Cooperation Behavior of Drivers at Inner City Deadlock-Situations

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Abstract In urban traffic, there are several situations in which the right of way is not regulated. For automated vehicles in mixed traffic to show behavior that is considered acceptable by all parties, the cooperation behavior of drivers in these situations must be understood. An observational study identified several behaviors in these situations at equal narrow passages and T-intersections that can be classified as offensive and defensive. These behaviors were tested in an experiment whether they can communicate the intention to drive or to stop. Drivers respond to defensive behaviors of the cooperation partner by continuing to drive, and stopping when the behavior is offensive. In the equal narrow passage, drivers felt safest when they drove first, whereas at the T-intersection, drivers felt safest when the cooperation partner drove first. In further experiments, it was shown that at T-intersections the entry position has an influence on whether drivers drive first or stop. Pedestrians or other traffic do not have an influence on the behavior. However, if drivers follow a vehicle that is driving ahead of them, they drive first through the deadlock situation. Recommendations for the behavior of automated vehicles in these situations are derived from the findings of the studies.

1 Introduction

The introduction of highly automated vehicles in the coming years holds great potential for road safety [44]. Nevertheless, potential problems can also arise, especially in mixed traffic of manual and automated vehicles. This is particularly critical in inner-city traffic, for example at intersections, where there is a higher risk of accidents [38]. These critical situations include situations that are not clearly regulated by road traffic regulations. Here, the behavior of other road users must be predicted in each case in order to then cooperate adequately. These deadlock situations occur, for example, at equal narrow passages or T-intersections with a certain constellation of road users (Fig. 1). Here, none of the drivers has the right of way and the situation

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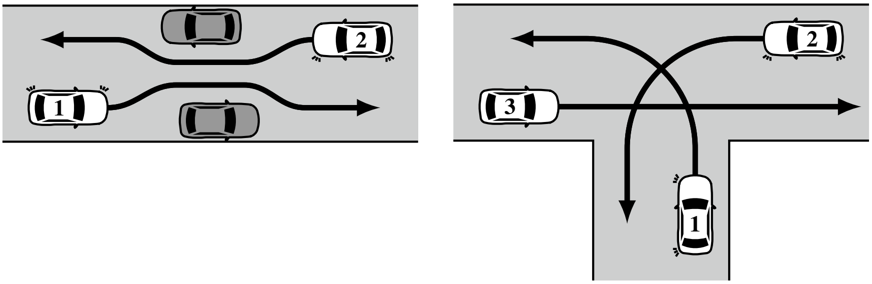


(a) equal narrow passage (b) T-intersection

Fig. 1 Examples of deadlock situations

must be resolved by cooperative behavior. In this case, an automatic vehicle guidance must also be able to solve the situation cooperatively and recognize the intention of the manual drivers. At first glance, the safest solution would be for the automated car to stop and allow the other road users to drive first [9]. However, this behavior is not necessarily the most comfortable and accepted behavior. For example, if another road user is driving defensively and wants to yield the right of way, it would cause a complete stillstand. This undesirable and possibly unexpected behavior could degrade the acceptance of automated vehicles by both the passenger and interaction partner. In order to cooperate successfully, it is necessary to correctly classify the behavioral decisions of other road users and to be able to predict the intention of the other driver. If the behavior of the other person is not correctly anticipated, this can lead to unsuccessful cooperation, which in turn can lead to conflict [42]. In deadlock situations, it is therefore necessary for both manual drivers and automatic vehicle guidance to recognize the intention of the other in order to resolve this situation successfully. The intention of the other can be recognized by communication signals. Therefore, the first goal of our project was to understand the communication of drivers in the two presented deadlock situations and thus to be able to predict the intention of the drivers. Since one of our findings was that the complexity of the situation could affect cooperation behavior, as a second step, the influence of complexity in the sense of the presence of other traffic participants on cooperation behavior was investigated. Based on the findings, recommendations for the behavior of automated vehicles can be derived.

The chapter is structured as follows: First, an overview of the theoretical background of communication in road traffic is given. Then, two studies are described that examine communication in deadlock situations. Furthermore, the theoretical background on the influence of other road users on driving behavior in the context of complexity and the conducted studies are described. Finally, recommendations are given for the behavior of automated vehicles in deadlock situations.

2 Communication in Road Traffic

Communication is a necessary requirement for successful cooperation [29]. According to Hoc [15], cooperation occurs when two agents interfere on goals or resources and try to manage these interferences to facilitate each individual goal. Because communication is also necessary for cooperation, no cooperation takes place when two road users meet briefly on a road from the oncoming direction, for example. The same resource is shared, but communication does not take place [23]. In contrast, the two deadlock situations to be investigated fulfill the requirements of a cooperative situation. All road users need to use the same part of the road and need to communicate in some way to resolve this situation without conflict by agreeing who will drive first. Drivers must effectively communicate with each other so that they can understand and predict each other's intentions and actions. If this is not successful, the situation cannot be understood correctly and thus the drivers cannot react appropriately in the situation [23]. Furthermore, the way in which drivers communicate with each other can have an influence on their decisions to act [49]. Since the communication of the intentions is essential in these cooperative situations, it is important to understand how drivers communicate.

