

Measuring and Describing Cooperation Between Road Users—Results from CoMove



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Abstract Safe and efficient traffic requires that road users interact and cooperate with each other. Especially in situations which are not explicitly regulated, and the right of way is not clearly defined, it is of great importance that road users are able to communicate their own intentions and understand the communication and cooperation behaviour of the other involved road users. When automated vehicles enter the current traffic system, their ability to fit into the system, that is their ability to communicate and cooperate, will determine their success. Therefore, the development of cooperatively interacting, automated vehicles requires detailed knowledge about human cooperation behaviour in traffic, which can only be obtained using appropriate methods and measures. By focusing on road narrowings and lane changing, this chapter gives an overview on how to measure cooperation between road users, considering methods for data collection, subjective and objective measures of cooperation as well as behaviour modeling, to support the systematic research on

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cooperation in road traffic. This overview is extended by findings from studies conducted within CoInCar, including results on factors influencing human behaviour in cooperative situations, either in a manual or an automated setting, and initial findings from modeling the cognitive processes underlying cooperative driving behaviour.

1 Introduction

Given the technological development in recent years and the expected further development, the introduction of automated agents, such as highly or fully automated vehicles, into the traffic system seems to be within reach in the near future. According to previously published roadmaps of many car manufacturers, suppliers and other stakeholders, driving highly automated in certain driving contexts was expected to occur in the next decade [19]. With reference to the defined automation levels by the Society of Automotive Engineers (SAE) [35], this means that the vehicle automation is able to perform the longitudinal and lateral control, to monitor the environment and to bring the vehicle into a safe state if necessary in any given situation, not requiring the human driver as a back-up for the automation if the vehicle is in the high automation level. The efforts behind these developments are motivated by the promise that the technology will bring benefits regarding traffic safety and efficiency, convenience for drivers, mobility for different types of road users etc.

However, these promised benefits can only be achieved if these automated vehicles are not only able to drive safely but also possess the required communicative and cognitive capabilities to cooperate with the human road users effectively and efficiently. The reason for this is that the traffic system can be seen as a social system in which different types of road users, such as drivers, pedestrians, or bicyclists, try to safely, efficiently and comfortably achieve their goals. This in turn requires that either possible goal conflicts in the future are detected and prevented by an appropriate adaptation of behaviour or, if road users are already in a conflict situation, that negotiation strategies are available to solve the conflict. In many situations, this requires that different individuals cooperate with each other to achieve their own goals. These interactions between them have essential influences on traffic safety, such as the interaction or communication between driver and pedestrian [63].

Accordingly, in Germany, for example, the road traffic regulations explicitly call on road users to show mutual consideration (§1, StVO) and to communicate (§ 11, StVO). Both aspects are especially important in situations which are not explicitly regulated, and the right of way is not clearly defined, e.g., two drivers simultaneously arriving at a two-sided road narrowing from opposite directions. To resolve this situation safely and efficiently, the two drivers have to be considerate of each other and cooperate by communicating who will pass the bottleneck first. Additionally, road users can cooperate with other road users by facilitating their intended maneuvers, e.g., drivers on highways adapting their speed to facilitate a lane change for other vehicles. Therefore, it is of great importance that road users are able to understand the behaviour of the other involved road users and infer their intentions, i.e., that

they can correctly interpret the signals of other road users, and send clear signals themselves.

As a new participant in the traffic system, automated vehicles need to be able to participate in these interaction and cooperation processes with human road users, in order to integrate themselves smoothly into the traffic system, negotiate conflicting action plans and adapt efficiently to the traffic situation. For this it is necessary that automated vehicles are able to understand and predict others' states and behaviour, that they are able to establish and maintain a shared situation representation with their interacting human partners [6, 23], and that these vehicles are able to change their own action plans and/or trigger their cooperating human partners to adapt their action plans in the light of changing situational characteristics and demands [14, 90].

Consequently, introduction of cooperatively interacting vehicles demonstrates the relevance of understanding cooperation in traffic. When automated vehicles enter the current traffic system, their ability to fit into the traffic system will determine their success [78], that is their ability to communicate and cooperate. Current automated vehicles lack an understanding of human behaviour in traffic, making conservative and defensive behaviour necessary for safe operation, which is associated with reduced traffic flow and higher accident involvement [77, 80]. Therefore, the development of cooperatively interacting, automated vehicles requires detailed knowledge about human cooperation behaviour in traffic, which can only be obtained using appropriate methods and measures. For example, we must understand how human drivers communicate their intentions, e.g., via movement patterns or explicit signals, how human drivers understand these signals, in which contexts which signals are used, what kind of situational characteristics trigger cooperative behaviour, especially when cooperation is optional, and what cooperative behaviour looks like.

The aim of our work within the project CoMove as part of the priority program "Cooperatively Interacting Vehicles" (CoInCar) of the German Research Foundation was, on the one hand, to find measures for the systematic description and evaluation of cooperation and, on the other hand, to identify situational factors which influence human behaviour in cooperative situations in order to develop a comprehension- and decision-based model of driver-vehicle cooperation. The present chapter gives an overview on how to measure cooperation in traffic, considering potential methods for data collection (Sect. 2), subjective and objective measures of cooperation (Sect. 3) as well as behaviour modeling (Sect. 4). This overview is complemented by selected findings and results of studies conducted as part of CoMove. In this chapter, we focus on two concrete scenarios that are prototypical for two classes of cooperation situations: lane changing situations as an example of cooperation situations where not cooperating is an option, and two-sided road narrowings where cooperation is necessary to solve the deadlock in the situation.

The term *cooperation* requires a domain-specific definition since interaction and cooperation in traffic differ from other forms of social interaction. For example, drivers will most likely never meet again [45]. In this chapter, cooperation is understood as a specific form of interaction between two or more (human) road users whose actions interfere with each other (space-sharing conflict; [57]), and who adjust their behaviour to support each other and to solve the potential conflict [30, 54]. This coop-

eration is achieved by means of communication [30], which includes explicit (e.g., horn, indicator, hand gesture) and implicit signals (e.g., deceleration, acceleration) [17, 59]. Cooperative situations are characterized as being often non-symmetrical, meaning one of the involved road users has to make a compromise [58].

2 Methods for Data Collection

Appropriate data collection methods are a prerequisite for studying cooperation. This section describes exemplary studies that have investigated cooperation in road traffic in order to give a brief overview of potential data collection methods, mentioning some important advantages and disadvantages of the different methods. Traffic observations, video-based online and laboratory experiments as well as test track and simulator studies are considered. Special attention is given to coupled simulator studies, as they represent a promising but under-researched method.

2.1 Traffic Observations

On-site observations are an inexpensive and simple tool to study cooperative behaviour, but are limited in that not every detail can be recorded, such as the duration and exact sequence of signals. Imbsweiler et al. and Rettenmaier et al. [31, 71], for example, conducted on-site observations of drivers at narrow passages. Observation protocols included lateral and longitudinal behaviour (e.g., swerving to the side of the road, accelerating, stopping), use of horn, indicators, headlights, and hand gestures, and order of arrival and departure. These protocols were used to examine implicit and explicit communication signals and to derive prototypical offensive and defensive approaching behaviours, which were evaluated in further studies (e.g., [34, 70]).

Traffic observations using video cameras that are either permanently installed or set up for a specific period of time (see Fig. 1 for an example) allow a much more detailed analysis of traffic behaviour. Schuler et al. [76], in comparison to [31, 71], based their analysis on video data, and were able to determine not only the frequency and sequence of communication signals, but also the spatial occurrence of the signals with respect to the distance to the narrow passage. Quante et al. and Zhang et al. [67, 94] demonstrate that additional trajectory data is useful in pre-selecting relevant interactions (e.g., based on surrogate safety measures such as time to collision) and allows the inclusion of precise measures of, for example, drivers' velocity and relative position, in the analysis.

Traffic observations have in common that the observers take an external perspective on the situations and thus the subjective experience of the observed road users is usually missing. In addition, the observed behaviour usually shows a large variance, so that only limited conclusions can be drawn about factors influencing behaviour.



Fig. 1 DLR's application platform for intelligent mobility (AIM) research junction (right) and mobile installations (left)

2.2 *Online Experiments*

One possible tool to efficiently study the reactions of a large number of human drivers to highly controlled traffic scenarios in a standardized manner are online experiments (e.g., [49, 59]). Online experiments are generally easy to implement and time- and cost-efficient and allow both the collection of specific reaction data, such as decision data, and even reaction times, as well as subjective data, such as ratings. However, they partly lack realism since participants only passively experience a situation sitting in front of a computer screen. One such example is [59]: In two video-based online experiments, Miller and colleagues presented videos of vehicles approaching a narrow passage in which participants took the perspective of the driver approaching from the opposite direction. The approaching behaviour was systematically varied with respect to the longitudinal and lateral vehicle movements as well as the timing of a given movement. Participants were asked to rate the other driver's intention, the intention's explicitness and the cooperativeness of the observed behaviour.

2.3 *Laboratory Studies*

Similar to online studies, laboratory-based studies using video material allow a high level of standardization of the investigated situations, since the exact same situation

can be presented to the participants. It allows the measurement of reaction time and eye-tracking parameters. Compared to online studies, the number of participants is smaller. However, it is easier to control that participants fully focus on the study. In CoMove, these kinds of studies were carried out to identify situational factors that influence the driver's behaviour in lane changing situations both when changing lanes on the highway and when a car merges onto the highway from an on-ramp [85–87], which were then further investigated in a driving simulator setting [83, 84] (see Sect. 3.3).

2.4 Test Track and Simulator Studies

Test track and simulator studies, in comparison to online and laboratory video-based studies, allow both subjective experience and objective behaviour to be studied in a more realistic, yet controlled and standardized (but costlier) setting. Imbsweiler et al. [34], for example, conducted a study on a test track in which participants encountered another driver at a narrow passage. The other driver was trained to approach the narrow passage in six predefined ways. After every encounter, participants rated the other driver's cooperativeness, the degree of cooperation in the given situation and the participants' confidence to pass first or second. Rettenmaier et al. [70] performed a similar study in a driving simulator: Participants repeatedly encountered a vehicle at a narrow passage, which showed nine different approaching behaviours. With the goal of designing movements for autonomous vehicles, participants' driving behaviour and subjective ratings were used to evaluate the implemented approaching behaviours. In [83], the selected behaviour in lane changing situations when another vehicle wants to overtake a slower truck were investigated. Participants were told to support their automated vehicle to find the best decision. In [84], the automated vehicle was carrying out the decision on its own and participants were asked if they agree with their vehicle's decision.

When comparing test track and simulator studies, test track studies offer the advantage of interaction with real road users. This, however, may bear a certain risk for the participants and is therefore not always ethical. However, simulated road users are usually only human-like to a limited extent, which can be problematic when studying cooperation. A promising alternative are coupled simulators, in which two or more participants move and interact in the same simulated environment [24, 60, 61, 64, 75].

