”.
	Right of Way Schema	Schema related to expectations of who has right of way at the narrow passage	“Parked cars on my side of the road means they have right of way”.
	Vehicle Type Schema	Statements regarding the schema related to vehicle type. This could be related to the physical vehicle types (e.g., a van or a smaller vehicle) or driving style (i.e., aggressive).	“[A coach is coming down], so they need more space to pull in”.
	Surrounding Vehicle Schema	Schema associated with experiences related to surrounding vehicles (i.e., vehicles beyond the lead interaction partner and the participant).	“[There is a stream of vehicles behind that car] so it’s easier to just let them all go through”.
	Hazards Schema	Schema related to hazards in the narrow passage environment. This includes, pedestrians, car doors, animals, etc. but not references to oncoming vehicles beyond the fact that they may be in the narrow passage environment and may pose a hazard. Additional comments regarding oncoming vehicles may be better placed in right of way or action schema.	“[Watching out for pedestrians] as they sometimes just walk out onto the road” or “There may be someone coming the other way”.
	Road Geometry and Properties Schema	Schema related to the road geometry of the narrow passage. This includes schema related to the road width, gradient and the bendiness of the road as well as the location of give way gaps in the road. May include references to schema related to the bumpiness of the road and road signs.	“[This is quite a steep road], so cars might be accelerating quite quickly coming up it” or “I expect that my interaction partner has gaps on their side”.
	Direct Past Experience Schema	Direct personal experience of similar events or situations in the past. This includes both experiences in training (driving lessons) and non-training environments.	“I have had pedestrians step out in front of me in these situations before”.
	Insufficient Schema	Inadequate or a lack of knowledge, i.e., schema is not developed for the situation.	“I have not been here before, so I don’t know what to expect”.
World	Absent (General)	References to a lack of world information being present. If referencing a lack of oncoming vehicles, surrounding vehicles or gaps (etc.) code to the specific absent code instead.	“I can’t see much”.
	Display Indicators	Information originating from in-vehicle indicators	“My speedometer is saying I am at 30 miles per hour”.
	Natural Environment	References to the natural environment	“It’s raining quite heavily”.
	Lead Interaction Vehicle	Reference to lead oncoming vehicle at narrow passage	“They are pulled in” or “They are central on the road”.
	Participant Location	Statements related to own location	“I am central on the road”.
	Pedestrians or Animals	References to pedestrians or animals that are in the area	“Pedestrian just crossing the road”.
	Road Geometry and Properties	References to any aspect of the geometry of the road (e.g., road curvature, road width or the gradient of the road) or its properties (e.g., road signs, bumpiness)	“The road bends slightly” or “It is quite narrow here”.
	Road Narrowing Obstacle	Information related to the obstacles causing the road narrowing	“Lots of parked vehicles here”.
	Side Roads and Vehicles	Statements relating to side roads in the world environment and vehicles at these side roads	“Vehicle waiting to turn onto the road”.
	Surrounding Vehicles	Reference to vehicles beyond the participant and the lead interaction partner. Does not include vehicles coming from side roads	“There are vehicles behind me” or “There are vehicles following the vehicle coming towards me”.
	Give Way Gaps	Statements referencing gaps that vehicles could move into to give way	“There are gaps on my side of the road”.

deductive thematic analysis was used to code the data against the schema-action-world structure of the Perceptual Cycle Model (following the procedure in [Plant and Stanton, 2013](#)). In addition, sub-themes within these three themes were derived from the previous literature in this initial stage of analysis. The coding scheme was then refined in an iterative inductive analysis process that sought to reveal more detailed themes within the higher-level themes and confirm the sub-themes hypothesised from the literature. Throughout the coding process, the visual recordings collected were used to aid the interpretation of the verbalisations. The higher-level structure of the final coding scheme can be seen in [Table 2](#).

2.6. Reliability assessment

Inter-rater reliability of the coding was also assessed after an individual (external to the research project) with experience of qualitative analysis coded 10 % of the concurrent and retrospective verbalisations after they were trained to use the coding scheme. As per [Plant and Stanton \(2013\)](#), the inter-rater reliability of the higher-level themes was calculated using Cohen's Kappa ([Cohen, 1960](#)). This resulted in a value of $\kappa = 0.84$ and a percentage agreement value of 88.2 %, which indicates a strong level of agreement ([McHugh, 2012](#)).

3. Results and discussion

3.1. Thematic analysis overview

Throughout the nine drives, 175 narrow passage interactions were recorded, see [Table 3](#), with participants verbalising their thoughts at an average rate of 138 words/minute throughout (min = 105.7 words/minute, max = 158.1 words/minute) – a rate within the normal speaking rate range ([Rayner & Clifton, 2009](#)).

A breakdown of the average occurrence of the schema-action-world themes across the participants within the think aloud and retrospective interview datasets is shown in [Fig. 4](#). Across both datasets, 33.52 % was classified as world information, 46.78 % as schema, and 35.31 % as action. As expected ([Plant & Stanton, 2016b](#)), [Fig. 4](#) highlights that during the on-road portion of the study participants were most likely to verbalise information perceived from the world and the actions they were undertaking, whilst during the retrospective interview references to how these actions and information aligned with the schema they held were more commonplace. This is in line with expectations, as retrospective interviews seek to investigate a subject's knowledge ([Bainbridge, 1979](#)), to understand why the participant made the decision that they had done ([Greene & Higgins, 1994](#); [Yamashita, 2003](#)), by gaining inferences that were not previously verbalised when thinking aloud ([Whyte et al., 2010](#)).

Breaking down the Action theme further, two broad categories of verbalisations were produced by the participants: 'Narrow Passage Actions' and 'Situation Assessment and Monitoring', see [Table 4](#) and [Fig. 5](#). The 6 sub-themes within the 'Situation Assessment and Monitoring' category are associated with the participant observing and/or interpreting different aspects of their environment (e.g., a potential interaction partner), whilst the 'Narrow Passage Actions' category contains 12 sub-themes related to manoeuvring and interacting with other agents in the narrow passage environment (e.g., slowing down and flashing headlights).