In general, communication is understood as the exchange of information. A sender transmits a signal or message to a receiver who is intended to get this information [36]. The challenge in transmitting the information is to ensure that the signal sent arrives correctly at the receiver [35]. A characteristic of human communication is that both verbal and nonverbal channels can be used. Nonverbal communication through gestures and body language can be used for very fast communication [29] and can also initiate, coordinate, or be used to avoid cooperation [5]. However, these general findings of communication cannot be fully applied to communication in road traffic. Road traffic is a volatile system in which situations can be dynamic and very complex. In order to cope with the complexity of situations in road traffic, road users apply schemata in which behavior is concluded from road user characteristics or they signal the expected action to other road users. A different strategy is to wait in a situation and first gather as much information as possible about it or to follow the actions of other road users [30]. Another limitation in road traffic is the limited options for communication, which can lead to misunderstandings [41], as communication is limited to the nonverbal level and is also anonymous [30]. Furthermore, drivers cannot escape the situation. This means that any actions at any time can be interpreted by others as a communication signal. It can thus lead to both intentional and unintentional communication in road traffic [3]. In the context of everyday communication, the axiom of Watzlawick, Bavelas, and Jackson [46] is applicable here, which states that one cannot not communicate. Since there is always communication, it can further be divided into explicit and implicit communication. This division can also be assigned to the different driving tasks according to Geiser [13]. Here, the driving task is divided into three subtasks. The primary driving task includes navigation as well as maneuvering and stabilizing the vehicle. The secondary driving task supports the primary driving task and mainly serves to inform other road users and to react to environmental conditions. This includes, for example, using the indicator or the headlight flasher. The tertiary driving task is independent of the actual driving task and serves primarily to increase comfort by, for example, operating the air conditioning or radio. It can be concluded that the implicit communication through the driven trajectories falls under the primary driving task, while the explicit communication belongs to the secondary driving task. According to this categorization, implicit communication always takes place, while explicit communication is always just an additional form of communication that can support implicit communication.

Communication in road traffic can only take place non-verbally and this can be a challenge. Different areas of non-verbal communication can be distinguished [1, 9, 33]: Facial expression and eye contact, gestures and body movements, voice and manner of expression, spatial behavior, and technical signals. Merten [30] proposes the thesis that without eye contact no communication can take place in road traffic. However, Witzlack, Beggiato, and Krems [48] showed that eye contact is often overestimated in driver-pedestrian interactions. Eye contact only served as confirmation and is thus not a necessary requirement. Moreover, in mixed traffic, eye contact would not be helpful under certain conditions, for example, when the driver of the automated vehicle is looking at the traffic but is not involved in the driving task [9]. Among the most commonly used gestures are gestures indicating to other road users that they should slow down, that they can or should drive, and that the driver's own right of way is being yielded [9].

Kitazaki and Myhre [25] showed that at intersections, using a hand gesture combined with the vehicle behavior showed larger effects on the drivers' anticipation of intention and therefore decision compared with the vehicle behavior alone. Possible technical signals that drivers can use include the turn signal, horn, headlight flashers, and hazard warning lights [33]. Ba, Zhang, Reimer, Yang, and Salvendy [2] investigated these explicit signals (with the exception of the headlight flasher) for different traffic situations. They found that drivers prefer when the other driver uses an explicit signal. However, even without an explicit signal, subjects can recognize the intention of drivers. Lee and Sheppard [26] showed subjects both pictures and videos of a vehicle approaching an intersection that would either continue straight or turn. The vehicles used a valid or invalid turn signal. Even though the subjects were better to judge the behavior of the vehicle when it gave a valid signal, in most cases they were also able to correctly judge the behavior despite the invalid signal. Thus, the explicit signal is helpful to estimate the intention of a driver, but not necessary. This is also supported by the finding that the intention could be better estimated in the videos than in the pictures. Drivers therefore also use the dynamic behavior of the vehicle, such as the braking behavior, to estimate the intention.

When looking at all these explicit signals, it becomes clear that they cannot be used alone, but only in combination with other signals. This is especially true for spatial behavior, since the driver is moving on the road at all times and thus the driven trajectory can be interpreted as a communication signal at any time. The driven trajectory from lateral and longitudinal driving behavior is considered to be implicit communication. In some situations, this is even more meaningful than the explicit signals [48]. Especially longitudinal behavior, i.e. approaching, is used for intention detection. For example, when changing lanes, deceleration behavior, speed reduction, and reaction speed in particular are used as indicators of cooperative behavior [24]. At intersections, when the other driver maintains speed or accelerates, drivers expect the other to proceed through the intersection. In contrast, when slowing down, the vehicle is expected to yield and stop [4].