2.5 Coupled Simulator Studies

Coupled simulators have been used to study, for example, traffic safety (e.g., [26]), driver-assistance systems (e.g., [66]), and automated vehicles (e.g., [24]), not only considering drivers but also pedestrians (e.g., [52]), cyclists (e.g., [53]), and motor-

cyclists (e.g., [92]). With respect to cooperation, only a limited number of published studies exists. For example, [25, 28] investigated cooperative behaviour in a lane-change scenario in a multi-driver simulator. In both studies, the driver on the right lane had to perform a lane change to the left lane because of a braking lead vehicle, interfering with the driver in the left lane. In this scenario, [28] studied the effects of the availability of a left lane, indicator use and the brake strength of the lead vehicle on the occurrence of cooperative behaviour. Friedrich et al. [25], in addition, manipulated participants' belief about whether the other driver was a human driver or simulated.

2.5.1 Exemplary Coupled Simulator Study

Within CoMove, a coupled driving simulator study was conducted to describe and evaluate cooperative behaviour of two drivers encountering narrow passages (S6 in Table 1). Two scenarios were implemented: In one scenario, drivers came from opposite directions and had to pass a narrow passage caused by traffic beacons on both sides of the road (two-sided bottleneck; Fig. 2A). In the other scenario, drivers came from the same direction but on separate lanes. The right lane was blocked by an excavator (one-sided bottleneck; Fig. 2B), so a lane change was necessary. The two drivers were driving through a city on a fixed route, which took them past the two narrow passages eight times each. They were synchronized by traffic lights to ensure they would encounter each other in the two scenarios.

The coupled driving simulator MoSAIC (Modular and Scalable Application-Platform for ITS Components) at the Institute of Transportation Systems at the German Aerospace Center (Braunschweig, Germany) was used. For the study, two fixed-based driving simulators were coupled. Each driving simulator was equipped with a steering wheel, accelerator and brake pedal. Three monitors created a 180° view (see Fig. 2C). The driving simulators were placed on the right and left side of the room, separated by a third simulator which was not used during the study. Participants could use the headlights, indicators, and horn. The sound of the engine and horn was transmitted via headphones. The environment was designed using Unreal Engine (Version 4.24) and Trian3DBuilder. In-house software was used to connect and control the driving simulators.

Twenty-two participants, i.e. eleven pairs, took part in the study (16 male, 6 female). The mean age was 27.3 years ($SD=6.6$ years). After receiving general information and driving a ten-minute training session, participants encountered each other 16 times in the two scenarios. After every encounter they stopped and answered several questions about the interaction. At the end of the study, they filled out different questionnaires regarding demographic information, driving behaviour, personality, and their experience with the simulator. In addition to subjective data, driving data (e.g., velocity, acceleration, pedal positions) and videos of the experimental drive from the drivers' perspective were recorded. Participants knew that they were interacting with each other in the simulation.



Fig. 2 The cooperative scenarios of the simulator study, two-sided bottleneck (A) and one-sided bottleneck (B), which were implemented in DLR's coupled simulator AIM MoSAIC (C)

Besides the aim to describe and evaluate participants' cooperation behaviour (not published yet), part of the analysis was also to answer whether cooperative behaviour could be provoked within the study and whether it felt realistic. Focusing on the two-sided bottleneck, in more than 80% of the encounters, drivers stated that they cooperated with the other driver. On average, the driving and communication behaviour of the other driver as well as the interaction with the other driver were rated as realistic. When asked what aspects of the interaction behaviour were not realistic, 14 participants mentioned limited communication, noting the absence of hand signals and missing eye contact.

2.5.2 Implications for Future Studies

Based on these findings, future studies on cooperation in a coupled driving simulator should investigate whether performing and perceiving hand gestures and seeing the other driver's head orientation increases the feeling of realistic interaction and cooperation. It should also be considered that drivers might behave more defensively and cooperatively when knowingly interacting with another human driver (see also [25]). At this point, it is important to note that neither the influence of limited communication possibilities, the awareness of interacting with real humans, nor other factors such as the repeated encounter of the same participants, the spatial proximity in the laboratory, the degree of familiarity of the participants, (lack of) sympathy, and participants' characteristics (e.g., age, gender) have been systematically investigated so far. Accordingly, there is a great need for research to ensure that cooperative

behaviour shown in a coupled simulator is equivalent to cooperative behaviour shown on the road.

3 Measures of Cooperation

In order to study cooperation systematically and gain a detailed understanding of how and when road users cooperate, the construct of cooperation has to be operationalized, i.e., cooperation must be made measurable. This requires, on the one hand, a precise definition of cooperation and its aspects and, on the other hand, measures that can reliably capture these different aspects of cooperation. Within CoMove, we have therefore conducted several empirical studies to methodically advance the systematic and scientific assessment of cooperation (see Table 1 for an overview).

This section first presents one of these studies which was conducted with the goal of better understanding the construct of cooperation and identifying aspects of cooperation in road narrowings and lane changing situations, followed by an overview of existing objective and subjective measures of cooperation. Finally, it is complemented by a detailed outline of experiments investigating factors influencing cooperation in lane changing scenarios in order to give a practical example of how to measure cooperation.

3.1 *Identifying Aspects of Cooperation*

Focused interviews were conducted and qualitatively analysed to identify potential criteria and metrics for the description and evaluation of cooperation (see also [69]). It was focused on two cooperative scenarios: drivers encountering each other from opposite directions at a narrow passage and a lane change with surrounding traffic. Twelve traffic researchers (5 male, 7 female) were interviewed. They were between 26 to 37 years old ($M=30.08$ years, $SD=3.87$ years) and owned a driver's licence for at least eight years ($M=11.67$ years; $SD=3.37$ years). Interviewees were presented with short videos of traffic encounters. For the lane change, the video material was recorded from within a vehicle driving either on a highway or in an urban environment. One camera was directed to the front, the other camera was directed to the back (see Fig. 3B). For the narrow passage, videos were recorded from two perspectives at a road narrowing in Braunschweig, Germany (see Fig. 3A) via two portable sensor poles which are part of DLR's Application Platform for Intelligent Mobility Mobile Traffic Acquisition [46] (see Fig. 1).

Encounters between two or more drivers were extracted and rated with respect to their degree of interaction by two raters. Videos with identical ratings and different degrees of interaction were chosen for the interview study, resulting in 29 videos of encounters at the narrow passage and 51 videos of lane changes (of which 12 were recorded in an urban environment). After answering demographic questions, every

Table 1 Empirical studies conducted within CoMove to improve the systematic assessment of cooperation

No.	Method	Scenario	Goal	Refs
S1	Focussed interviews	NP, LC	Identification of potential indicators/metrics of cooperation	[69]
S2	Video-based online experiment	NP	Influence of arrival order and time delay on evaluation of cooperation	
S3	Video-based online experiment	NP	Influence of arrival order, time delay, perspective and stopping distance on evaluation of cooperation	
S4	Traffic observation	NP	Identification of metrics to quantify arrival order	[67]
S5	Online survey	NP	Development of questionnaire for the subjective evaluation of cooperation (CoopQ)	[68]
S6	Coupled simulator	NP, LC	Further development of CoopQ; exploratory analysis of cooperation in coupled simulator setting	
S7	Coupled simulator	NP	Influence of arrival order and approaching behaviour of oncoming driver on evaluation of cooperation and cooperation behaviour	
S8	Online survey		German validation of the Prosocial and Aggressive Driving Inventory (PADI)	[82]

NP = narrow passage; LC = lane change

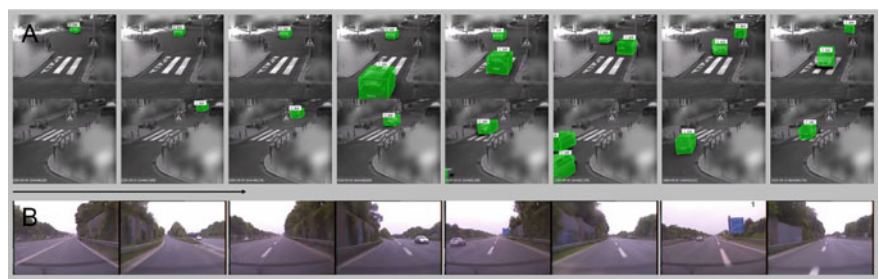


Fig. 3 Examples of video material used in the interview study. **A** shows a narrow passage scenario, **B** shows a lane change

participant sequentially watched 37 videos while commenting aloud on the drivers' behaviour. The instruction was given as follows (translated from German):

"Please comment aloud on the videos by describing and evaluating the behaviour of the drivers. The following questions serve as a guide: How do you evaluate the behaviour of the drivers? What do you base your evaluation on? Did the drivers communicate with each other? If so, who communicated what? And how did the other react? On what do you base this? In what order did they communicate?"

The order of blocks (lane change vs. narrow passage) and trials were randomized between participants. Four interviews were conducted in person, eight were conducted via Skype for Business calls due to Covid-19 restrictions. Participants' answers were recorded, transcribed and analysed via MAXQDA Analytics Pro 2020. As an example, a participant's comment on a narrow passage video is presented below (translated from German):

"Here we see that two vehicles are approaching the bottleneck at relatively the same time and therefore also meet in the bottleneck or shortly before it. And you can already see that the vehicles have to brake heavily in any case, or at least one of them, namely the 734, is really hitting the brakes. The, what is it, the T5 or whatever, it's speeding through it quite recklessly, I would say. So, he says I'm the stronger one and, yes, okay, admittedly, because he's faster, he's also the first to get into the bottleneck. Well, how do I evaluate the behaviour of the drivers? Well, one of them [...] drives defensively. That's the one who brakes, of course. The T5 is driving [...] offensively, [...], also drives much faster".

Codes were developed in an iterative process and organized into four categories: description of behaviour, interpretation of behaviour, factors influencing behaviour, and evaluation of behaviour. The results for the categories description and evaluation of behaviour are summarized in Tables 2 and 3. Aspects mentioned by at least half the interviewees are listed.

Particularly relevant for the description and evaluation of the narrow passage scenario seem to be (1) the time delay with which drivers arrive at the narrow passage, and (2) the arrival and departure order (who arrives first and who passes the narrow passage first). For the lane change, (1) the distance between vehicles, (2) the speed difference of vehicles, and (3) the necessity of a lane change seem to be most relevant.