Since this study aims to improve the understanding of driver decision-making during narrow passage interactions by highlighting what drivers perceive during the interaction and how they evaluate this information, the analysis presented is organised according to the sub-themes within the "Situation Monitoring and Assessment" theme, given their definitions (see [Tables 2 and 4](#)). Although [Table 4](#) and [Fig. 5](#) show that drivers monitored and assessed their vehicle's system (e.g., speedometer) and external hazards beyond the narrow passage and/or interaction partners (e.g., pedestrians and side roads), these sub-themes are excluded from the subsequent analysis. Whilst these two monitoring and assessment actions can be considered to be important to the safe navigation of the narrow passage environment (and indeed the road environment generally), it is argued that they are not critical to the resolution of a narrow passage interaction with another vehicle. As such, both sub-themes are deemed to be beyond the scope of this study.

All quotes presented throughout this section are denoted with the number assigned to the participant who provided them and whether the quote originated from the think aloud (TA) or retrospective interview (RI) dataset.

Table 3
Breakdown of recorded narrow passage interactions per participant.

Participant ID	Number of Interactions Encountered	Proportion of Interaction Dataset
1	21	12 %
2	6	3 %
3	29	17 %
4	16	9 %
5	18	10 %
6	23	13 %
7	18	10 %
8	18	10 %
9	26	15 %

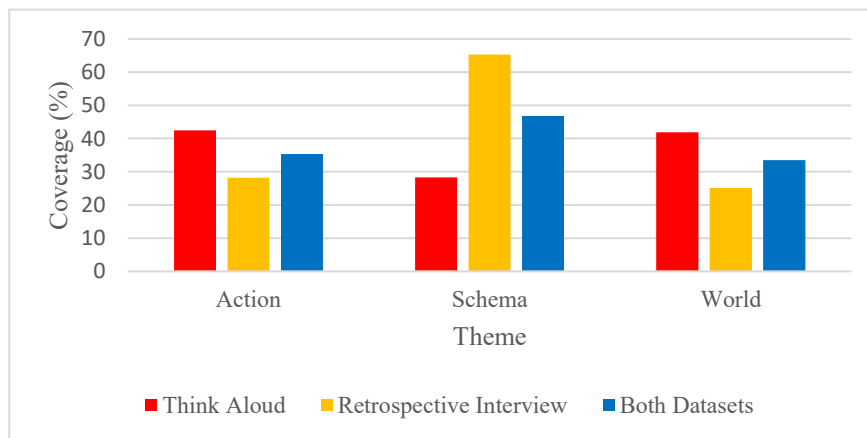


Fig. 4. Average occurrence of the Schema, World and Actions themes across the nine participants.

3.2. Narrow passage monitoring and assessment

Amongst the first assessments verbalised by participants in narrow passage environments related to the evaluation of the physical aspects of the road narrowing. Specifically, the assessment of a road narrowing can be argued to involve two main considerations: the location of the road narrowing obstacles and the width of the narrowing.

3.2.1. Road narrowing obstacle location

The location of the obstacles of the road narrowing was typically associated with evaluating priority. Whilst the assessment of priority is less clear for roads narrowed on both sides (e.g., “Whose right of way is it...because it (parked vehicles) is both sides” Ppt2(RI)), for narrow passages only narrowed on one side (unequal narrow passages) a clear expectation of who has priority is formulated. In instances in which the road is narrowed on the interaction partner’s side, drivers expect their interaction partner to “pull in because the cars are blocking them” Ppt3(RI), with the opposite being true when the vehicles are on their own side. For roads narrowed on both sides, the informal “first-come, first-served” was found to be used by UK drivers to evaluate right-of-way, through evaluations of the positions of the interaction partners in relation to the location of the road narrowing (e.g., “If I thought, because they were quite far away, if I could have made it... I probably would have gone” Ppt2(RI)).

Whilst a universal understanding of priority exists at unequal narrow passages, an element of caution remained during interactions at these locations – “But at the same time, I would not assume that they would (stop). So, I would slow down in an ideal world” Ppt1(TA). This distrust was a recurring theme across the data (e.g., “I kind of expect when the cars are on the other side that people on the other side will stop...obviously not everyone does that” Ppt3(RI)), and is, perhaps, not misplaced. In this study, 32 % of the interactions at unequal narrow passages resulted in the interaction partner whose side was obstructed passing through first. Whilst this finding does not account for interactions in which the “first-come, first-served” rule may override other considerations, it does highlight the complexity of narrow passage interactions and the need for drivers to assess additional pieces of information.

3.2.2. Road narrowing width

One such additional piece of information that is assessed is the road width at and around the road narrowing. Whilst the verbalisation of this assessment often led to participants slowing down, perhaps in anticipation of having to negotiate a narrow passage interaction, (“Fairly narrow sort of road here. Let’s just take it easy through here... I’ll just have a lookout” Ppt9(TA)), this information also formed the basis of evaluations of the utility of the different actions available to a participant at a road narrowing. For example, in their review of a narrow passage interaction, one participant remarked that they had assessed that continuing to give way at their current location was the “safer, easier (thing) to do” as there was “a lot of space around” to allow the opposing vehicles to pass through, as opposed to trying to “squeeze (past)” the vehicles – Ppt6(RI).