Implicit behavior is especially interesting for automatic vehicle guidance to predict the intention of other road users. One reason for this is that it is technically easier to interpret implicit behavior rather than explicit signals, which may not be used consistently, especially in situations that are not clearly defined, such as deadlock situations. In mixed traffic, it is crucial that both automated vehicle guidance and human drivers are able to recognize each other's intentions. This is especially true in deadlock situations, where the intention must be anticipated in order for the situation to be resolved. Since intentions can be communicated via both explicit and implicit signals, an automatic vehicle guidance system must be able to interpret both in order to react appropriately. At the same time, it should also be able to use the signals itself to display behavior that the human cooperation partner expects. There has not yet been sufficient research on how intentions are communicated and which combination of possible signals is used in deadlock situations. In a first step, the use of communication signals at intersections and equal narrow passages was investigated.

2.1 *Observational Study*

The aim of the observational study [17] was to identify cooperative behavior, to classify it into offensive and defensive behavior, and to derive behavioral sequences from the behavioral patterns. For this purpose, a T-intersection and an equal narrow passage in Karlsruhe (Germany) were each observed for five hours by two and three trained observers, respectively. The behavior of the cooperating drivers were recorded: the order of arrival and departure, the direction of driving (right, left, straight ahead), driving behavior (acceleration, deceleration, stopping, maintaining speed), and explicit signals (turn signal, horn, gesture). Analysis of individual gestures as well as the recording of drivers' gaze direction was omitted, as this is difficult to observe and technical aids could not be used for data protection reasons. The observations of the individual observers were combined afterwards in order to extract behavior sequences for the individual situations.

A total of 33 events with 12 different traffic situations could be observed at the T-intersection. The results of the observation showed that explicit communication plays a minor role. In fact, 71 implicit signals were observed in contrast to only 32 explicit signals. Of these explicit signals, the indicator was mostly used to indicate turning. Of the behaviors, defensive behaviors such as stopping and braking were more frequently exhibited than offensive behaviors such as accelerating or maintaining speed. In particular, left-turning was associated with a defensive behavior pattern, while right-turning showed more offensive behavior. For the deadlock situation at the T-intersection, six different situations could be observed. These could be classified into defensive and offensive behavior patterns and were used in the following experiment (see Sect. 2.2).

At the equal narrow passage, 40 events could be registered. As at the T-intersection, the observation showed that explicit communication takes a minor role compared to implicit communication. The most frequently used explicit signal was the headlight flasher. When drivers arrived first at the narrow passage but drove second, defensive behaviors were mainly exhibited and they stopped. Conversely, drivers who arrived second at the equal narrow passage but drove first could be observed to exhibit mainly offensive behaviors such as maintaining speed and accelerating. Our findings from the T-junction and equal narrow passage suggest that implicit communication plays an important role in deadlock situations in order to be able to recognize the intentions of the other drivers. Furthermore, behavioral sequences can be classified well into offensive and defensive behaviors.

2.2 Experiments

The behaviors identified in the observational study were further examined in two experiments to test whether they are suitable for conveying intention and whether it is possible to determine from the behaviors whether drivers want to drive or stop in deadlock situations. For this, subjects drove a test vehicle on a traffic training area through a deadlock situation at an equal narrow passage [19] and a T-intersection [20] (Fig. 2). The cooperation vehicles in these situations were driven by one respectively two instructed examiners, who followed predefined behavior scripts. These behaviors were intended to convey the intentions to drive or not drive and to represent offensive or defensive behaviors. For the defensive behavior, the examiner was to stop and let the subjects drive first. For the offensive behavior, on the other hand, the examiners were asked to drive through the equal narrow passage or T-intersection first, if the subject's behavior allowed. For both the equal narrow passage and the T-intersection, six different situations were presented, each with three offensive and three defensive

Fig. 2 Deadlock-Situation at the T-intersection during the experiment at the traffic training area

Table 1 Approaching behaviors of the examiners at the T-intersection [20]. The number of the examiner describes the position in the T-Intersection (see Fig. 1)

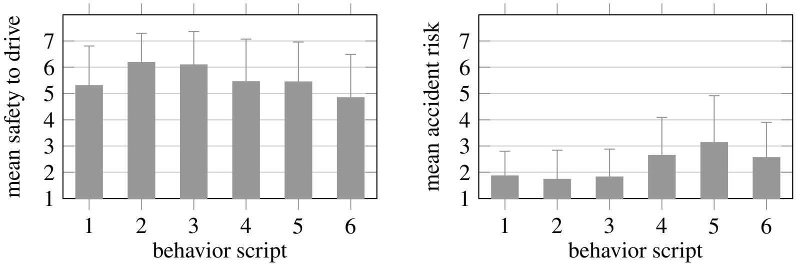
Situation	Behavior classification	Behavior
1	Defensive	Examiner 3 decelerates, stops, uses flasher Examiner 1 or 2 indicates and stops
2	Defensive	Examiner 3 decelerates and stops Examiner 1 or 2 indicates and stops
3	Defensive	Examiner 1 or 2 decelerates and indicates Examiner 1 or 2 decelerates, indicates, uses flasher
4	Offensive	Examiner 3 maintains speed Examiner 1 or 2 indicates and decelerates
5	Offensive	Examiner 3 decelerates Examiner 1 or 2 indicates and decelerates
6	Offensive	Examiner 1 or 2 decelerates and indicates Examiner 1 or 2 indicates, decelerates, uses gesture