3.2 Operationalizing Cooperation

Once it has been worked out which aspects of cooperation are to be investigated, these aspects need to be operationalized to be either experimentally manipulated

Table 2 Aspects used to *describe* drivers' behaviour (number of interviewees who mentioned a given aspect)

Individual behaviour	Narrow passage		Lane change	
Longitudinal behaviour	Wait Stop (standstill) Decelerate Constant Accelerate	(12)	Decelerate Constant Accelerate	(12)
Lateral behaviour	Movement to the right side	(12)	To/from left/middle/right lane Fast/slow lane change	(12)
Velocity	Fast Slow	(12)	Fast Slow	(12)
Start of behaviour	Early Late	(10)	Suddenly Early Late Simultaneously	(12)
Explicit communication	Headlight flash Indicator	(4)	Headlight flash Indicator	(12)
Relative behaviour	Narrow passage		Lane change	
Time/space distance	Successive Simultaneous	(12)	–	
Arriving/leaving vehicle	Same Different	(10)	–	
Distance between vehicles	–		Large Small	(12)
Speed difference	–		Large Small	(11)

as independent variables or analyzed as dependent measures. Based on the definition of cooperation given in Sect. 1 and the findings from the focussed interviews (Sect. 3.1), at least three aspects of cooperation could be derived: the temporal and spatial proximity of road users, costs and benefits of a cooperative situation, and the dynamics between interacting road users. Section 3.2.1 provides an overview of potential objective measures to assess these three aspects. Since cooperation in road traffic is not a clear-cut phenomenon but depends on the subjective evaluation of the involved road users, subjective measures of cooperation are presented in Sect. 3.2.2.

Table 3 Aspects used to *evaluate* drivers' behaviour (number of interviewees who mentioned a given aspect)

Aspect	Narrow passage		Lane change	
Defensiveness	Defensive, passive, calm, considerate, careful, cautious, cooperative	(12)	Polite, considerate, defensive, anticipatory, cooperative	(9)
Clarity	Predictable, explicit, unambiguous, certain, clear, anticipated, expected	(11)	Clear, ambiguous, unexpected	(8)
Offensiveness	Offensive, aggressive, inconsiderate, careless, dynamic, brash, brazen, impatient, uncooperative	(10)	Ruthless, aggressive, egoistic, impudent, brash, reckless, uncooperative	(7)
Criticality	Critical, safe, risky, dangerous, unproblematic	(10)	Critical, uncritical, dangerous, safe, unsafe, unproblematic	(12)
Efficiency	Efficient, well timed, fast, flowing, time saving, obstructive	(8)	Flow, time saving, obstructive	(10)
Necessity	–		Necessary, unnecessary, causeless, needless	(7)

3.2.1 Objective Description of Cooperative Behaviour in Traffic

A space-sharing conflict [57], i.e., a certain temporal and spatial proximity of road users, is a precondition for cooperation. The measurement of temporal and spatial proximity is particularly relevant with respect to traffic safety. Well-known surrogate measures of safety have been described [36], for example, the time to collision (TTC) or the post encroachment time (PET), which can provide information on the criticality of a situation and thus, on the presence of a space-sharing conflict. In addition to temporal and spatial proximity, cooperation is associated with facilitated goal achievement and, in the case of non-symmetrical cooperation, with the postpone-

ment of one's own goals. Therefore, it might be of interest to measure the costs and benefits of cooperating road users, for example, in terms of safety, efficiency or comfort. Safety, as described above, can be assessed by surrogate measures of safety, for example TTC, PET, deceleration to safety time or conflict severity [36]. Efficiency, in turn, can be measured by, for example, passing time (e.g., [70]), journey time and standard deviation of speed (e.g., [94]). Driving style, which can be described in terms of acceleration, jerk, quickness, and lane deviation, among others, has a major influence on experienced comfort [7]. Düring and Pascheka [20], for example, took the idea of costs and benefits and determined the type of cooperation, namely altruistic, rational, and egoistic, by comparing the utility of a maneuver (calculated by cost functions for both agents involved) with a reference behaviour.

A major challenge is to describe the dynamics between interacting road users, since there is usually not only one stimulus (e.g., a headlight flash) and one reaction (e.g., acceleration), but an interplay of multiple stimuli and reactions evolving over time. So far, mainly scenario-specific approaches exist. Hidas [29], for example, used the gaps between following and leading vehicles before and after a lane change to infer whether behavioural interference occurred between road users and to classify a lane change as free, forced or cooperative. For a convoy of vehicles, the length of the convoy and the standard deviation of the lateral position of the vehicles have been used to describe the interactions between the convoy's vehicles [60, 61, 64]. Oeltze and Schießl [64], in addition, used the distances between vehicles to describe the adaptive behaviour of vehicles within a convoy in response to a driver assistance system. We adapted this approach in order to estimate the arrival order of drivers at a narrow passage [67]. In this study, trajectory data was used to calculate both the distance and time to arrival (TTA) to the narrow passage for both drivers. Next, the difference in distances/TTAs was calculated such that this difference was positive (negative) for one driver if he/she was closer (more distant) to the narrow passage than the other driver. The arrival order was then defined based on the minimum of this difference over a given space. The relationship of arrival order and cooperation for the narrow passage scenario has been investigated in further studies but results have not yet been published (S2, S3 and S7 in Table 1).

A more general approach is to correlate time series data, e.g., drivers' velocity, to capture the dependency of two road users and thus their interaction behaviour [51, 52, 61]. Furthermore, different visual descriptions have been used to study the interplay of road users, such as interaction plots (e.g., [61, 92]), time-space-diagrams (e.g., [61]), and sequence diagrams (e.g., [91]). Figure 4 depicts two encounters from the coupled simulator study (S6 in Table 1), illustrating interaction plots, time-space diagrams and cross correlations. The upper interaction plot in Fig. 4 illustrates an encounter, in which the two drivers arrive simultaneously at the narrow passage (i.e., they are the same distance away from the bottleneck for a longer period of time; see also the upper time-space diagram) until the driver passing second (red) stops while the other driver (green) passes the bottleneck. In contrast, the lower interaction plot visualizes an encounter, in which the two drivers arrive after each other, i.e., the driver passing first (green) is always closer to the narrow passage than the driver passing second (red). The cross-correlation plots show that for the upper encounter

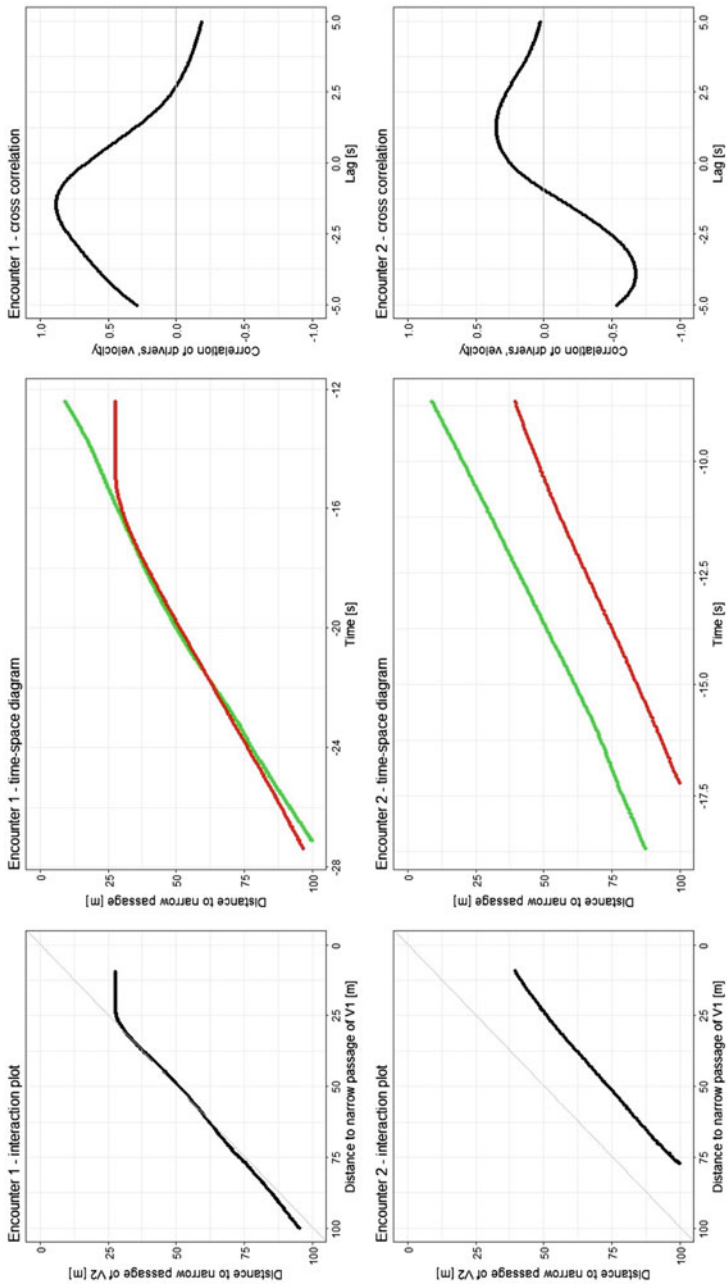


Fig. 4 Interaction plots, time-space diagrams and cross correlations of two exemplary encounters, in which two drivers encounter a two-sided narrow passage from opposite directions. The data comes from the coupled simulator study described in Sect. 2.5.1

drivers' velocities show a high positive correlation (i.e., velocities are similar) when the time series are shifted by -1.25 s, whereas for the lower encounter, the highest correlation is negative (i.e., velocities are in reverse) for a lag of -3.75 s. The lag for which the correlation maximizes might allow to identify the leading and following driver [51].

It must be emphasized that so far there are only isolated cooperation-specific objective measures. Most of the measures originate from other research areas, so that the relationship with cooperation has yet to be investigated. Thus, on the one hand, measures to objectively capture cooperation are still missing, and on the other hand, existing measures' reliability and validity for the construct cooperation still have to be proven.

3.2.2 Subjective Evaluation of Cooperation: PADI and CoopQ

To complement objective measures, cooperative behaviour in traffic also needs to be captured from a subjective perspective, for example by self-reporting questionnaires. The Prosocial and Aggressive Driving Inventory (PADI; [27]) is based on two scales, addressing both prosocial and aggressive driving behaviour, which distinguishes this questionnaire from other self-reporting driving questionnaire that only focus on one of the two (e.g., The Positive Driver Behaviour Scale by [65]). It is based on the assumption that driving behaviour is a stable and enduring characteristic of drivers [27]. Since prior studies linked unsafe driving behaviour to dimensions of the Five-Factor Model of personality, [15, 27, 89] correlated the PADI scales with the Big Five traits. Since no comparable questionnaire existed in German before, the questionnaire was translated into German and successfully validated during the course of this project [82] and used in different studies [81]. Based on [11], PADI was translated into German by two independent translators. These two versions were compared and combined into a third version which was translated back into English by a third translator. Finally, the third version was compared with the initial English version regarding the meaning of each single item. After some minor wording adaptation, a final version was used for the questionnaire's validation. In an online study, $N = 291$ filled in the PADI, NEO-Five-Factor Inventory (NEO-FFI) [10] and driving-related questions. A confirmatory factor analysis, a principal component analysis with varimax rotation and a logistic regression supported the structure of the original questionnaire. Only one item had to be excluded in the German version. The German version of PADI consists of 28 items: 16 measuring prosocial driving (e.g., "drive more cautiously to accommodate people or vehicles on the side of the road (e.g., slow down, move over)") and twelve measuring aggressive driving (e.g., "speed up when another vehicle tries to overtake me") [82].