Perhaps more interestingly, the assessment of a road narrowing’s width, in tandem to assessing the widths of the interacting vehicles, was verbalised by multiple participants during interactions in which both interaction partners passed through a narrowing at the same time (e.g., “They can’t honestly fit it (their car) through (at the same time)” Ppt4(TA); “There’s a motorcyclist coming up towards me... We can both move through the space” Ppt5(TA)). Indeed, 24 % of the interactions in the study resulted in both interaction partners passing through a road narrowing at the same time, see Fig. 6, with this outcome typically taking place at unequal narrow passages in which the interaction partner whose side of the road wasn’t narrowed cooperated by pulling in slightly (e.g., “Car coming. He’s pulled in a bit. So, I am going to proceed” Ppt9(TA)). This, therefore, not only indicates that drivers actively assess the widths of the vehicles and the narrow passage in their decision-making process, but it also challenges the idea that interactions at narrow passages are dichotomous in their outcomes (i.e., only one interaction partner can pass through a narrow passage at a time), as is typically stated in the literature. Indeed, the finding suggests that an interaction at a narrow passage may sometimes be better classified as a time-pressured dynamic cooperative interaction (Stoll et al., 2019), as opposed to a deadlock cooperative interaction, as the driver with “priority” at

Table 4

Definition and examples of the sub-themes within the Action theme.

High Level Action Theme	Sub-Themes	Definition	Example
Situation Monitoring and Assessment	Narrow Passage Monitoring and Assessment	Statements relating to the monitoring and assessment of the physical aspects of a narrow passage.	“This road is very narrow” or “Just looking for where the parked vehicles are”.
	Lead Interaction Vehicle Monitoring and Assessment	Actions related to observing the lead oncoming interaction vehicle (i.e., the lead opposite stream vehicle if there is a convoy of vehicles moving in the opposite direction) and any information that is produced by that vehicle, as well as the evaluation of this information.	Observing and assessing the vehicle type that is being interacted with (e.g., a lorry) and the actions taken by this vehicle (e.g., speed choice).
	Give Way Gap Monitoring and Assessment	Statements related to looking for gaps that either interaction vehicle can yield into and/or assessing the suitability of these yielding gaps.	“Looking for a gap to go into, but I can’t see any big enough for me to fit into”.
	Surrounding Vehicles Monitoring and Assessment	Statements relating to monitoring and evaluating vehicles beyond the lead interaction partner, parked vehicles, or vehicles coming from side roads.	“Just trying to see if there are any other vehicles coming through”.
	External Hazard Monitoring and Assessment	Statements related to observation and evaluation actions taken regarding hazards that are not directly linked to the narrow passage and the interaction partners. These include (but are not limited to) pedestrians and animals in the narrow passage vicinity, vehicles coming from side roads, car doors opening.	“Looking for any pedestrians that want to step onto the road”
Narrow Passage Actions	System Monitoring and Assessment	Statements relating to observing and evaluating their own vehicle and the associated artefacts to gain an understanding of vehicle status.	“Just looking at my speedometer”.
	Eye Contact Action	Action by the participant related to making or trying to make eye contact with another road user when in a narrow passage environment.	“Just trying to make eye contact with the pedestrian”.
	Fast or Speeding up Action	Action related to driving fast or accelerating in the narrow passage environment.	“Just accelerating slowly”.
	Flashing Headlights Action	Action related to the participant flashing their headlights in a narrow passage environment.	“Just give a quick flash of my lights”.
	Hand Gesture Action	Action related to the participant giving a hand gesture to another road user in a narrow passage environment.	“Just give them a quick wave”.
	Indicating Action	Action related to using own indicators when in a narrow passage environment.	“Just indicating as I pull in”.
	Maintaining Speed Action	Action related to keeping a constant speed when in a narrow passage environment. This does not include being stopped.	“Keeping a constant speed through here”.
	Move Central or Stay Central Action	Actions taken by the participant to either stay central on the road or to move central on the road in a narrow passage environment.	“Just moving to the centre of the road”.
	Pull(ed) In Action	Any action related to the participant moving towards the kerb or staying towards the kerb in the narrow passage environment.	“Just moving in” or “Just staying pulled in”.
	Reverse Action	Action taken by the participant that involves reversing the vehicle in a narrow passage environment.	“Going to reverse back slightly”.
	Slow or Slowing Action	Action relating to slowing down or going slowly in a narrow passage interaction.	“Slowing down slightly”.
	Stopping or Stopped Action	Action related to stopping or staying stopped when in a narrow passage environment.	“Just going to wait here”.
	Thanking Action	Action related to thanking their interaction partner in a narrow passage environment.	“I say thank you”.

the narrow passage may have a limited time opportunity to cooperate and facilitate the desired action of their interaction partner (to pass through the narrowing as soon as possible) dependent on their assessment of the width of the road narrowing.

3.3. Lead interaction vehicle monitoring and assessment

3.3.1. Implicit and explicit communications

The assessment most frequently verbalised by participants (8.44 % coverage) was the monitoring and evaluation of the lead interaction partner and their intention. This monitoring action, often triggered by the perception of the narrow passage and the potential for an interaction (“[After seeing parked vehicles] I should look for the car that is coming” Ppt1(RI)), typically involved interpreting