behaviors. Each situation was driven through twice, resulting in a total of 12 runs through the intersection or equal narrow passage for each subject. For the equal narrow passage, the defensive behaviors of the examiners were: 1. stopping distinctly, 2. braking to a speed of 15km/h and using the flasher, 3. stopping distinctly and using the flasher. The offensive behaviors were: 1. maintaining speed, 2. accelerating, 3. braking to 15km/h and continuing to drive toward the equal narrow passage. The behaviors of the examiners for the T-intersection are shown in Table 1.

After driving through all situations, subjects were shown video clips of their driving and asked to rate how confident they were to drive first or second, how high they perceived the risk of an accident and the willingness of the involved drivers to cooperate. During the drive, the CAN bus data of the test vehicle were also recorded, as well as the eye movements of the subjects using an eye tracker. The results of these data can be found in [18, 21]. In total, the experiments lasted approximately 90 min. For the equal narrow passage, 22 subjects (21 males, average age $M = 23.91$, $SD = 2.10$) were surveyed, for the T-intersection 20 subjects (18 males, average age $M = 23.35$, $SD = 3.51$).

2.2.1 Results and Implications for the Situation “Equal Narrow Passage”

For the equal narrow passages, defensive behaviors by the examiners resulted in a significantly higher probability of subjects driving first rather than stopping. For defensive behaviors 1 and 2, the subjects had a probability of 83% to drive first through the equal narrow passage, for behavior 3 the value was 75%. For the offensive behaviors, the probabilities of driving first were significantly lower at 31% (behavior pattern 4), 35% (behavior pattern 5), and 9% (behavior pattern 6). Furthermore, for the



(a) perceived safety

(b) perceived accident risk

Fig. 3 Perceived accident risk and safety to drive for the different behavior scripts at the equal narrow passage

different behaviors, there were significant differences in how confident the subjects were in driving first or second ($F(1, 3.426) = 4.42$, $p < .05$). They felt the safest when the cooperative vehicle braked and flashed its lights (defensive behavior). In contrast, they felt least safe when the oncoming vehicle slowed down from 30 to 15 km/h (offensive behavior) (see also Fig. 3a). The perceived accident risk also differed significantly between the different behaviors ($F(1, 3.221) = 6.942$, $p < .001$) (Fig. 3b). In particular, when the cooperation vehicle accelerated before the equal narrow passage, the accident risk was perceived to be significantly higher compared to the defensive behaviors. For the perceived willingness to cooperate, there were significant differences between the behaviors, $F(1, 5) = 14.096$, $p < .001$. Defensive behaviors of the cooperation partner were perceived to be more cooperative than offensive behaviors. Perceived willingness to cooperate further influenced whether subjects would drive first or yield the right-of-way to their counterparts. When perceived willingness to cooperate is considered very low, the probability of driving first decreases significantly even for the defensive behaviors. For the offensive behaviors, the probability of driving first increases accordingly if the behavior is perceived as cooperative.

Overall, the results of the study show that all six behavior patterns produce the expected behavior in the cooperation partner and are therefore also suitable for producing a desired behavior in a certain situation. An important requirement is that the behavior is perceived as cooperative. This works very well with behavior pattern 2, for example, braking with the headlight flasher. Here, the behavior is perceived as cooperative, the drivers drive first with a high probability, and are very confident in their decision to do so. Thus, this behavior seems to be suitable for automatic vehicle guidance at an equal narrow passage. Behavior 5, acceleration, on the other hand, also shows the expected behavior: the drivers stop and let the other person drive first. With this decision, they also feel safe. However, this behavior is not perceived as cooperative. Since automatic vehicle guidance should probably be perceived as cooperative in order to be accepted, such behavior would likely be inappropriate for automatic vehicle guidance.

2.2.2 Results and Implications for the Situation "T-Intersection"

As in the case of the equal narrow passage, the different behavior patterns of the cooperation partners showed a significant influence on whether the subjects drove through the T-intersection first or gave way to one of the other two vehicles. For defensive behaviors 1 and 3, the probabilities of driving first were relatively high at 58% and 74%, respectively. Defensive behavior 2, on the other hand, failed to produce the expected behavior. Here, the probability of driving first was only 5%. The offensive behaviors showed lower probabilities to drive first with 56% (behavior 5), 8% (behavior 4) and 30% (behavior 6). The increased probability of behavior 6 may have been due to the fact that some subjects thought they were driving on a main road. Thus, with the exception of one behavior, a desired behavior can be achieved among drivers at a T-intersection, similar to the equal narrow passage. Subjective evaluations of the situation also showed differences between the different behavior patterns. For the offensive behaviors, subjects were significantly more confident with their decision to drive than for the defensive behaviors ($\chi^2(5) = 621.776$, $p < .001$). Additionally, the order in which subjects drove through the intersection had an influence. When subjects drove second or third, they were significantly more confident in this decision than when they drove first. There was also a significant difference between behaviors for perceived cooperativeness ($\chi^2(5) = 5.190$, $p < .001$). The offensive behaviors were rated less cooperative than the defensive behaviors. The accident risk, on the other hand, is estimated to be the same for all behaviors. A possible reason for this could be that in many cases the vehicles were in a standstill, thus minimizing the objective risk of accidents. In addition, this experiment aimed to investigate whether the subjects themselves gave explicit signals. Explicit signals were used in only 42 of the 240 cases. It is noticeable that half of them were given to the right cooperating partner, i.e. the one who has the right of way over the subject anyway according to the road traffic regulations. This could be an indication that the deadlock situation is sometimes not correctly understood and that accordingly no adequate strategy is used to resolve the situation.

