Transportation Research Part F: Psychology and Behaviour 120 (2026) 103620

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

journal homepage: www.elsevier.com/locate/trf

Understanding and resolving deadlock situations: Drivers' perception, rule application and behavior at T-intersections

Nadine-Rebecca Strelau *, Barbara Deml

Institute of Human and Industrial Engineering, Karlsruhe Institute of Technology, Engler-Bunte-Ring 4, 76131 Karlsruhe, Germany

ARTICLE INFO

Keywords:
Deadlock situation
Driver behavior
Intersection
Traffic rule understanding
Perception

ABSTRACT

Intersections are critical points for traffic accidents, often resulting from drivers' failure to correctly apply right-of-way rules. A particular challenge arises in deadlock situations, where the right-of-way is not clearly regulated. This study investigates how accurately drivers perceive deadlock situations at T-intersections and how these perceptions influence their behavior. Participants watched videos from a driver's perspective showing approaches to a T-intersection from all three directions, where two other vehicles arrive simultaneously, creating an unresolved deadlock. After each video, participants reported their intended behavior. Additionally, they were asked to either identify the vehicles' travel direction, anticipate their behavior or determine the right-of-way. The results show that most drivers fail to correctly identify the right-of-way, often misattributing priority to one vehicle. This likely stems from applying only one of the two relevant right-of-way rules, leading to priority being assigned primarily to the vehicle approaching from the right. Drivers also assigned right-of-way more frequently to an approach direction when they were not approaching from that direction themselves. The approach direction and assumed priority further influenced how drivers anticipated the behavior of the other vehicles and how these expectations shaped their own behavior. The two relevant vehicles were not equally attended to, leading also to errors in detecting their intended trajectories. Overall, drivers do not appear to consider all relevant information, resulting in an inaccurate representation of the situation, and their behavior can only be interpreted in relation to their approach direction. Based on the findings recommendations for autonomous vehicles are given.

1. Introduction

Driving in urban environments presents significant challenges, particularly at intersections, where complex interactions between multiple road users occur. Intersections are known to be high-risk areas for traffic accidents, with a substantial proportion of crashes occurring in urban areas (Statistisches Bundesamt, 2024b). Nearly a third of these accidents are caused by failure to give way or errors when turning or crossing intersections (Statistisches Bundesamt, 2024a). Among intersection-related crashes, left-turn collisions are particularly prevalent. Approximately 45% of accidents at intersections occur when drivers turn left and collide with oncoming vehicles or vehicles approaching from the left. Additionally, around 20% of accidents result from collisions between vehicles traveling straight from different directions (ADAC Unfallforschung, 2023). These statistics highlight the complexity of navigating intersections and the associated risks.

* Corresponding author.
E-mail address: nadine-rebecca.strelau@kit.edu (N.-R. Strelau).

https://doi.org/10.1016/j.trf.2026.103620
Received 15 May 2025; Received in revised form 26 March 2026; Accepted 14 April 2026
Available online 23 April 2026

1.1. Deadlock situations at T-intersections

While many intersection conflicts arise in situations where the traffic rules clearly define the right of way, there are also scenarios where priority is not explicitly assigned to any vehicle. One example is a deadlock at a T-intersection, which can occur under right-before-left rules in combination with left-turn yielding regulations. In some countries, such as Germany, Austria, and the Netherlands, this combination can lead to a deadlock when three vehicles arrive simultaneously (Fig. 1). The vehicle from the left intends to go straight, and the other two vehicles intend to turn left. The vehicles from the left and the bottom must yield to the vehicle to their right due to the right-before-left rule. The vehicle from the right must yield to the vehicle from the left, as it crosses the latter's path when turning left. Since all vehicles must yield to another, they must cooperate to determine which vehicle will drive first. In this paper, the term deadlock situation refers to this rule-based configuration in which no vehicle has priority according to traffic regulations. It does not describe a potential behavioral outcome (e.g., a stillstand). An observational study at an intersection found that 9% of vehicle interactions over a five-hour period resulted in deadlocks (Imbsweiler et al., 2016). This indicates that such situations, while not the most frequent, occur regularly in everyday traffic.