The subjective evaluation of cooperation in a specific encounter, on the other hand, has mainly been measured uni-dimensional using multilevel response scales. Kauffmann et al. [37], for example, asked their participants to rate how cooperative another driver was on a scale from 0 = not at all to 15 = very cooperative. Similarly, participants in [59] rated another driver's cooperativeness on a 7-point rating scale

(1 = not cooperative at all, 7 = completely cooperative). In [32], the willingness to cooperate (of themselves and another driver) and the intensity of cooperation in a given situation were each judged on 7-point rating scales. In contrast, [96] assessed the subjective perception of cooperation in more detail by addressing the dimensions satisfaction, relaxation, accordance, and trust. Their participants rated twelve adjective pairs (e.g., frustrating/satisfying, delaying/time-saving) on 6-point forced choice semantic differential scales, with four items related to the experienced situation, three to the participant him-/herself, three to the other driver, and two to the situation impact.

Building on [96], a questionnaire has been designed within CoMove to assess the subjective evaluation of cooperation in a traffic encounter in even more detail (see also [68]). The questionnaire was developed to answer the following questions: (A) Could a given encounter between road users be considered cooperation? (B) Did road users cooperate successfully? For question A, 39 statements reflecting different aspects of cooperation were formulated, for example “The drivers competed with each other”. Based on different definitions of cooperation, aspects like altruism, coordination, communication, competition, goal orientation, reciprocity, dependence, interference, mutual agreement, negotiation, costs and benefits were considered [8, 18, 20, 22, 30, 39]. To answer question B, 40 adjective pairs were identified, which reflect common motives in road traffic, for example safety and efficiency [8, 79, 88]. Based on an online survey with 123 participants, the number of items was reduced. By means of descriptive statistics, item analysis and factor analysis, ten items and 22 pairs of adjectives were selected for a first version of the cooperation questionnaire (CoopQ; Table 4). The CoopQ questionnaire was used in studies S2, S3, S6, and S7 (Table 1). An evaluation of the questionnaire’s reliability and validity has still to be published.

3.3 Situational Characteristics Influencing Cooperative Lane Changing

3.3.1 A Model of Recognition-Primed Decision Making in Cooperative Situations

Within CoMove, we adapted the recognition-primed decision (RPD) model by [41, 42] to investigate how situational factors influence the behaviour in the cooperative situation of a lane change [81]. The RPD model is a naturalistic decision-making model. According to this model, rather than trying to find the best possible option in a decision situation, the first workable option is selected by the decision maker. The RPD model was developed to describe decision making for experienced agents under complex and uncertain conditions facing personal consequences of their actions and having to react fast. As these assumptions fit to the dynamics of traffic situations and the context of drivers’ decision making in traffic the model has been selected to describe decisions made by drivers.

Table 4 Selected items and adjective pairs for the first version of CoopQ

Part A—Could a given encounter between road users be considered cooperation?	
The drivers wanted to occupy the same space at the same time	
The drivers have adapted to each other	
The drivers cooperated	
The drivers competed with each other	
The drivers acted amicably	
(At least one driver/Driver X) showed the other driver consideration	
(At least one driver/Driver X) acted selfishly	
(At least one driver/Driver X) were at an advantage because of the situation	
(At least one driver/Driver X) were at a disadvantage because of the situation	
(At least one driver/Driver X) acted with foresight	
7-point rating scale (“does not apply at all” to “applies perfectly”)	
Part B—Did road users cooperate successfully?	
Beneficial/obstructive	Supportive/hindering
Relieving/burdening	Enjoyable/unpleasant
Satisfying/frustrating	Pleasant/unpleasant
Relaxed/stressful	Calm/aggressive
Effective/ineffective	Efficient/inefficient
Goal-oriented/unplanned	Coordinated/uncoordinated
Harmonized/not harmonized	Consensual/non-consensual
Fair/unfair	Controlled/uncontrolled
Safe/unsafe	Harmless/dangerous
Risk-free/risky	Understandable/misleading
Unambiguous/ambiguous	Necessary/unnecessary
5-point forced choice semantic differential scale, e.g. efficient ☐ ☐ ☐ ☐ ☐ inefficient	

Following the model, well experienced drivers do not have to weigh several alternatives but match the current situation with patterns they already know [43]. The most relevant clues are highlighted by the patterns, which also provide expectations, identify plausible goals and suggest typical forms of reactions in the specific situation [42]. If the situation contains similarities to an already known situation, the most typical alternative is mentally simulated regarding its outcomes in the context of the current situation. If the mental simulation is successful, the intended action will be carried out. Otherwise, this action will be modified mentally until the expected outcome can be reached. Our adapted version of the model is presented in Fig. 5.

In [33], we combined the RPD model with a questionnaire survey inspired by [9], which investigated yielding behaviour in crossings. They surveyed the usage of formal and informal traffic rules and showed that traffic decisions can be portrayed using questionnaires. We used their approach in a questionnaire study on cooperative

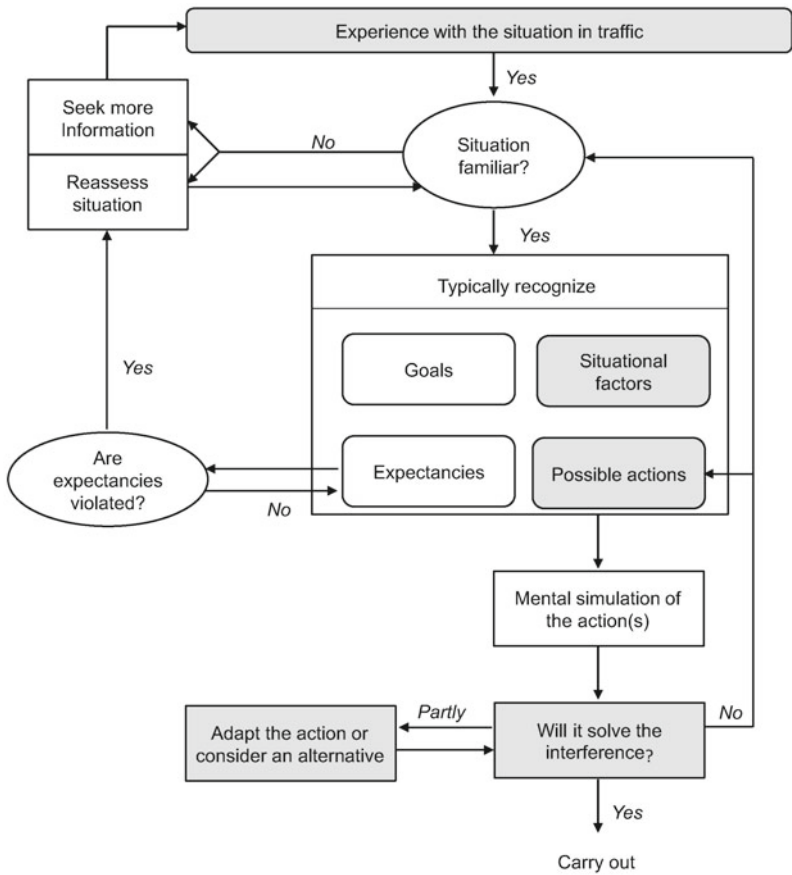


Fig. 5 Adapted decision making model from [81] after the original model from [41]; grey shading represents changes from the original. If experienced drivers encounter a familiar situation, they typically recognize goals, possible actions, situational factors and expectancies. If there are no violations of expectations this knowledge structure allows to simulate actions and their effects to decide whether these actions will solve the current interference. If such an action is found, it is carried out

traffic situations with $N = 281$ participants, which was analysed with the Natural Decision Making approach. This approach made it possible to categorize individual communication signals into offensive or defensive signals and thus make predictions about the intention of the driver.

When a cooperative situation occurs, both partners have to detect the interference and figure out if the situation is familiar. Therefore, the process shown in Fig. 5 has to be carried out by both partners and will be influenced by the actions of the cooperating partner. Moreover, since the cooperative situations are dynamic, it might have to be assessed multiple times depending on the changing conditions due to the behaviour

of the interfering partners or other involved agents (e.g., drivers in additional lanes or behind the agents). In a lane-change scenario, the driver who is asked for cooperation has to assess the situation as familiar or not. Since lane changing is a common driving situation, drivers are expected to have experience with this situation and to be able to recognize the situation.

The mental simulation is influenced by expectancies, different situational factors, the goals as well as the possible actions that could be carried out [41]. If a mental simulation indicates that a certain action would solve the interference this action is chosen and carried out. During the simulation process, it might be detected that a certain action only partly solves the interference, which implies that the action has to be adapted or reconsidered. It might be necessary to decelerate even stronger than originally simulated or to adapt the behaviour in another way.

Meanwhile, the driver that wants to change lanes has to indicate the intention and wait until the behaviour of the driver being asked for cooperation indicates that the cooperation being asked for is accepted and the corresponding actions are or will be carried out. This action has to be interpreted correctly by the partner asking for cooperation which has to react to that. Nevertheless, this is the optimal process. At every step of the process, errors might occur. If an interference is not detected or one of the involved drivers finds him-/herself in an unfamiliar situation, the process might be very different and the cooperative situation might not be solved successfully. It could be that the driver that wants to change lanes does not wait, which forces the other driver to step back (e.g., open a gap) even though this driver decided not to accept cooperation.

To better understand which situational characteristics facilitate drivers' recognition of an interference situation and under which circumstances which actions are preferred to solve the situation, we carried out several studies [81, 83–87] investigating how situational factors influence the processes in cooperative situations on the example of lane changing on highways. An overview over these studies – which will be discussed in the following – is given in Table 5.

In these studies, participants were taking the perspective of a vehicle on the faster, left lane on the highway (egocar). On the slower right lane, a vehicle (lane changer) was driving behind a slower commercial vehicle (see Fig. 6a). This scenario describes a discretionary lane change meaning a vehicle merges into another lane to maintain the desired speed level [2] but being not obliged to change the lane. In contrast to that, in [87] we investigated a mandatory lane change [2] in the form of an on-ramp scenario: The egocar drives on the highway when approaching an on-ramp from which another vehicle (lane changer) wants to merge onto the highway (see Fig. 6b).