2.2.3 Conclusion from the Experiments

In summary, both at the equal narrow passage and at the T-intersection, certain offensive as well as defensive behaviors influence the behavior of drivers, i.e. whether they stop in a deadlock situation or drive first. There is an interesting difference in terms of perceived safety for driving: subjects rate their confidence of driving at the equal narrow passage higher when the cooperation partner shows defensive behavior. In contrast, at the T-intersection, confidence of driving is rated higher when the cooperation partners show offensive behavior. In other words, it can be concluded that drivers prefer to drive first themselves at the equal narrow passage, while they prefer to give way to other vehicles at the T-intersection. One difference between the two situations is their complexity. At the equal narrow passage, only one lane needs to be considered and there is only one cooperation partner, making it a relatively simple situation. In contrast, at the T-intersection, two lanes and two cooperation partners must be considered. Therefore, it is apparent that in more complex deadlock situations, drivers prefer not to drive first. Following this logic, drivers should show different cooperation behavior within the same situation, which differs only in its complexity. This was further investigated using the deadlock situation at the T-intersection.

3 Complexity and Driving Behavior

In order to examine the effects of different aspects of complexity on cooperation behavior at deadlock situations, it is useful to look at the definition of complexity in the context of road traffic as well as its effects on drivers' behavior. The influence of complexity on driver behavior and workload has been studied for a variety of situations, but not for cooperation behavior at deadlock situations. Additionally, there is no precise consistent definition or operationalization of complexity among these studies. A basic classification of traffic situations in terms of their complexity was established by Fastenmeier [10]. According to him, the task complexity of traffic situations results from the demands on information processing and vehicle handling. Faure, Lobjois, and Benguigui [11] used this classification to measure the subjective and objective mental workload of drivers. They classified driving on the highway with low demands on both information processing and vehicle handling, driving in rural environment with high demands on vehicle handling and low demands on information processing, and an urban environment that is visually rich with buildings, street furniture, traffic lights, intersections and roundabouts with high demands on both information processing and vehicle handling. Driving on the highway showed the lowest mental workload according to both the subjective ratings of the participants as well as eyetracking and steering wheel parameters. The results for rural and urban environment were not quite as expected. Although the subjective workload was higher for the urban environment, the eyetracking and steering wheel parameters indicated a higher workload for the rural environment. A possible explanation according to the authors is that there were only few intersections or roundabouts on the urban roads and thus the demands on vehicle handling were low. In contrast, on the rural roads there were many sharp curves, which resulted in very high demands on vehicle handling. Similarly, Oviedo-Trespalacios, Haque, King, and Washington [31] found that sharp bends on roads increase task demands and drivers therefore adapt their speed more compared to straight roads. Another reason given by Faure et al. [11] is that there were no other road users in their urban environment and therefore little information processing was required. This is in contrast to the results of Oviedo-Trespalacios et al. [31], who showed that in urban areas a greater speed adaptation takes place due to higher demands compared to suburban areas, even if in both no other traffic is present.

Jahn, Oehme, Krems, and Gelau [22] also used Fastenmeier's [10] classification, but interpreted it differently from Faure et al. [11]. Like Faure et al. [11], they classified highway as a situation with low demands on information processing and vehicle handling. In contrast to Faure et al. [11], however, they classified a rural environment and urban environment without interactions with other traffic with low requirements on both dimensions. According to them, only city centers and complex intersections are situations with high requirements for information processing and vehicle handling. They also found the expected differences in mental workload between these two differently defined complexity groups. However, since Faure et al. [11] also found differences between highway and rural environment, this division is apparently not sufficient. Patten, Kircher, Östlund, Nilsson, and Svenson [32] used another group in addition to the two groups of low and high demands: they defined situations with high demands on information processing and low demands on vehicle handling and vice versa, such as intersections regulated by traffic lights or by road signs where the driver has the right of way. Compared to the situations with low demands in both categories, drivers who do not drive much showed significantly longer reaction times for a peripheral detection task and thus higher workload in these medium situations, but not drivers with high mileage. The latter, on the other hand, showed worse performance in the high demand situations compared to the medium demand situations. Driver experience thus also appears to play a role in how different situations affect drivers. Overall, these studies with the different classifications of complexity and results show that the classification according to Fastenmeier [10] into different traffic situations is not sufficient in that way and can only give a first indication of the complexity. Instead, the exact specific conditions within these situations must also be defined, as these can have a direct influence on driver behavior.