Although there are no specific accident statistics for this exact scenario, it is reasonable to assume that it presents a considerable risk. The most common causes of intersection crashes—left-turn conflicts and potential right-of-way violations—are all present in this situation. Given the lack of an explicit priority rule, drivers must correctly interpret the situation to resolve the deadlock safely. Understanding how drivers recognize such ambiguous right-of-way scenarios and how they behave in those situations is therefore critical for both human drivers and autonomous vehicles (AVs). This is particularly important as mixed traffic environments, where both manual drivers and AVs share the road, will remain common in urban traffic for the foreseeable future.

A better understanding of how human drivers perceive and act in such situations can inform the design of AVs that are able to anticipate human behavior and adapt accordingly. Prior research suggests that human drivers feel more comfortable when another cooperation partner resolves the deadlock by driving first (Imbsweiler et al., 2018). Deadlock situations at intersections thus pose a unique challenge for AVs: While a conservative strategy such as stopping may appear safest, it can also prevent the resolution of the situation and cause a stillstand. To cooperate effectively in such scenarios, AVs must therefore go beyond merely applying formal traffic rules and take into account how human drivers actually interpret and enact these rules in practice. By integrating this knowledge into cooperative decision-making strategies, AVs could help prevent standstills and improve both efficiency and comfort in ambiguous right-of-way situations.

1.2. Driver behavior in deadlock situations

At present, the understanding of driver behavior in deadlock situations at T-intersections is quite limited. Imbsweiler (2019) found that drivers in these situations predominantly rely on implicit communication (e.g., acceleration, deceleration) rather than explicit signals (e.g., horn, gestures). The drivers' behavior can be categorized into offensive and defensive behavior patterns, which communicate the driver's intention to either stop or drive. It was also shown that these different behavioral intentions significantly influenced whether the participants stopped or drove through the intersection first. Furthermore, drivers felt more comfortable when others exhibited offensive behavior, as it allowed them to proceed second or third. In contrast, at deadlock situations involving only two vehicles, such as at narrow passages, drivers felt more comfortable driving first themselves. Imbsweiler (2019) therefore concluded that in more complex situations, drivers prefer others to drive first.

Building upon these findings, Strelau and Deml (2025) investigated whether the complexity of the environment influences drivers' cooperation behavior at deadlock situations at T-intersections. They found that the complexity of the situation had little to no impact on cooperation behavior. However, they observed that the direction from which drivers approached the intersection did influence their probability to drive first. Additionally, their studies revealed that drivers' expectations about the behavior of the cooperating vehicles were influenced by both the approach position of those vehicles and their relative right-of-way to the participants. Based on their findings, Strelau and Deml (2025) interpreted that many drivers likely did not recognize the scenarios as deadlock situatios and therefore misapplied the relevant right-of-way rules. Notably, there was no clear pattern regarding which vehicle, whether approaching from the left or right, was expected to drive first, suggesting a fundamental inconsistency in how drivers understand right-of-way in such situations. However, these conclusions were inferred from behavioral outcomes rather than directly measured, as the study did not assess how drivers perceive and interpret the situation.

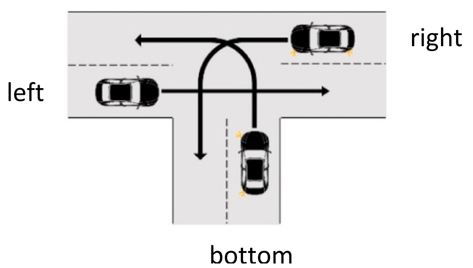

Fig. 1. Deadlock situation at a T-intersection (Strelau & Deml, 2025) with the three approach positions left, right and bottom.

Previous research has largely treated deadlock situations at T-intersections as coordination problems, implicitly assuming that drivers share a common and correct understanding of the situation, i.e. that no vehicle has the right-of-way and that the challenge lies in deciding who should proceed first. However, deadlock situations are complex as they involve multiple vehicles and require simultaneous application of more than one traffic rule. Given this complexity and the findings from Strelau and Deml (2025) that suggest that drivers may not correctly interpret this situation, it cannot be assumed that drivers form accurate and consistent representations of the situation. If drivers interpret the situation differently than traffic regulations prescribe, this likely shapes both their behavior and their expectations of other, and needs to be taken into account when trying to understand cooperation behavior in these situations.