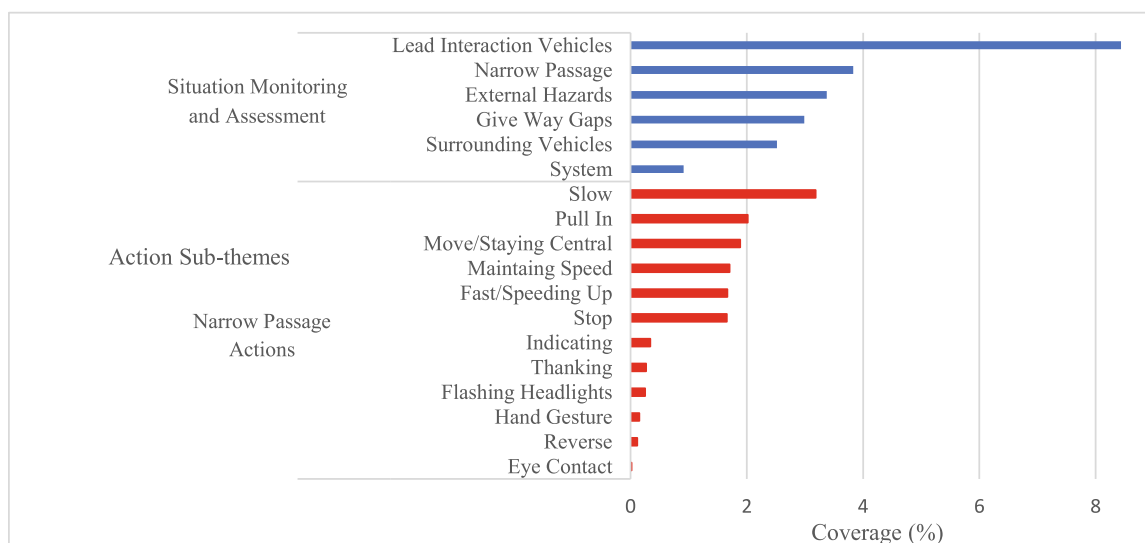


Fig. 5. Average occurrence of Action sub-themes across the nine participants for both the think aloud and retrospective interview datasets.

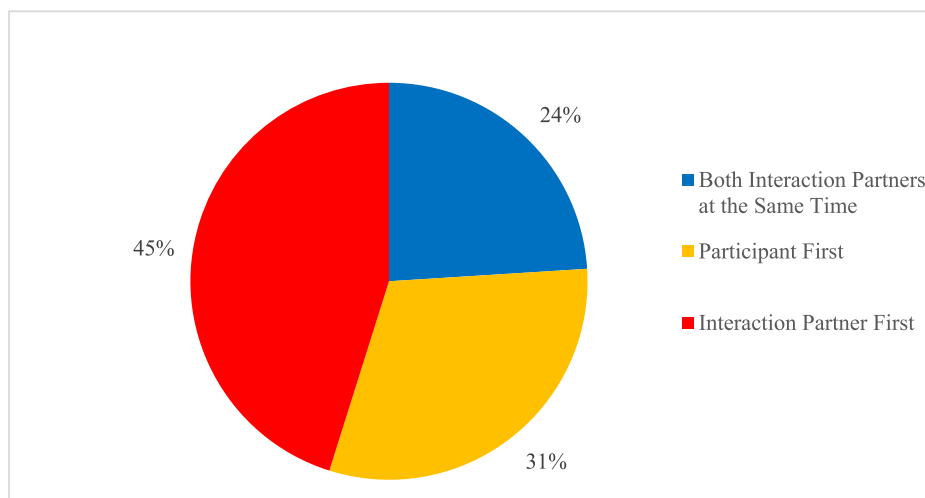


Fig. 6. Breakdown of the outcomes of the 175 recorded narrow passage interactions.

the longitudinal and lateral movements (implicit communications) of their interaction partner (e.g., “If they are fast, rash, or if they are staying to the left of the road, staying to the centre of the road” Ppt1(RI)), as well as any explicit communications produced (e.g., “If he gives (flashes) me a head beam...I will just drive straight away” Ppt8(RI)), to decipher the intent of an interaction partner as stated in the literature (Rettenmaier & Bengler, 2021).

Interestingly however, the assessment of explicit communications was seldom verbalised in the retrospective interview and think aloud datasets. This is perhaps a reflection of the infrequent use of explicit communications during narrow passage interactions, which is in line with the findings of previous studies (Rettenmaier, Requena Witzig, et al., 2020) and what was observed throughout this study, with explicit communications in this study commonly coming in the form of flashed headlights (used in 4.5 % of all interactions) or hand gestures (used in 3 % of all interactions). Perhaps more noteworthy was the finding that significant proportions of hand gestures (85 %) and flashed headlights (47 %) were used during interactions in which the producer of the explicit communication passed through the narrowing first, contrary to suggestions from the literature regarding the association of explicit signals and giving way (Imbsweiler et al., 2018) and indeed verbal reports from this study (e.g., “Ok they flashed their lights, so I am just going to pull forward” Ppt3(TA)). An explanation for this may lie in the timing of the explicit communications, as all hand gestures and flashed headlights produced prior to the resolution of an interaction resulted in the interaction partner that produced the explicit communication giving way, in line with previous findings. Conversely, hand gestures and flashed headlights produced after the resolution of an interaction (i.e., as an interaction partner was leaving the narrow passage) were mostly used by drivers passing through the narrowing first (83 %) as a thanking action, with the use of these explicit communications by drivers that gave way done in reciprocation

(e.g., “(If) I am waiting for a car to go by and they give a gesture, then I give a gesture because they are thanking me” Ppt6(RI)). This, therefore, demonstrates the temporal element that is considered by drivers in their assessments of interaction partners at narrow passages and the need to incorporate this in subsequent analyses of these interactions.

Focusing on the lack of explicit communications produced prior to the resolution of interactions, one explanation may be that further information was not required by the interaction partners to have the compatible understanding of the situation needed to safely navigate the narrow passage. This compatible understanding of the ongoing narrow passage interaction may be due to the clear intentions that are communicated by the implicit movements of the interaction partners (e.g., “Sometimes I will flash my lights to let them know that I am waiting. I don’t think that I did on this occasion because it felt to me quite obvious what the situation was” Ppt5(RI)). For example, having concluded that they should give way, participant six decided to communicate this intention by remaining stationary, as “the longer I stay the more indication of you should go” Ppt6(RI). This, supports the idea that the compatible understanding of a situation between interaction partners at narrow passages can be aided by a more consistent, “stronger” message of intention (Fuest et al., 2018; Kauffmann et al., 2018). Given that the use of explicit communications was often done to provide certainty in ambiguous interactions (e.g., “I just thought I’d wait and see if he wanted to go but he made the signal (a hand gesture) first so I went” Ppt7(RI)), this rationale may also explain why the use of explicit communications was hypothesised to be advantageous in the successful resolution narrow passage interactions (Imbsweiler et al., 2017), in that explicit communications may be used to help reinforce the intention communicated to an interaction partner during the interaction.