Törnros and Bolling [45] showed this for the urban environment. They found that reaction time of drivers in a complex urban environment is higher than in a medium or low complex urban environment. The high complex urban environment was thereby described with buildings on both sides, pedestrian tracks, car and pedestrian crossings, parked cars and busses. The medium and low complex urban environments, on the other hand, featured only some traffic, parked busses and were residential areas. Drivers also show lower speed and higher subjective ratings of mental workload when driving on streets where buildings and shops are located directly to the sidewalk compared to streets where the buildings are set far back from the road [34]. The same can be shown for areas where cars are parked at the roadside compared to streets with no parking spaces or empty parking spaces [8]. The amount of visual information a driver pays attention to seems to have an influence on behavior. At intersections with more visual information (vehicles, pedestrians, stores, construction site) drivers reduce their speed. On the highway with a lot of visual information (advertisements, billboards, buildings, highway furniture), drivers do not estimate their subjective mental workload higher than for stretches of road with little visual information, but do decrease their speed here nonetheless [16], indicating that there is an effect of those visual information on drivers.

Other road users themselves have an effect on drivers' behavior and workload. For example, traffic congestion causes drivers to behave more aggressively in the section after the congestion than if they had not driven through any congestion [27]. Individual road users also influence drivers. When a vehicle is in front of their own vehicle, drivers adjust their speed more than when they are free to drive on the road [31]. In turn, overtaking a vehicle in front also leads to an increased workload compared to driving freely [6]. Traffic density also has a negative impact on the workload of driving. This is true for both driving on the highway [43] and at intersections [28].

To the authors knowledge, up to now, the influence of complexity on cooperation behavior and especially on deadlock situations has not been studied. Since the studies presented so far only give an indication of the influence of complexity on general driving behavior and, as described, do not provide a comprehensive description or definition of complexity, the task-capability model of Fuller [12] was considered. According to this model, driving behavior can be explained in terms of task difficulty. This is composed of the relative proportion of task demands on the driver's capability. The task demands can have both information input and response output character. The incoming information of the task demands includes a variety of factors such as operational characteristics of the vehicle, route choice, environmental characteristics and other road users. Task demands in the sense of output factors are the driver's own behavior, i.e. speed and trajectory. The capability includes knowledge and skills arisen from training and experience, the mental representation of the situation as well as physiological characteristics like information processing capacity or reaction time. The task difficulty then results from the task demands and the capability, for which in turn each driver has an individual range that they accept. If this threshold is exceeded, compensatory actions are taken to reduce the task difficulty. This is usually done by reducing the speed, i.e. an output function of the task demands. Applied to cooperation behavior at deadlock situations, this would imply that compensatory actions should be taken in more difficult deadlock situations and that drivers should therefore stop rather than proceed through the intersection or equal narrow passage first.

The environmental factors according to Fuller [12] are not broken down in detail. Since this can be essential for describing a situation as described above, the classification of visual clutter according to Edquist [7] was further considered. This concept is closely related to that of task difficulty, but offers a further breakdown of the relevant factors. The visual clutter is divided into objects that must be attended for safe driving and objects that distract from safe driving. The latter, together with the background complexity, are called built clutter and refer, for example, to stores, advertising or infrastructure such as light poles. The objects that must be observed for safe driving can be further subdivided according to this taxonomy. Road markings, traffic signs or signals are referred to as designed clutter. The situational clutter consists of vehicles, cyclists and pedestrians. For the deadlock situation in the present study, the influence of other vehicles and pedestrians on the perceived visual clutter as well as the perceived difficulty was investigated. In addition, the position from which the intersection is entered was considered. At intersections, it has an impact on the workload whether drivers drive straight ahead or turn. This difference was implemented in the methodology of the experiment described above for communication at deadlock situations [20]. Yet, it was not distinguished from where the drivers approached the intersections. However, this position also has an influence on the driving behavior

Fig. 4 The screenshot of a video used in study 1 shows the approach from entry position left with a vehicle in front of the ego vehicle

[14], which is why the entry position to the intersection was additionally taken into account in the following experiments.

3.1 Experiments

To investigate the influence of entry position of the T-intersection and complexity in a controlled setting, two online studies [39, 40] were conducted with 30 and 34 subjects, respectively. The subjects were shown videos of the approach to T-intersections from the driver's perspective, which were created using the driving simulation software SILAB 6.5 (see Figs. 4 and 5). All three possible entry positions to a T-intersection were shown. The two cooperation vehicles as well as the own vehicle decelerated before the intersection and came to a stop at the intersection. One second before this, the videos were cut off so that the situation had not yet been resolved. The subjects were then asked to state how likely they themselves would then be to drive through the intersection first in this situation. In addition, they were asked to rate the perceived difficulty and visual clutter. In study 1 [39], it was varied whether a vehicle passed through the intersection in front of the ego vehicle, whether other vehicles were traveling behind the cooperation vehicles at the intersection, and whether other traffic was seen during the approach to the intersection. Study 2 [40] examined the influence of pedestrians. For this, the number of pedestrians walking on the sidewalk was varied (none, 20, 80). In addition, it was varied whether the pedestrians were walking close to the front of the house or street as well as a barrier separating the sidewalk from the street.