3.3.2 Investigating Influencing Factors on Preferred Actions in Cooperative Situations

Scope of Action and Situation Criticality

Table 5 Empirical studies conducted within CoMove to investigate the effect of situational characteristics on drivers' recognition of and behavioural preferences in cooperative situations

No.	Method	Scenario	Goal	Refs
S9	Video-based laboratory experiment	Highway LC (2 lanes)	Investigating influence of scope of action and criticality for the lane-changing vehicle on the preferred action.	[85]
S10	Video-based laboratory experiment	Highway LC (2 vs. 3 lanes)	Investigating influence of scope of action, criticality for the lane-changing vehicle, indicator usage and additional lane on the preferred action	[86]
S11	Video-based laboratory experiment	On-ramp (2 vs. 3 lanes)	Investigating the influence of criticality for lane changer vehicle, indicator usage, additional lane and traffic signs on the preferred action	[87]
S12	Driving simulator	LC (2 lanes)	Investigating influence of scope of action, criticality for the lane-changing vehicle and indicator usage on the selected action.	[83]
S13	Driving simulator	LC (2 lanes)	Investigating the acceptance of automated behaviour depending on scope of action, criticality for the lane changing vehicle, indicator usage and the maneuver which was carried out by the automation	[84]
S14	Driving simulator	LC (2 lanes)	Investigating the influence of highlighting relevant situational factors on the preferred action	[81]

LC = lane change

In S9 [85], a video-based study, the preferred behaviour of the driver in the faster lane was investigated based on manipulating the scope of action (here called distance in time and space) and the situation's criticality for the other driver (lane changer) in the slower vehicle. The participants took the perspective of a driver in the faster left lane (egocar) while the simulation-controlled lane changer driving in the right lane approached a slower truck. An experimental setting using videos allowed strict control over these influential factors at a fixed decision point, on which certain lev-

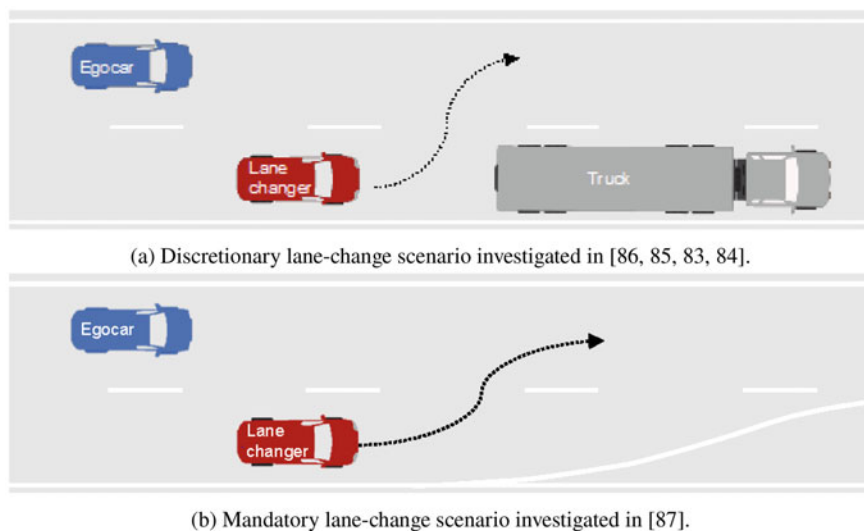


Fig. 6 These two sketches show the principal scenarios investigated in the different experiments. The participants were always situated in the car on the left lane (blue car called “Egocar”) from where they observed the development of the situation. The red car (called “Lane changer”) was always controlled by a simulation and represented a vehicle that might intend to change the lane. In Fig. 6a the situation of a discretionary lane change of the “Lane changer” is depicted, in Fig. 6b a mandatory lane change situation of the “Lane changer” is shown. The captions of the figures list the experiments where each of the situations was applied

els of situation’s criticality for the lane changer and scope of action were reached. Each of the 43 participants assessed 81 lane-change scenarios regarding the preferred behaviour (accelerate, decelerate or maintain speed) and the situation’s criticality (on a five-point rating scale) when the video stopped. The scope of action was operationalized in two ways: first by TTC and second by headway distance (HW) between the egocar and the lane changer. The situation’s criticality for the lane changer was operationalized by TTC between the lane changer and the truck and the HW between the lane changer and truck. TTCs were manipulated on three levels, ranging from a critical TTC (2 s) to ambivalent (4 s) and an uncritical TTC (6 s). The HWs between these vehicles were set at 6 m, 13 m, and 20 m. One aim of the exploratory study was to identify the best operationalizations for the scope of action and situation’s criticality for the lane changer. The study design was a 3x3x3x3 within-subjects design with a randomized presentation of each scenario. For the egocar, the speed was between 87 km/h and 152 km/h. The truck’s speed was kept at 80 km/h which is the maximum allowed speed level for trucks on German highways. The speed of the lane changer varied between 84 km/h and 116 km/h. These ranges result from the combination of TTC and HW manipulation. All vehicles kept their speed constant during the video.

Results showed that the preferred behaviour was almost equally distributed between the options accelerate, decelerate, and maintain speed. A generalized linear

mixed model was used to analyze the effects of TTCs and HWs. It showed that the TTC between egocar and lane changer was a significant predictor for the preferred behaviour: By increasing this TTC (higher scope of action), the frequency of decelerating increased, and the frequency of maintaining speed decreased. In contrast, if the TTC between changer and truck increased (a less critical situation for the changer), the frequency for decelerating decreased, and the frequency for accelerating and maintaining speed increased. HW between egocar and changer showed to be a significant factor for accelerating but not for decelerating, while the HW between changer and truck was a significant factor for decelerating but not for accelerating. When the participants decided to decelerate the mean criticality rating was highest and lowest when they decided to maintain speed. This study [85] indicates that the situational factors criticality for the lane changer and the scope of action are both relevant for the participants to adapt their decision in accordance with the interference in this lane change situation. Furthermore, the results showed that the manipulation of TTC was the more useful manipulation for the scope of action and criticality for the lane changer compared to HW, even though it might be more difficult to estimate [40].

Following [85], a second video-based study was carried out [86] (S10). In [85], the options regarding the preferred behaviour for the participants were limited to a longitudinal adaptation of vehicle speed due to the two-lane paradigm. In [86], the possibility for lateral adaptation by changing to a third lane as an additional option was investigated. Changing lanes is considered less costly compared to decelerating [28]. We expected participants to prefer the less costly alternative and, therefore, to change lanes if possible. In [85], the lane changer used the indicator in all presented situations. Since we expected that the communication of intention has an effect on the preferred behaviour, we also manipulated the communication of intention in the form of indicator usage in [86].

The scenario was similar to the one of [85]. 51 participants had to assess different lane-change scenarios. Four factors were manipulated: The scope of action by the distance between egocar and lane changer (TTC; 2 s vs. 6 s), the availability of a lane change to the left (2 vs. 3 lanes; lane change possible yes vs. no), the criticality for the lane changer (TTC; 2 s vs. 6 s), and the way the intention to change lanes was indicated. The latter was manipulated on four levels: (1) no indicator usage, (2) brake lights, (3) indicator usage, and (4) indicator and an additional arrow over the vehicle as an augmented-reality (AR) display. With this fourth way of indication, we investigated if the indicator is salient enough or if a more salient stimulus is needed. Additionally, by flashing brake lights, we investigated how another form of communication influences the participants' behaviour because braking lights might be interpreted such that the vehicle is slowing down in order to stay behind the truck. Every combination of the four factors was shown twice as a repeated measurement. To hide this repetition the surrounding landscape was changed between the repetitions. The presented highway was a three-lane highway, but in half of the scenarios, the left lane was closed due to a construction site, creating a two-lane scenario. If the left lane was free, participants had the additional option to change lanes to solve the interference in the situation.

The results of S10 [86], displayed in Fig. 8 (left), showed a clear behavioural preference for a lane change to the left to solve the cooperative situation when an additional lane was available which was in line with our expectation. In the two-lane condition, without the possibility to change lanes for the participants, participants preferred maintaining speed over decelerating and accelerating. Moreover, the factors situation's criticality, scope of action, and the indicator usage affected the preferred behaviour. If a third lane was available, a lower scope of action increased the preference to change lanes compared to maintaining speed but not for accelerating or decelerating. In the two-lane condition, indicating the intention to change lanes increased the preference for lane changing to the left, decelerating, and even accelerating compared to maintaining speed.

An additional arrow had only a small additional effect compared to a regular indicator due to a ceiling effect. When the braking lights were turned on or when no signal was presented, the preference was to maintain the current speed. In these cases, no need for cooperation was detected by the participants.

The main difference to S9 [85], the introduction of an additional option on how to solve the cooperative situation and the indication of the intention to change lanes were both influential on the preferred behaviour. The results indicate that indicator lights seem to be salient enough. Therefore, a missing adaptation in behaviour can not be explained by the low salience of an intention signal.

Discretionary Versus Mandatory Lane Changes

The aim of S11 [87] was to investigate the behaviour in an on-ramp situation (see Fig. 6b), which is categorized as a mandatory lane change [2]. On-ramps are considered as challenging situations that are a cause of traffic jams [3, 55]. We aimed to investigate if the factors indication of the intention (blinking) to change lanes and the situation's criticality for the lane changer are influencing the preferred behaviour as they did in a discretionary lane change situation on highways [85, 86]. Based on earlier studies, we expected more adaptation of the behaviour (any behaviour which is not to maintain the current speed) (1) if the situation's criticality for the lane changer is high, (2) if the intention to change lanes is communicated explicitly, and (3) if the third lane was available. Additionally, a traffic sign explaining merging traffic was shown. We expected more adaptation in behaviour if this sign was presented at the beginning of the scenario since it should help drivers identify the interference. Moreover, we expected a two-lane scenario to be perceived as more critical than a three-lane scenario.

The videos were presented to the same 51 participants as in [86]. Again, the perspective was the one of a vehicle driving on the highway while, this time in front of them, another vehicle wanted to merge onto the highway coming from an on-ramp. As in S10 [86], we manipulated the way the merging vehicle indicated its intention to merge onto the highway on the same four levels ((1) no indicator usage, (2) braking lights turn on, (3) indicators usage, and (4) indicator and an additional arrow over the vehicle as an AR display). The situation's criticality for the merging vehicle was operationalized by manipulating the TTC towards the end of the on-ramp (2s vs. 6s). Additionally, we manipulated the availability of unoccupied lanes. In half the

scenarios, the left lane was free, while in the other half of the scenarios, this lane was blocked by a construction site. As in S10 [86], this leads to the additional option “change lanes” in these scenarios. Every factor combination was presented twice. Therefore, each participant experienced 64 lane-change scenarios.

Results show that when having the possibility to change lanes to the left, this was the preferred behaviour (see Fig. 8). When this option was not given, the preference was to decelerate (see Fig. 7). The situation’s criticality for the lane changer was considered in the two-lane condition both for maintaining speed versus decelerating as well as accelerating vs. decelerating, increasing the preference for decelerating if the criticality for the lane changer was raised.

In the three-lane condition only the odds of accelerating compared to changing lanes increased if the criticality for the lane changer decreased. The indicator usage or the indicator usage with an additional AR arrow decreased the odds of maintaining speed or accelerating compared to decelerating in the two-lane condition, which was not found in the three-lane condition. When braking lights of the other vehicle were turned on, the odds of accelerating compared to decelerating increased significantly in the two-lane condition and also in the three-lane condition in comparison to lane change. The traffic sign explaining merging traffic only had an effect in the two-lane condition for maintaining speed compared to decelerating, in the form that the odds for maintaining speed were lower when the sign was presented. In all other cases, it was not significant. The participants assessed the two-lane scenario as more critical than the three-lane condition.

Comparable to [86], participants preferred the less costly alternative of changing lanes if possible [28]. This human behaviour corresponds with the maneuver automated vehicles most likely will carry out in these situations [12].