3.3.2. Vehicle type schema

Beyond the implicit and explicit communications produced by interaction partners, drivers also verbalised assessments related to the vehicle type they were interacting with, supporting previous findings (Youssef et al., 2024). As noted previously, this included evaluating the dimensions of an opposing vehicle in relation to the physical properties of the narrow passage but also reflected the schema drivers held of different vehicle types when developing an initial expectation of their interaction partner and their intention (e.g., “You don’t necessarily have to give them (big SUVs/BMWs) way, they just take it all the time!” Ppt7(RI)). Indeed, the expectations formed from a person’s schema of a vehicle type was noted on several occasions to be a major factor in a participant’s decision to give way or not (e.g., “Ahh, coach coming down! Just got to let that one through whatever” Ppt9(TA)), with factors such as safety (e.g., “they would crush me...I would come off worse than they would because of size” Ppt4(RI)) and practicality (e.g., “if the other car is a lot bigger if they want to go for you (give way) it might be still quite difficult for you to get past” Ppt3(RI)) verbalised in these assessments.

3.4. Give way gap assessment

Alongside the monitoring and assessment of interaction partners and narrow passages, the surveillance and evaluation of gaps to give way in was another key input in the decision-making of drivers (e.g., “Cor blimey, cars on either side here, where’s the gaps?!” Ppt9(RI)). This process required drivers to assess the suitability of gaps based on two key criteria. First, is the gap large enough for their vehicle to fit into (e.g., “I know I can fit after the white car” Ppt6(TA)) and second whether it is possible to give way in that gap given the speeds and locations of the interacting vehicles (e.g., “In my head I judge how fast they are moving and whether I can get to the next gap” Ppt2(RI)). Indeed, the risk of not finding another suitable gap resulted in participants giving way in the first available and suitable gap in the majority (57 %) of the interactions that took place (e.g., “the first place that I could find where my car fits, that’s when I stopped” Ppt1(RI)), such was the disbenefit associated with having to reverse back if further suitable gaps were absent (e.g., “I try and avoid reversing back. I’d rather stop at the earlier (gap) and let the other person come past” Ppt3(RI)).

Whilst the majority (68 %) of verbalisations made by the participants regarding give way gap assessments concerned monitoring gaps that they could potentially give way in, a significant proportion (36 %) related to monitoring gaps for their interaction partner (e.



Fig. 7. Screenshot of case study one showing the centrally positioned bus and the potential give way gaps available to the vehicle.

g., “I can’t see that it can get in on that side” Ppt9(TA)), with similar considerations of vehicle size in relation to the size of potential give way gaps being made (e.g., “There is a big van up ahead, and not very much space to pull in” Ppt5(TA)). By considering the suitability of gaps that both interaction partners may have access to, drivers are able to assess the viability of the different outcomes of a narrow passage interaction. For example, given the participant’s schema regarding the vehicle type they were interacting with and the speed they maintained during the interaction, the participant was “certain that I needed to stop” as the “bus can’t pull between that gap...it just wouldn’t work” Ppt1(RI), perhaps in reference to the manoeuvrability and/or length of the bus in relation to the possible give way gap, see Fig. 7. This reflects a wider trend in the study that saw 91 % of all vehicles that did not have a suitable give way gap pass through the narrow passage first. This not only make intuitive sense, but also suggests that Deppermann’s (2019) hypothesis that drivers assess the spaces that they can give way in should be expanded to include the assessment of spaces that their interaction partner can give way in.

3.5. Surrounding vehicle assessment

The monitoring and assessment of surrounding vehicles (i.e., interacting vehicles beyond the lead interaction partners) was made throughout the nine drives (e.g., “There are a couple more (cars) up ahead” Ppt3(TA)), with the assessment of the actions available to the surrounding vehicles often a key factor in a driver’s decision-making process. For example, during an interaction, see Fig. 8, whilst the lead interaction partner had indicated it was giving way, the participant evaluated whether the vehicles behind the lead vehicle were “able to move a bit for you (me) to go past” Ppt6(RI). Once they had assessed that the surrounding vehicles couldn’t do anything to facilitate the participant passing through the narrowing first, the participant then had the requisite information to make a definitive evaluation to give way, despite their lead interaction partner giving way initially.

The presence of these surrounding vehicle was also associated with schema that reflected upon the difficulty of interacting with a stream of opposing vehicles (e.g., “It just would have been more of a messy situation, because there’s more cars tail backed” Ppt7(RI)). This is perhaps reflected by the finding that in situations in which a participant gave way to the lead opposing vehicle, references were commonly made as to how they would continue to give way to the rest of the opposing vehicles (e.g., “I am stopped and waiting anyway... it’s just like a rolling blockade, they have the right to go through” Ppt4(RI)), as “it is easier” to do when compared to pulling in and out multiple times (e.g., “I can’t be bothered pulling in and out” Ppt9(RI)). Complementary to this, participants also noted that when following a vehicle into a narrow passage, the vehicle in front is used as a “judgment” throughout the narrowing (Ppt2(RI)) and could be used to evaluate the actions that they should proceed with (e.g., “There are cars ahead of me, they’re moving, so that suggests to me that the route ahead is pretty clear (maintains speed)” Ppt5(TA)). Indeed, in circumstances in which an opposing vehicle had given way to the vehicle in front, participants reflected that “most people don’t really expect you to then pull over” Ppt3(RI). Together, these findings suggest that the expectation held by drivers that a vehicle will continue to give way to the vehicles behind the lead vehicle is indicative of the presence of an informal “convoy” rule at narrow passages.