3.1.1 Results

Across all situations, the probability of driving first was relatively low at 24% in both study 1 and study 2 (Fig. 6). The entry position had a significant effect on

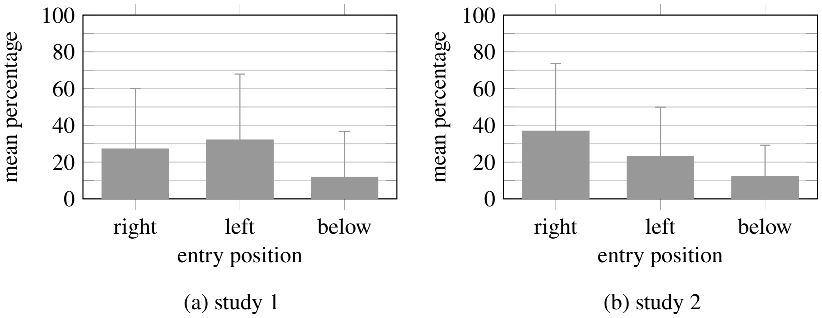
(a) many pedestrians with a barrier

(b) few pedestrians without a barrier

Fig. 5 The screenshots of videos used in study 2 show the approach from the left for two different scenarios

whether subjects would drive first through the T-intersection or not (study 1: $\chi^2(2) = 88.14$, $p < .001$; study 2: $F(2, 776) = 64.35$, $p < .001$). When drivers approach from below, the intention to drive first is lowest. Study 2 additionally showed a significant difference between entry positions left and right. The lower probability when approaching from below could be an indication that the deadlock situation was not recognized correctly and that the straight-through road was possibly interpreted as a priority road. This was also the case for some subjects in the previously described study at the traffic training site [20]. In addition, Björklund and Åberg [4] were able to show that this main road effect exists at intersections (however, they did not consider deadlock situations). If one were to assume such a main road effect exists also in deadlock situations, one would expect that drivers from entry position left would drive first, since this would be in accordance with the right-of-way rule of a main road. However, this is not evident in the data from either study. In study 1, there are no differences between the entry positions left and right. In study 2, there is even a higher probability of driving first from entry position right compared to left, i.e. an opposite behavior to the right-of-way rule on a main road. Overall, therefore, there seems to be no accurate understanding of the deadlock situation. An automated vehicle must therefore be aware that manual drivers may think they have the right of way at a deadlock situation. The prediction of the intention through the displayed behavior then plays a special role.

The perceived difficulty of the situation does not differ between the three positions. For the assessment of the visual clutter, however, there are significant differences for the different entry positions (study 1: $\chi^2(2) = 13.461$, $p = .001$; study 2: $\chi^2(2) = 13.58$, $p = .001$). When approaching from below, visual clutter is rated



(a) study 1

(b) study 2

Fig. 6 Probability to drive first through the T-intersection for study 1 and 2

higher than from the other positions; in study 2, visual clutter is also rated higher when approaching from the right compared to the left. This is against the expectation according to Edquist (2008) that drivers should show a lower probability to drive first in situations with high visual clutter. The entry positions below and right were both rated with higher visual clutter than the position on the left. Nevertheless, for these two positions different tendencies for the probability to drive first can be seen: For the position below, a lower probability of driving first is shown, whereas for the position on the right, a higher probability of driving first is shown than for the position on the left. Again, a lack of or incorrect understanding of the situation could be an explanation. Overall, it can be concluded from these results that both perceived difficulty and visual clutter do not seem to be adequate to explain or predict cooperative behavior in deadlock situations.

Situations with no pedestrians (27%) showed on a descriptive level a slightly higher probability to drive first than those with few (24%) or many pedestrians (23%), but this difference was not significant. The zone in which pedestrians walked as well as the barrier did not affect the subjects' indicated behavior. As with the different entry positions, there were no differences in perceived difficulty. For the visual clutter, however, differences could be observed. The presence of many pedestrians increased the perceived visual clutter of the situation in contrast to situations with no pedestrians. However, since the pedestrians had no influence on the cooperation behavior, it can also be assumed that there is no correlation between behavior and visual clutter in deadlock situations.