The effect of a traffic sign explaining merging traffic was small. However, a carry-over effect might have influenced the results since participants might have remembered the traffic sign even in the scenarios in which the sign was not presented at the beginning of the video. Therefore, further studies should investigate whether this sign or other signs facilitate the recognition of an oncoming interference using a between-subjects design.

The results indicate that participants considered the mandatory character of the lane change due to the end of the on-ramp in their preferred behaviour.

Since [86, 87] were carried out together, it was possible to investigate whether more behavioural adaptation is shown when the lane changer intends to carry out a mandatory lane change compared to a situation in which the lane changer intends to carry out a discretionary lane change [81]. As Fig. 7 shows, the preferred action in the discretionary lane change condition with two lanes was to maintain the speed, while in the mandatory lane change condition, the preferred option was to decelerate. The proportion of accelerating was marginally lower in the mandatory condition compared to the discretionary lane change condition. In the three-lane condition, the preferred choice was to change lanes both in the discretionary lane change and in the mandatory scenario (Fig. 8). However, in the mandatory scenario, the other behaviour options were rarely selected, while in the discretionary lane-change scenario, maintaining speed was selected in 35 % of the cases.

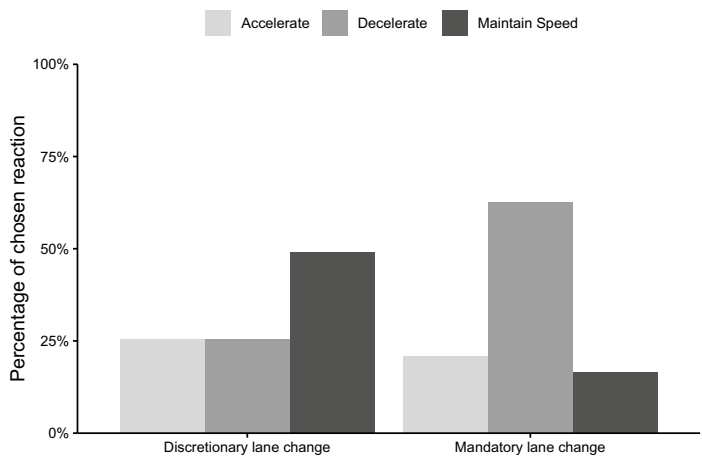


Fig. 7 Percentage of chosen actions in discretionary (left) from [86] and mandatory (right) from [87] lane change situations

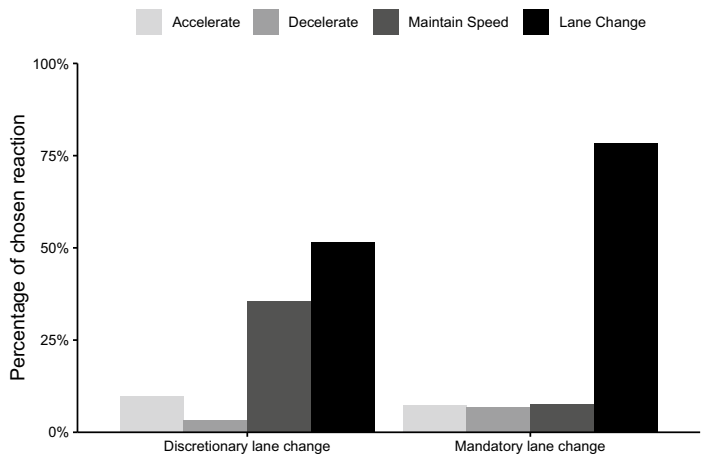


Fig. 8 Percentage of chosen actions in situations with three lanes either for discretionary lane chances (left) or mandatory lane changes (right)

The results support the hypothesis that more behavioural adaptation is shown when the lane changer intends to carry out a mandatory lane change compared to a situation in which the lane changer intends to carry out a discretionary lane change for the two-lane condition. The difference between discretionary lane change and mandatory lane change was significant both for accelerate vs. maintain speed, and decelerate vs. maintain speed. The differences between discretionary and mandatory lane change were significant for accelerate versus maintain speed, decelerate vs. maintain speed and change lanes versus maintain speed.

If a mandatory lane change was intended, the willingness to adapt the behaviour increased in this study. This is in line with the research by [2]. However, the behaviour carried out in actual traffic might differ from the first intention participants show in this study.

Besides the intention to facilitate a necessary lane change, the results might be influenced by the experience participants made in this situation. Zheng [95] assumes that the decision making for the driver changing lanes is different in a mandatory lane change compared to a discretionary change. Their research indicates that drivers carrying out a mandatory lane change are willing to take higher risks than drivers in a discretionary lane change situation. Further studies investigating these lane changes will be needed, also focusing on the agent intending to change lanes regarding the decision making when and how to change lanes.

In three studies [85–87] the focus was on the preferred behaviour at a particular moment rather than the behaviour the participants would show when experiencing this situation as a driver supported by an automation. However, the behaviour they would carry out might differ from the preferred behaviour of an automated vehicle they are sitting in. Therefore, the next step was to investigate the effect of the influencing factors when the situation was experienced in the driving simulator [83].

3.3.3 Preferred Actions of Automated Vehicles in Cooperative Situations

To achieve comparability to the previous studies [85–87], the same levels of TTCs were set to investigate the scope of action and the criticality for the lane changer. To do so, automated driving was introduced, since individual differences in speed, acceleration, and deceleration under manual driving would have affected comparability between participants as well as to the earlier results.

Based on the results of the video studies, we expected an adaptation in behaviour (deceleration or acceleration) if (1) the scope of action was high compared to when it was low, (2) if the criticality for the lane changer was high compared to when it was low, and (3) if the lane changer used the indicator to communicate the intention to change lanes compared to no communication of intentions.

In a driving simulator study, 32 participants experienced 36 lane-change scenarios on a two-lane highway. Three factors were manipulated: The scope of action (TTC 2 vs. 6 s), the criticality for the lane changer (TTC 2, 4 and 6 s), and indicators usage

(yes vs. no). Every scenario was presented twice. The landscape around the highway was altered in the scenario so that the participants did not notice the repetition.

Participants were instructed that their automated vehicle would ask for their preference in specific situations and would carry out the selected maneuver automatically. This preference had to be provided at a specific point in time, indicated by an acoustic signal. The specific point varied based on the manipulated factors. Participants had to answer within 2 s, and if they did not decide, the car would continue with the current speed, and the lane changer would stay behind the truck. No change in behaviour was shown by the lane changer if participants selected maintaining speed or accelerating. When decelerating was selected, the lane changer would change the lane to the left and overtake the truck and return back to the right lane after the maneuver.

Results showed that maintaining speed was the maneuver that was selected the most, followed by decelerating and accelerating. As expected, the indicator usage had a significant effect on the selected behaviour: If the lane changer used the indicator to indicate the intention to change lanes, the preferred behaviour was to decelerate. In line with the hypothesis, the adaptation in selected behaviour was significantly influenced by the criticality for the lane changer. When the TTC was low, decelerating and accelerating were selected more often compared to when TTC was high.

Additionally, an interaction between criticality for the lane changer and indicator usage occurred: More adaptation of the behaviour was shown both for decelerating and accelerating when the scope of action increased. The additional effect that the indicator was stronger in situations with a low criticality for the lane changer might indicate that participants need this additional information that the lane changer has the intention to merge into the faster lane when the situation is uncritical, while in situations with a high criticality for the changer, the short distance to the truck in front might need less additional explanation through the indicator. Therefore, additional possibilities to communicate one's intentions were focused on in the final study [81].

Moreover, it is relevant to know how the actively chosen behaviour differs from the acceptance of a behaviour carried out by an automation since future technology might work like that, which was addressed in study [84].

3.3.4 Investigating Acceptance of Automated Maneuvers in Cooperative Situations

In [84], we investigated the acceptance of the performed maneuver by an automated vehicle in the same lane-change scenario as used in [83]. Different to the study described above (see Sect. 3.3.3), here the automation suggested a maneuver and participants were asked whether they would accept the suggestion.

Research related to driving style and comfort indicates that participants would accept behaviour carried out by an automation that differs from their manually performed driving behaviour [4, 93]. Therefore, it is necessary to know if a comparable pattern can be found in cooperative situations and how situational factors that influence the preference of certain behaviour influence the acceptance when an automated vehicle is in control.

It was investigated if drivers prefer the automation to adapt its behaviour over not adapting the behaviour when another vehicle wants to change lanes. Additionally to the studies before, the influence of being cognitively distracted by a secondary task on this preference was investigated. Higher acceptance for the automated behaviour was expected (1) when the behaviour was an adaptation (decelerating or accelerating) and the lane changer used its indicator, (2) when the scope of action was small and (3) when the participants were cognitively distracted. That third hypothesis was based on the assumption that distracted participants would have less situation awareness and agree with any decision made by the automation. Additionally, it was expected that higher criticality for the lane changer increases the acceptance of a behavioural adaptation.

In a driving simulator study, 20 participants experienced 48 lane changes in an automated vehicle. The vehicle was either accelerating, maintaining speed, or decelerating when it approached the lane changer driving behind the truck. The scenarios were the same as in the study before [83], with the same manipulations of indicator usage, the scope of action, and criticality for the lane changer. After each scenario, participants had to decide if they accepted (yes vs. no) the automated vehicle's behaviour. In half the scenarios, participants were distracted by an auditory one-back task.

Overall, the acceptance rate was generally high (74%). The highest acceptance was shown for decelerating, resulting to be a significant factor. Acceptance for maintaining speed or accelerating decreased when the lane changer was using the indicator compared to decelerating. We expected a higher acceptance both for decelerating and accelerating compared to maintaining speed, when the indicator was turned on. However, the effect was only significant for decelerating compared to maintaining speed. Therefore, this hypothesis had to be rejected. In line with the hypothesis, a small scope of action resulted in a significantly higher acceptance compared to a large scope of action. Also, the indicator usage significantly affected the acceptance. Being engaged in a secondary task had no significant effect on the acceptance, which contradicts our hypothesis.

Participants, sitting in a simulated automated vehicle, showed a clear preference that the automation adapts the behaviour when another vehicle plans to change lanes with the highest acceptance rate for decelerating. They preferred a more defensive driving style than the participants in the studies before when being the driver: In comparison to [83], they accepted maneuvers performed by the automation that differed from what participants would have preferred when asked before the maneuver. Indicator usage influenced the acceptance rate. The general high acceptance of the automated behaviour dropped, if the automation accelerated or maintained the speed.

The results show that with a higher scope of action, the preference or selection of deceleration increased while accelerating or maintaining speed decreased. Decreasing the speed allows the lane changer to merge in front of the egocar while accelerating would close the gap. Additionally, the less critical the situation was for the lane changer, the more maintaining speed was selected. Therefore, it can be assumed that participants considered the criticality of the situation. Moreover, also the necessity of the lane change is taken into account as the results showed: Partic-

ipants' selection of decelerating was higher in the on-ramp scenario when the lane change was necessary compared to the lane change on the highway when the lane change was discretionary. When given the additional option to change lanes to a third lane on the left, participants preferred this option, which is generally seen as a less costly alternative [28].