The present study directly addresses this research gap, by empirically examining drivers' perception and interpretation of deadlock situations at T-intersections. Specifically, it investigates whether and to what extend drivers misinterpret the applicable right-of-way rules, which alternative priority assignments they tend to make, and whether this misinterpretation differs across the three approach positions. It further investigates whether the (in)correct identification of the two cooperating vehicles' intended directions of travel contributes to the failure to recognize the situation as a deadlock, what behavior drivers anticipate from the other two vehicles, and how each of these factors influences cooperation behavior in deadlock situations at T-intersections.

Strelau and Deml (2025) used the task-interface model (Fuller, 2011) to examine driver behavior in deadlock situations at T-intersections. This model provides a comprehensive framework for understanding driver behavior in dynamic traffic environments by considering the interaction between task demands and driver capability. Task difficulty arises from the interplay between task demands (e.g., environmental factors, other road users, and vehicle characteristics) and driver capability (e.g., attention, perception, skills, knowledge, and the mental representation of the situation). A key principle of this model is that drivers strive to keep the perceived task difficulty within an acceptable range. If the demands of a situation exceed this threshold, drivers adjust their behavior—such as by reducing speed—to regain control over task difficulty. An essential aspect of this model is calibration, referring to how accurately drivers assess both the demands of a situation and their own capability. Miscalibration, such as overestimating one's capability or underestimating the demands, can lead to an underestimation of the actual task difficulty, potentially influencing decision-making and driving behavior. Strelau and Deml (2025) focused on task demands in their study and found that these had little effect on cooperation. A miscalibration of driver capability, specifically their understanding of the situation and traffic rules, may therefore have played a crucial role, rather than an increase in task demands.

In Fuller's (2011) model, the mental representation of the situation is a key component of driver capability, which aligns with the concept of Situation Awareness (SA) as described by Endsley (1995). SA refers to an individual's understanding of their environment and is fundamental for decision-making in dynamic systems. It represents a state of knowledge—essentially "knowing what is going on" (Endsley, 1995, p. 36) —rather than the process leading to this knowledge. Endsley's hierarchical model of SA consists of three levels: (1) perceiving all relevant elements in the environment, (2) comprehending their meaning, and (3) projecting their future status. SA considerably influences the decisions and actions of people, which in turn impact the environment, requiring continuous adjustments to SA in response to the dynamic changes in the environment. Reduced SA results in poorer driving performance and more errors, such as speeding violations, increased lane deviations, navigation mistakes, unsuccessful overtaking, and a higher likelihood of collisions (Jeon et al., 2015; Kaber et al., 2016; Ma & Kaber, 2007). Various factors, including distractions, fatigue, negative emotions like anger and poor weather conditions, can impair SA (Jeon et al., 2014; Kass et al., 2007; Wijayanto et al., 2021). Conversely, experience, sufficient observation time, and driver assistance systems can enhance SA by supporting perception and decision-making (Chandrasekaran et al., 2019; Kass et al., 2007; Lu et al., 2017; McKerral & Pammer, 2021; Tinga et al., 2022; Yang et al., 2018).

To accurately have a mental representation of a deadlock situation at an intersection, drivers must first perceive all relevant information in their surroundings. This includes identifying all traffic participants involved in the situation and recognizing their turn signals to understand their intended direction of travel. In a deadlock situation, both cooperating vehicles must be observed to correctly recognize the situation, rather than focusing solely on the seemingly more relevant vehicle to whom right-of-way must be yielded. Additionally, any traffic signs regulating right-of-way must be noticed. However, in this study, participants were informed that the intersections followed the right-before-left rule unless signs indicated otherwise. Therefore, traffic signs play a minor role in this specific context.