A vehicle passing through the intersection before one's own vehicle increased the probability that drivers themselves would be the first to pass through the intersection. Further traffic, on the other hand, had no influence. When considering additionally the perceived difficulty and visual clutter, an interesting pattern emerges. A vehicle ahead significantly increases both the difficulty and visual clutter of the situation. In this more difficult and more cluttered situation, the probability of driving through the intersection first increases. The effect of position, on the other hand, showed the opposite pattern. Here, situations that were rated higher in visual clutter showed a lower probability of being the first to drive through the intersection. These results support two findings: First, the concepts of visual clutter and difficulty are not effective in explaining or predicting drivers' cooperation behavior in deadlock situations at T-intersections. Since the complexity of intersections without deadlock can contribute to predicting certain behaviors [47], this seems to be exclusive to deadlock situations. This in turn supports the second finding: deadlock situations do not seem to be comprehended sufficiently or there seems to be an uncertainty about how to proceed in such situations. In an uncertain situation, where one is not clear how to behave, the behavior of others is imitated [37]. This is precisely what can be observed in the deadlock situation: In a situation that is perceived as more difficult, subjects follow the vehicle in front, thus imitating the behavior of another road user.

4 Conclusion

The aim of the work was to better understand the cooperation behavior of drivers in deadlock situations in inner city traffic, so that automated vehicles can show cooperation behavior in mixed traffic of automated and manual vehicles, which is similar to that of humans and thus is accepted by all involved parties. To identify the communication behavior that drivers exhibit in these situations, an observational study was conducted, and these observations were then further investigated in an experiment. In addition, building on the findings from the experiment, video studies were conducted in which the influence of complexity, in this case other traffic and pedestrians, as well as the entry position of the T-intersection was investigated.

The observational study showed that drivers communicate at intersections and equal narrow passages primarily through implicit signals, that is, driving behavior. Explicit communication, on the other hand, plays only a minor role. Of the explicit signals, the headlight flasher was most often used as a sign of defensive behavior, especially at the equal narrow passage. For deadlock situations at both T-intersections and equal narrow passages, several behaviors could be observed that can be classified into offensive and defensive behaviors. These were tested in an experiment to find out whether these behaviors can communicate the intention to drive or stop, and if drivers adjust their behavior accordingly. In both situations, participants showed a higher probability of stopping when the cooperating partner showed offensive behavior. In contrast, when the cooperating partner showed defensive behavior, they were more likely to drive first. Thus, in deadlock situations, drivers are able to recognize the intention of the other person based on his or her behavior and behave accordingly.

A difference between the T-intersection and the equal narrow passage can be seen in the subjective evaluation. At the equal narrow passage, drivers feel safest when the cooperating vehicle shows defensive behavior, and they themselves can drive first and least safe when the cooperating vehicle shows offensive behavior. At the T-intersection, on the other hand, the opposite picture emerges. For the offensive behaviors, subjects were significantly more confident with their decision to drive when the cooperation partner showed offensive behaviors and participants therefore drove as second or third. Thus, for different deadlock situations, there also seem to be different expectations and behaviors. Since the two situations differ in the number of vehicles and lanes involved, it seems that the complexity of the situation has an influence on the cooperation behavior. For the simpler of the two situations, the equal narrow passage, it is therefore easier to make recommendations for the behavior of an automated vehicle.

Drivers prefer to drive first in deadlock situations at equal narrow passages. Accordingly, an automated vehicle should rather show defensive behavior in order to give the manual driver the opportunity to drive first. To show defensive behavior and the intention to stop, a use of the headlight flasher or a clear stop seems to be most suitable for the narrow passage. For the T-intersection, the recommendations for the behavior of automated vehicles cannot be derived quite as clearly. Since drivers tend to prefer to drive second or third here, automated vehicle guidance should tend to show offensive behavior and drive through the intersection first. Since there is no clear explicit signal for offensive behavior, driving behavior must be used here to indicate to the manual driver that the automated vehicle will proceed. For this purpose, it is most suitable to maintain the speed.

At the T-intersection, however, other aspects must be considered as well, as the findings from the video studies indicate. The entry position to the intersection can influence whether drivers stop or not. When approaching from below, most drivers would stop. Automated vehicle guidance encountering a manual driver from the entry position below in a deadlock situation should proceed through the intersection first. One possible reason why drivers from the position below do not drive first is that the deadlock situation is not recognized as such. This is especially important when a manual driver approaches from the positions on the left or right. Here, drivers show a higher probability of driving first themselves. Therefore, the automated vehicle guidance system must expect that manual drivers may want to drive first, because they may assume that they have the right of way in this situation. In its intention detection, the automated vehicle guidance system must therefore recognize whether drivers are approaching the intersection as if they have the right of way or whether there is uncertainty in their behavior that suggests they have recognized the deadlock situation. In the latter case, the automated vehicle should then drive first. Other traffic with which the vehicles involved in the deadlock situation do not interact, as well as pedestrians, have no influence on the cooperation behavior and can be ignored for the behavior decision. However, if a vehicle passes through the intersection before the manual vehicle, it can be expected that this manual vehicle will also pass through the intersection first in the deadlock situation. In this case, an automated vehicle should then exhibit defensive behavior, preferably by coming to a distinctive stop, and yield the right of way to the manual driver.

Overall, the studies provided initial insights into the cooperation behavior of drivers in two different deadlock situations. These provide indications of how an automated vehicle should behave in these situations in order to resolve the situation to everyone's satisfaction.

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