3.6. Narrow passage case studies

Whilst the analysis above showcases the different aspects of the narrow passage environment that are perceived and evaluated by drivers, it is important to emphasise that the decision-making of drivers requires these monitoring and assessing actions to occur in tandem, as part of a perpetual and cyclical process. In addition, like any interaction between two agents, the subsequent actions produced by one agent following an assessment of the situation, acts as the world information stimulus for the other agent to then assess and act upon. This may be exemplified through two case studies.

Case study 1: A Simple Case of Right of Way?

The first case study presents the amalgamated PCM (see Fig. 9) of interactions that occur at narrow passages narrowed on the interaction partner’s side, in which the interaction partner passes through the narrowing before or at the same time as the ego vehicle



Fig. 8. Screenshot of case study 2 showing the lead interaction partner pulling in prior to the road narrowing, as well as the vehicles following the lead interaction partner.

(e.g., Fig. 7). As shown in Fig. 9, the positioning of the road narrowing obstacles leads to the initial evaluation that the ego driver has priority during the interaction and should therefore pass through first. However, given the contextualised nature of driver decision-making, the safe navigation of narrow passages requires further monitoring of the narrow passage environment and an assessment of the potential outcomes of the interaction. In this case, the ego driver also evaluates that their interaction partner does not have a suitable gap to give way in, after monitoring and assessing potential give way gaps on the other side of the road and their interaction partner (e.g., “There is a big van up ahead, and not very much space to pull in” Ppt5(TA))). This, therefore, provides the stimulus required to evaluate other potential resolutions to the interaction. In these scenarios, this requires further assessing the widths of the interacting vehicles in relation to the assessment of the width of the road narrowing, in order to decipher the available manoeuvres to safely resolve the interaction; pulling in to facilitate both vehicles passing through at the same time or stopping to allow their interaction partner to pass through first.

Case study 2: Interacting with Multiple Vehicles:

The PCM in Fig. 10 summarises interactions with multiple opposing stream vehicles at narrow passages with no distinct right of way, in which both lead interaction partners initially give way, see Fig. 8. Whilst the lack of right of way at the road narrowing and the assessed intent of the interaction partner to give way may suggest that the ego vehicle should proceed through the narrowing first, the presence of the vehicles behind the lead interaction partner necessitates the evaluation of the potential actions of these surrounding vehicles. This process involves the monitoring and assessment of the surrounding vehicles in combination with potential give way gaps for these vehicles and the road width. In the case highlighted in Fig. 10, the lack of spaces for these surrounding vehicles to give way in/pass through at the same time, results in the ego vehicle giving way to the lead interaction partner and the following vehicles, in accordance with the schema held ‘convoy’ rule.

3.7. Implications for narrow passage models

As stated previously, to ensure the accurate representation of driver behaviours at narrow passages in microscopic traffic and