Regarding communication, participants expected the lane changer to communicate the intention to change lanes. If no intention was communicated, they kept their speed constant [83, 86]. An additional more salient indicator was not necessary [86]. In line with that, participants expected their automated vehicle to behave accordingly: If the lane changer used the indicators and the automated vehicles reacted with maintaining speed or acceleration, the acceptance was lower compared to the automated reaction of deceleration [84].

Further research will be needed but the results imply that participants prefer cooperative automated vehicles.

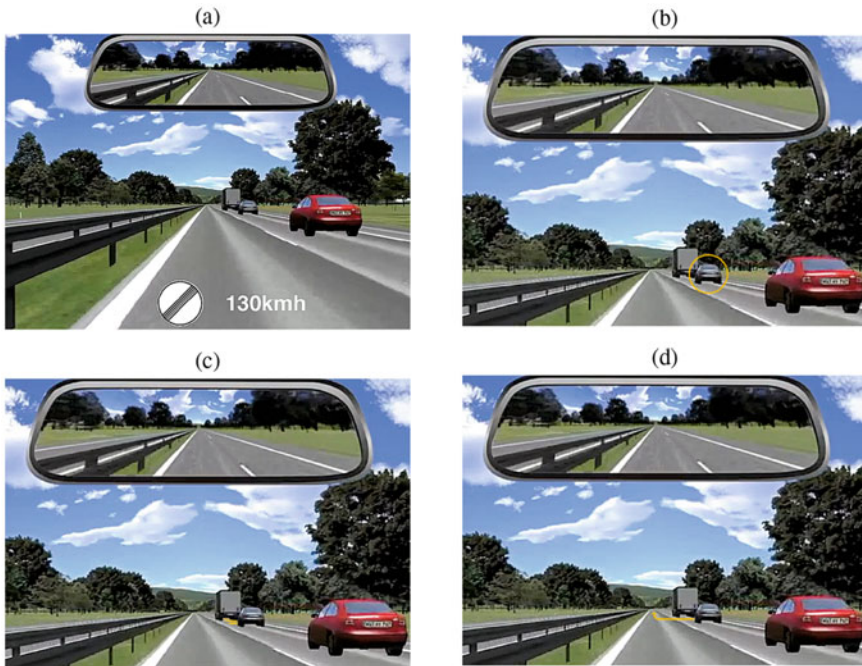


Fig. 9 Different presented information: **a** no additional information, **b** identifying the lane changer, **c** distance to the slower vehicle, **d** the planned trajectory. Note: The current speed was presented in all four conditions but was not presented here for better visualization. Original from [81]

3.3.5 Supporting Situational Awareness by Highlighting Situational Factors in Cooperative Situations

In the final study [81], situational factors were highlighted using an AR display to investigate how highlighting aspects of the situation influences the preferred action (see Fig. 9). Results of prior studies [38, 48] show that AR displays could be a suitable way of supporting human drivers in cooperative situations. Corresponding with the Situation Awareness model by Endsley [23], we highlighted either: (1) The vehicle that wants to change lanes, which should help the driver identifying the vehicle that wants to cooperate. This corresponds to the perception (Level 1) in Endsley's model. (2) The reason for the lane changer to change lanes, which in this case was the decreasing distance between the vehicle and the vehicle ahead. This should support the comprehension level (Level 2) in Endsley's situation awareness model. (3) The planned trajectory was shown, which should support the projection level of situation awareness (Level 3).

In the experiment, 29 participants took part. All participants held a valid driving license for at least one year. In contrast to studies so far, there were two vehicles following the truck. Between the scenarios, it varied which vehicle (Car A or Car B) wants to change lanes. The intention was to better test the HMI since one of the elements intends to improve the detection of a potential lane-changing vehicle.

The results from [81] indicate that highlighting relevant situational factors to support the driver in the understanding of being in a cooperative situation is a promising approach. Compared to not showing any additional information, highlighted relevant factors increased deceleration, which is seen as an increase in the willingness to support solving the cooperative situation. When highlighting the planned trajectory for the vehicle asking to change lanes, the preference to decelerate and open a gap was the preferred choice (Fig. 10).

3.3.6 Summary of the Empirical Studies on Factors Influencing Action Preferences in Cooperative Situations

The aim of these six studies was to deepen the understanding of the influence of situational factors on the action selected in cooperative situations under the theoretical framework of decision-making. For that reason different influencing factors were manipulated: The criticality for the changing vehicle, the scope of action, and indicating the intention to change lanes. These were investigated regarding their influence on the preferred action via video studies (S9, S10 and S11 in Table 5) and on the selected action (S12 in Table 5) as well as accepted action (S13 in Table 5). In the final study (S14 in Table 5), these influential factors were highlighted in an AR display to investigate how drawing attention towards these factors influences the preferred action.

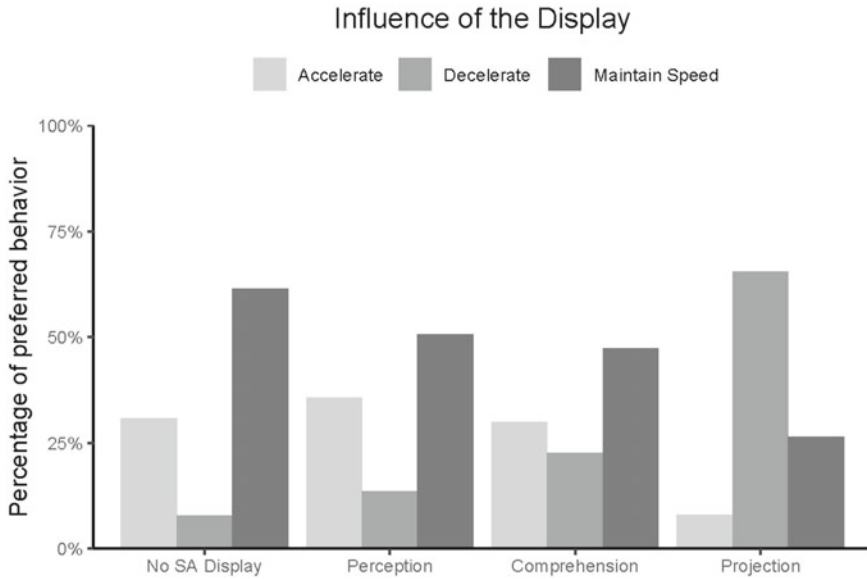


Fig. 10 Percentage of preferred automation behaviour with HMI supporting different levels of situation comprehension. Results from [81]

4 Modeling Cooperation Behaviour

In addition to the need for valid forms of measuring cooperative behaviour and for a firm empirical base on the factors that influence it, there is a need for theories of cooperative behaviour that are able to integrate the various empirical findings and that allow for generalization across various concrete scenarios. As driving is a task that involves many psychological processes, from perception to decision making and action execution, aspects of driving can only be described and explained by considering the interplay of these processes in a given situation and how it produces a given behaviour.

As described above, one of the theoretical concepts that is highly relevant to the field of cooperation in traffic is the understanding of the current situation and its future development [6, 21, 23]. Successful cooperation requires a shared understanding of the current situation and its requirements. This includes also a mutual understanding of the interaction partner’s goals, state and action plans [14, 44] to enable appropriate communication and plan negotiation between the partners [44] as seen in our experimental studies described above [83, 84, 86] and referred to in the cooperation model based on recognition primed decision making [33] (see Fig. 5).

Comprehension based models of situation understanding [6, 21] describe in detail the psychological processes and structures underlying the construction of a mental representation of a dynamic situation and thus provide a suitable basis for modeling

the cognitive processes involved in the construction of a shared situation representation in cooperation in traffic. In general, this construction includes the perception of the relevant situation elements, the understanding of these elements in relation to the overall situation and the prediction of the future development of the situation on the basis of learned expectations or active projections of the driver [23]. That means, the construction of this mental representation involves many cognitive processes and structures of the human information processing system. It is the interplay between perception, attention, long-term memory, working memory, evaluation processes and decision making that leads to a given representation in a given situation which is then the basis of, as in our experimental situation, the decision whether to accelerate, to decelerate or to maintain speed in the lane change situation depicted in Fig. 6a.

Consequently, to model the process of comprehending a dynamic situation and of maintaining and updating it requires to model the interplay of all these processes in a dynamic scenario. One possible framework that can be used for modeling this interplay are cognitive architectures based on Alan Newell's concept of unified theories of cognition [62]. Cognitive architectures represent a theory of how the brain achieves cognition. They are implemented as computational modeling platforms for cognitive tasks that enable the creation of models that can be used to explain and predict task performance. They have been used by researchers of artificial intelligence and cognitive psychology for many decades [47]. Many of these architectures are extensively used in modeling complex cognitive tasks involved in driving situations [73], piloting air-crafts [13], and air-traffic control [50].

4.1 ACT-R: A Unified Theory of Cognition

One of the most prominent candidates of unified theories of cognition is ACT-R [1]. ACT-R (which stands for Adaptive Control of Thought—Rational) underwent multiple revisions since its original publication, and has spawned over 1.100 publications in the field of cognitive science [72]. It is grounded on a firm empirical basis of basic psychological research on cognitive processes that play a major role in theories of how humans comprehend dynamic situations and was already successfully applied to model some aspects of the driving task [73, 74]. Therefore, we decided to use this architecture to develop a computational cognitive model of decision making in cooperative lane change situations such as those depicted in Fig. 6a.

The computational implementation of the ACT-R theory is a production-system architecture, that models knowledge either as declarative or procedural knowledge. Declarative knowledge is knowledge we are aware of and we are generally able to verbalize. An example would be “Berlin is the capital of Germany”. In ACT-R declarative knowledge is represented as a set of chunks of factual information. Each chunk consists of a collection of pairs of attributes and values. This declarative knowledge represents the knowledge that a person is assumed to have when she/he performs a task or solves a problem. An example of such a possible chunk of ACT-R's declarative knowledge database is shown in Fig. 11.

Procedural knowledge represents knowledge that controls behaviour but of which we are often not conscious. Examples are how we produce language or ride a bike. Procedural knowledge is represented as condition-action production rules in ACT-R as shown in Fig. 12. The condition side of a production rule specifies a set of features that has to be true for the rule to be selected and executed. The action side of the production rule consists of a set of actions that the model performs if the rule is selected, i.e. “fired”. It has to be noted that Figs. 11 and 12 represent an informal natural language description of chunks and production rules to provide an overview of what the concepts mean. “Real” ACT-R chunks and production rules have to be more precise and specific to be actually implemented in ACT-R.

Chunks and production rules are the basic building blocks of any ACT-R model that is executed by the ACT-R cognitive architecture. This architecture consists of a set of modules and each module implements a specific cognitive function. Information is exchanged between the modules via buffers. Each module includes any number of buffers and each buffer can hold one chunk at a time. The information held in a buffer is accessible for other modules to be read or modified. The chunks in the buffers of the modules consequently represent that set of information that is immediately accessible to the ACT-R model. The declarative module holds all chunks of the ACT-R model, that is it represents the model’s declarative memory. It has one buffer, the so called retrieval buffer. The declarative module reacts to requests to the module by searching through its set of chunks to find a chunk that matches the request. This chunk is then placed into the retrieval buffer.

The production rules of an ACT-R model are held in the procedural module. The procedural module does not have a buffer and it does not react to requests. The procedural module continuously checks the buffers of the other modules for patterns that match the conditions of some of the productions it holds. If it finds such a pattern the matching production rule is fired and the actions defined on the action side of the production rule are executed. Such actions usually modify the contents of buffers of

```
Car-023
  lane right
  lead-car yes
```

Fig. 11 An example of an ACT-R chunk that represents that there is a car on the right lane that has a lead car in front

```
IF the goal is to drive safe
  and you are driving on the left lane
  and there is a car in front of you on the right lane
  and this car is fast approaching the lead car on the right lane
THEN create the goal to provide space for this car on your lane
```

Fig. 12 An example of an ACT-R production rule that might represent a piece of procedural knowledge as part of a driving strategy that prioritizes safe driving

one or more modules. The procedural and declarative module are accompanied by a number of other modules, such as a visual module to process information from the visual field, a manual module to control motor skills, or a goal module to oversee and control objectives and intentions.

The internal structure and rules of the whole architecture are inspired by cognitive neuroscience and make ACT-R capable of validating experiments in cognitive science by matching human reaction times and predicting error rates and strategy choices [16, 56].

4.2 Modeling Decision Making in Cooperative Traffic Situations in ACT-R

As the starting point for an ACT-R model of cooperation in traffic we used the adapted decision making model of [81] depicted in Fig. 5 in combination with the basic ideas of theories of situation comprehension [6, 21]. In this chapter we can only sketch the main components of the assumed information processing steps of the first version of the ACT-R model of cooperation in traffic. These steps are depicted in Fig. 13.

As an empirical basis for the model development data and the experimental paradigm from previous studies with human participants [81, 83–87] were used. We designed a traffic simulation scenario in ACT-R identical to the one shown in Fig. 14. The ACT-R model is given the task to decide whether to accelerate, decelerate or maintain speed in dynamic scenarios with differing TTC values between the vehicles. In the visual field of the model, three visual objects are present: (a) the blue box representing the lane changer car, (b) the red block representing the slow truck, and (c) a virtual near point on the road in front of the egocar based on [73]’s model of gaze behaviour while driving. The model continuously moves its visual attention between the visual objects to gather relevant information about the situation. Visual information such as the indicator of the lane changer and the visual cues used for estimating the TTC values between the different vehicles are crucial in selecting the appropriate action for the given traffic situation. As can be seen in Fig. 13, perceiving these situational characteristics triggers a memory retrieval process by which a chunk representing a previously experienced comparable situation is retrieved. This corresponds to the recognition of familiar situations as described in the decision making model in Fig. 5. The retrieved chunk contains information about the possible development of the situation in the near future, and about the criticality that has been experienced in similar situations in the past. Consequently, based on this memory retrieval the model assesses the situation in terms of its criticality and whether an action has to be carried out to avoid a safety critical situation or whether no action is necessary. If the model comes to the conclusion that an action is required it selects the action that has led to a successful solution in the past and that is therefore connected to the retrieved situation representation. This process corresponds to the recognition based decision-making process as described in Fig. 5.

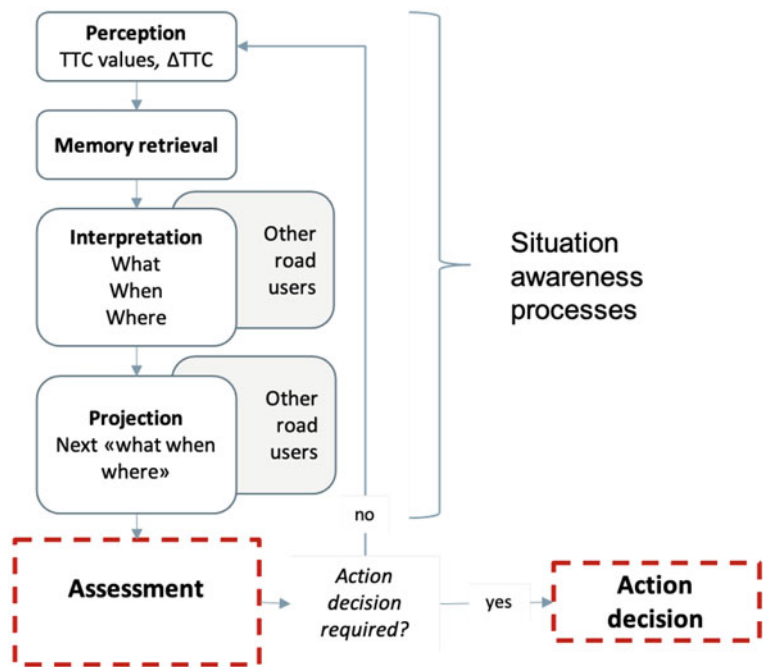


Fig. 13 Flow chart of the information processing steps of the first version of the ACT-R model for cooperation in traffic as described in [5]

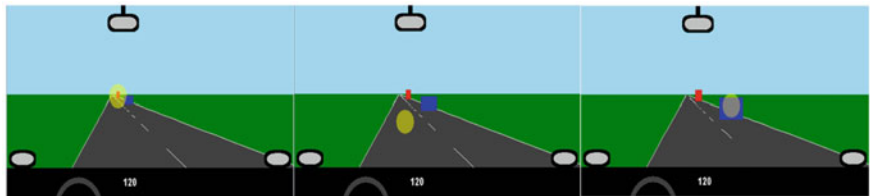


Fig. 14 The traffic scenario in the ACT-R simulation at different time stamps. The red rectangle represents the truck, the blue rectangle depicts the lane changer, and the yellow circle illustrates the location of the visual attention

To date, however, the necessary understanding of the role and underlying processes of criticality estimation and its integration into an understanding of the situation represented in a situational model of the driving situation has yet to be clarified to be able to model it precisely in ACT-R. The preliminary experiments conducted to validate the first model versions clearly show that the perception of the indicator status of the lane changer and the TTC values are crucial for the model's decision making. This is, of course, in line with the experimental data collected in the series of

experiments by Stoll and colleagues [81–87]. But the simulation data based on these first model versions also show that these situational characteristics are not sufficient to explain the observed behaviour. It became clear that, for example, the integration of assumptions about the other driver's perception and interpretation of the current situation and its projection into the near future into the situation representation of the driver on the left lane is necessary to be able to describe the observed behaviour of human drivers in such situations. In Fig. 13, this is represented by the grey boxes "Other road users" next to the "Interpretation" and "Projection" box. Filling these gaps and identifying general causal mechanisms underlying cooperation behaviour in a variety of driving situations are the goals of future studies on cooperation in traffic. Although the current studies in ACT-R are inconclusive to date, modeling the underlying psychological processes in ACT-R is a promising method to advance research on cooperation in traffic and to validate experimental results because it provides quantitative predictions of driver behaviour that enable robust hypothesis testing.

5 Conclusion

By focusing on road narrowings and lane changing, this chapter gives an overview on methods for data collection, subjective and objective measures of cooperation, factors influencing cooperation behaviour and behavioural and computational cognitive modeling to support the systematic research on cooperation in traffic. This overview is based on findings collected in studies conducted within CoInCar in the project CoMove. In this respect, the results on factors influencing human behaviour in cooperative situations, either in a manual or an automated setting, and initial findings from modeling the cognitive processes underlying cooperative driving behaviour are worth highlighting. This chapter illustrates that there is still a great need for research on cooperation in road traffic, which includes not only the manifold thematic research questions but also the methodological approach.

So far, there are only a small number of (scenario-specific) measures of cooperation and no standardized and established procedures to assess and measure cooperative behaviour. Coupled simulators are a promising method to investigate cooperative situations, but need further research on their behavioural validity. With respect to subjective measures of cooperation, the German version of the Prosocial and Aggressive Driving Inventory [27, 82] was successfully validated and an additional multidimensional questionnaire for the subjective evaluation of cooperation [68] was developed within the project. Both questionnaires now allow to assess cooperative traffic behaviour either in general or within a specific traffic situation. In addition, objective measures allow to quantify different aspects of cooperation, for example the temporal and spatial proximity, costs and benefits, and the dynamic interplay of road users, but their reliability and validity have yet to be confirmed. In particular the last aspect, the dynamic interplay, requires further measures in order to systematically describe cooperation. In this regard, within CoMove we have been able to

develop measures, at least for road narrowings, that allow us to quantify the arrival order of drivers [67].

In a series of highly controlled experiments various situational characteristics have been identified that influence drivers' decision making in dynamic cooperative situations. The results indicate that, besides others, the perceived criticality of the situation, the available scope of action, and the assumed planned actions of the interaction partner asking for cooperation clearly influence the decision-making process of the driver being asked for cooperation. The empirical results also show that there is a clear overlap between actions chosen by drivers when driving manually and which actions of an automation are preferred in cooperative situations. But this overlap is not complete and the origin of the differences has still to be explained in order to create automation behaviour that is accepted by human drivers.

The results of the first versions of an ACT-R model of cooperative behaviour in traffic show that considering the situational characteristics of a cooperative situation is important but definitely not sufficient to explain human cooperation behaviour in traffic. Clearly, the driver's assumptions about the situation understanding of the cooperating partners and their likely goals and action plans are strongly influencing the driver's own decision making in these situations. This becomes very clear when one considers the effects of situational elements that provide information about the future development of the situation or the cooperating partners' intentions. The first one was investigated via a HMI that highlights situational elements that should support different levels of situation understanding. The results clearly showed that it is the support of the projection that has the greatest effect on triggering cooperative behaviour. In the same sense, basically all empirical studies, in which indicator usage was manipulated, showed a significant effect on action selection of the indicator. This supports the importance of understanding the cooperating partner's intention for the selection of one's own behaviour in cooperative situations. Building a computational cognitive model of the underlying psychological processes is associated with many both theoretical and technical challenges, but offers a great potential both for the theoretical progress and for integrating behaviour into technical systems, such as the vehicle automation, that is accepted and trusted by humans as it considers human-like behaviour preferences.

In much more cases than we as psychologists and human factors specialists would wish, we have to admit that there is not enough empirical knowledge available, the available knowledge is too vague or our theories are not precise enough to provide the basis for the precise statements that are required when building such computational models. But exactly this requirement for precise theories make the existing gaps visible and help to fill this gaps by dedicated and theory-driven experimental studies. And the prize to win with such modeling is that the huge amount of empirical results that was collected in the past and will be collected in the future becomes available for the integration into technical systems as this knowledge is condensed and transformed into computational models that can be used by engineers and computer scientists to inform their automation algorithms. The vision is that this leads to technical systems, such as cooperatively interacting vehicles, that then behave in way that is accepted

and trusted by human road users as they possess an executable knowledge about human preferences, goals and needs.

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