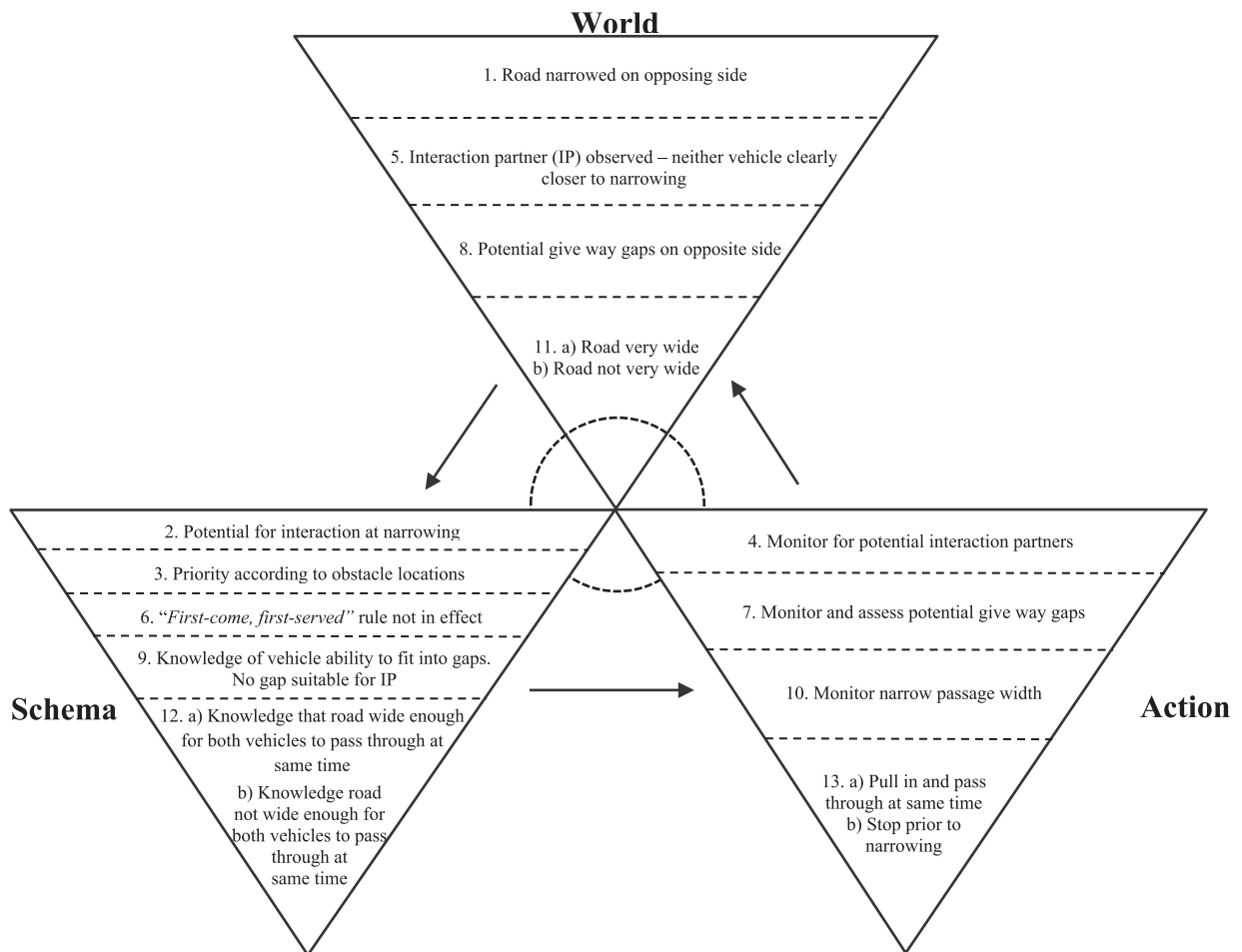


Fig. 9. Amalgamated PCM of interacting with a vehicle at a narrow passage narrowed on the opposing side of the road (Figure should be read following numeric sequence of text exerts).

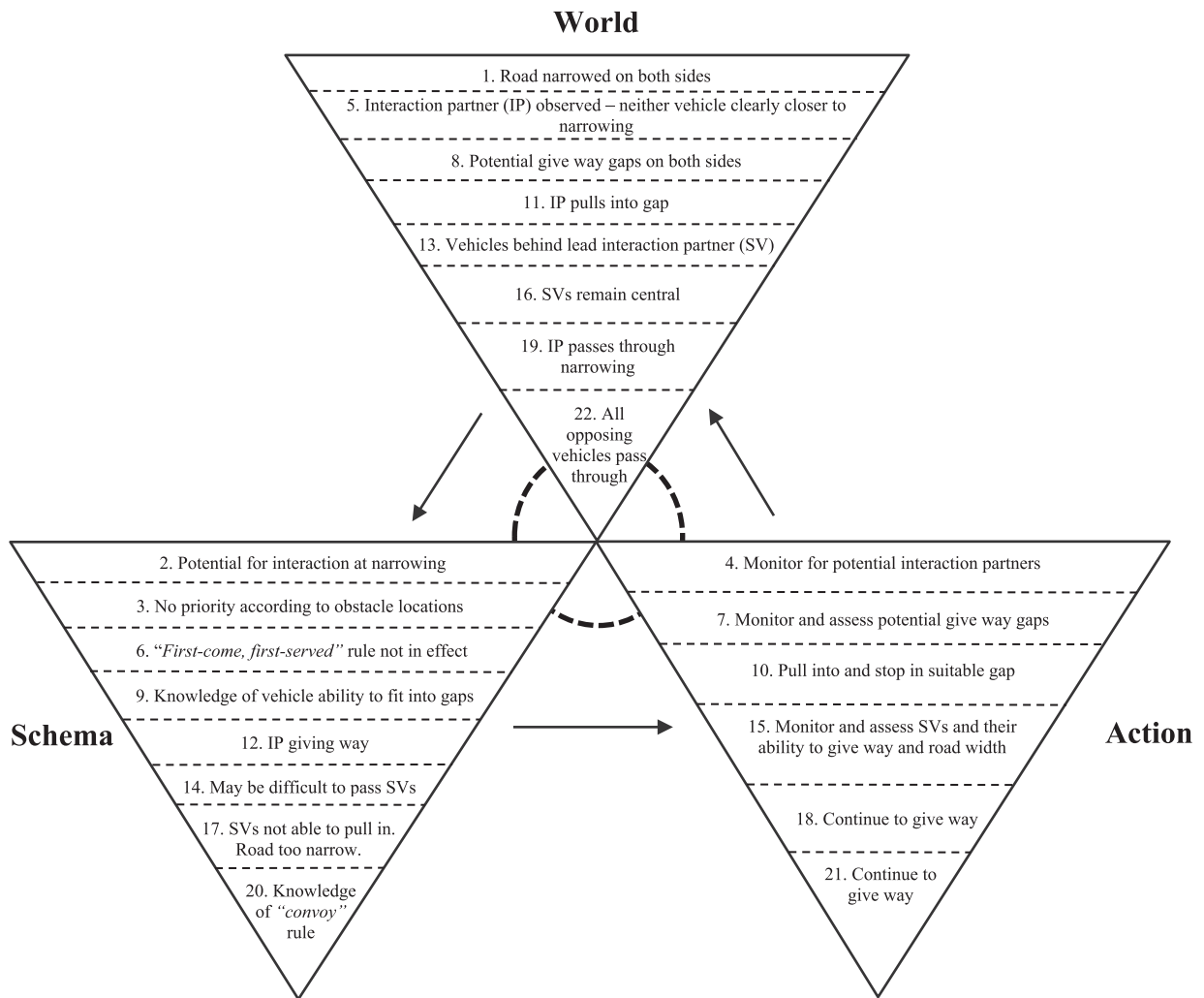


Fig. 10. Amalgamated PCM of interacting with multiple vehicles at a road narrowed on both sides (Figure should be read following numeric sequence of text exerts).

autonomous vehicles (AVs) models, it is vital to have a deep understanding of the decision-making processes that are undertaken by drivers. To this end, the analysis thus far has sought to highlight the different aspects of the narrow passage environment that are monitored by drivers during their navigation of the environment, as well as how this information is assessed and impacts decisions made. However, as exemplified by the case studies, it is argued that the highlighted assessments and monitoring actions are synthesised to answer five key questions for narrow passage decision-making that must be incorporated in future narrow passage models:

- **Who has priority?** This is evaluated via the position of the road obstacles and/or through the application of the informal “first-come, first-served” rule [Narrow Passage and Lead Interaction Vehicle Monitoring and Assessment – Case Studies 1 and 2].
- **What is the intention of my interaction partner?** As stated in the literature (Rettenmaier & Bengler, 2021), implicit and explicit communications produced by the interaction partner are interpreted by a driver’s schema. An initial expectation of an interaction partner’s intention may also be formed by schema related to the vehicle type being interacted with [Lead Interaction Vehicle Monitoring and Assessment – Case Study 2].
- **Where can I or my interaction partner give way?** An evaluation of the length of a potential give way gap in relation to the length of the vehicle that would use that space is made in this assessment. In addition, drivers also assess whether it is possible for a vehicle to manoeuvre into the space given the relative position of the vehicle to the gap, and the speed of the vehicle. Schema related to the vehicle type being interacted with may also influence this assessment [Give Way Gap and Lead Interaction Vehicle Monitoring and Assessment – Case Studies 1 and 2].
- **Does the width of the narrow passage in relation to the vehicle widths prohibit any potential resolution to the interaction?** This requires an assessment of the road width in relation to the widths of the interaction partners. Dependent on the outcome of this assessment, this may lead drivers to evaluate that it is feasible for both interaction partners to pass through a road narrowing at the

same time, given that both vehicles choose to cooperate [Narrow Passage and Lead Interaction Vehicle Monitoring and Assessment – Case Studies 1 and 2].

- **If surrounding vehicles are present, what are the actions available to these vehicles/is the informal ‘convoy’ rule in effect?** In addition to evaluating the potential actions of these vehicles, drivers expect that a driver will continue to give way to vehicles behind the lead interaction partner, as part of the informal ‘convoy’ rule [Surrounding Vehicle Monitoring and Assessment – Case Study 2].

These five questions build upon the framework proposed by [Deppermann \(2019\)](#), as they not only consider the priority at the road narrowing and the intention communicated by the main interaction partners, but also place emphasis on evaluating the actions available to all involved vehicles and how this may impact potential resolutions to the interaction. By perpetually asking and answering these five questions, it is argued that drivers are able to evaluate the three interaction outcomes, as shown in this study, that are available to them at narrow passages: pass through first, give way or seek to pass through at the same time. In the context of developing a narrow passage microscopic traffic model, these questions are valuable as they serve as a theoretical framework from which a potential model can calculate the utility of the different actions available to the simulated agent. Alternatively, the theoretical framework of this study could be used to develop initial rule-based models within microscopic traffic simulators, in the absence of the data required to calibrate and validate more complex models. Similarly, for the development of AVs this research provides a theoretical basis for the development of models that are both theory and data driven.

Beyond these questions, the results from this study also highlight the need for narrow passage models to consider a variety of information, as well as how drivers interpret that information according to their schema. The information considered by drivers not only includes the implicit and explicit communications produced during an interaction or the locations of the road obstacles, but also the number of vehicles and the vehicle types being interacted with. Without considering these factors, a developed model cannot adequately represent the decision-making processes of drivers, which may result in resolutions to narrow passage interactions that are not realistic in microscopic traffic models or that are not compatible with the expectations of human drivers and passengers in an AV context.

3.8. Study limitations

Despite the findings made in the study, there are limitations. First, the study’s relatively small sample size may mean that generalisations of these findings to the wider population are difficult to make, despite the analysis being based on 175 decision points, in which participants verbalised consistent and repeating themes. This suggests, therefore, that data saturation was reached, and that further participant recruitment would likely not have provided any additional insights. Second, given that this study only investigated the decision-making of car drivers at narrow passages, the findings cannot be generalised to drivers of other vehicle types (e.g., HGVs), whilst the study also did not investigate any variances in the decision-making processes of different demographic groups (e.g., experienced vs inexperienced drivers). Third, the study did not collect quantitative data to supplement the qualitative data attained. This meant that sophisticated quantitative insights to support the qualitative findings made in the study could not be made. Fourth, it is important to consider that the participants may have been more cautious in their driving because a researcher was present in the vehicle to give directions/remind them to keep talking ([Carsten et al., 2013](#)). This may mean that the verbalisation data collected is not reflective of the typical decision-making processes of the participants. As such, future studies may seek to eliminate the need for a researcher to be present in the vehicle. Future studies could also look to apply verbal protocol methods to investigate the differences in the decision-making processes of drivers from different countries, given that the findings reported are limited to UK drivers due to the cultural dependence of driving behaviours ([Edensor, 2004](#); [Factor et al., 2007](#)). Scaling up the approach of this study to other countries, to create a larger dataset, is however likely to induce significant time and financial costs ([Carsten et al., 2013](#)). Lastly, this study only collected insights into interactions from the perspective of one interaction partner. In order to form a synthesized and complete understanding of the events during narrow passage interactions, future studies may benefit from gaining the perspective of both interaction partners.

4. Conclusion

This study has sought to investigate the relationship between what is perceived by drivers during narrow passage interactions, their interpretation of this information and the actions they subsequently produce. To this end, the Perceptual Cycle Model was used to analyse both the think aloud and retrospective interview verbalisations produced by drivers throughout narrow passage interactions.

From the analysis, it has been shown that drivers monitor and assess information from four key sources in their decision-making process in narrow passage environments; this includes information related to the physical properties of the narrowing, the lead interaction vehicle, as well as interaction vehicles beyond the main interaction partners, and any potential gaps to give way in. The perpetual evaluation of this information through these assessments is argued to answer five key questions that drivers ask themselves at narrow passages, with the outputs of these questions evaluated by drivers in tandem to produce actions to safely resolve the interaction. Considering the findings of the study in the context of the development of models for autonomous vehicles and microscopic traffic simulators, the paper then made recommendations for how future models should look to represent the behaviours of drivers during narrow passage interactions. This, therefore, provides a set of criteria that future narrow passage driving behaviour models can be assessed from.

CRediT authorship contribution statement

Peter Youssef: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ben Waterson:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition. **Katherine L. Plant:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

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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Data availability

The authors do not have permission to share data.

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