Once all relevant vehicles and their intended directions have been identified, the next crucial step is correctly interpreting the situation—particularly regarding right-of-way rules. This requires sufficient knowledge of traffic regulations to correctly apply the two right-of-way rules governing this type of deadlock situation. However, studies suggest that drivers' understanding of traffic laws is often imperfect. A survey conducted by the ADAC (2022) among more than 3500 German drivers found that only 64% could answer at least half of the given official driving exam questions correctly. Specifically, for right-before-left priority rules at intersections, only 70% of respondents provided the correct answers. This lack of knowledge is not exclusive to German drivers; similar studies in other countries have also found that drivers do not always correctly answer questions about traffic regulations (Al-Rukaibi et al., 2006; Hasan & Al-Bar, 2009; Kulkarni et al., 2013).

If drivers lack the necessary knowledge to correctly interpret a deadlock situation, they may wrongly assume that they have the right-of-way. This could lead to them driving first without sufficient communication with the other two vehicles. Conversely, if they assume that another vehicle has priority, they might expect that vehicle to proceed first and adjust their own behavior accordingly.

While knowledge of traffic rules is crucial for correctly interpreting a deadlock situation, it is not the only factor influencing driver behavior. Traffic rules serve as indicators of the intentions and expected behavior of other road users, but drivers do not rely solely on them. Both the expected and actual behavior of other drivers can shape one's own decisions. Björklund and Åberg (2005) demonstrated that at intersections governed by right-of-way rules, the behavior of other drivers was just as influential as the formal priority regulations in determining how drivers acted. This highlights the importance of not only understanding the traffic rules that apply to a situation but also anticipating how other drivers will behave.

1.3. Research objective and questions

Based on the insights discussed in the previous sections, and addressing the research gap arising from Strelau and Deml (2025), the following research questions are derived:

1. Do drivers correctly perceive the intended direction of the two other cooperating vehicles?
2. Do drivers correctly identify and apply the right-of-way rules in this situation?
3. Do drivers accurately recognize and anticipate the observed behavior of the cooperating vehicles?
4. Does the correct (or incorrect) recognition of these factors influence drivers' own behavior, i.e. whether they drive first or yield, in deadlock situations?

In addition to these core questions, the study also examines two further aspects that may affect drivers' perception and behavior in deadlock situations. First, the time available to observe the intersection can influence how well drivers construct a mental representation of the situation. In this study, the width of the sidewalk determines how early drivers can see into the intersection and detect the cooperating vehicles. By varying this width, the study investigates whether differences in observation time affect the recognition of the deadlock situation and subsequent driving behavior.

Second, previous research has shown that the direction from which drivers approach a T-intersection significantly influences their decisions. Specifically, drivers approaching from the bottom of the T-intersection were found to have a significantly lower probability of proceeding first. However, the influence of approaching from the left or right side remains unclear (Strelau & Deml, 2025). Moreover, it is unknown whether the approach direction also influences how drivers perceive and interoret the situation. To address these gaps, the study examines how the approach direction affects drivers' perception and interpretation of the deadlock situation and their subsequent behavior.

2. Method

2.1. Participants

A total of $N = 146$ participants took part in the study. Six participants were excluded from the data analysis due to incorrect answers to control questions. The remaining 140 participants are approximately evenly distributed across the 4 groups (see Table 1).

2.2. Materials

The study was conducted as an online survey using the software LimeSurvey. Participants viewed videos of a 50-m approach to a T-intersection created with the driving simulation software Silab® 7.0. From each of the other two roads of the intersection, a vehicle approached, traveling at 30 km/h, decelerating 25 m before the intersection, and then coming to a stop. The 25 m braking distance corresponds to the beginning of the cooperation zone, and the shown vehicle behavior represents a defensive cooperation pattern described for deadlock situations at T-intersections (Imbsweiler et al., 2016; Imbsweiler et al., 2018). The ego vehicle followed the same behavior. The direction of travel of the other two vehicles was indicated by the turn signal. A displayed arrow on the screen indicated to the participant the direction the ego vehicle would travel at the intersection. One second before all three vehicles came to a stop, the video was cut off, and a black screen appeared, leaving the deadlock situation unresolved. The videos were shown from all three approach directions of the T-intersection (left, right, bottom). Additionally, the width of the sidewalk was varied to manipulate the visibility into the intersection and the first sighting of the vehicle in the intersection (see Fig. 2). With the highest visibility, the vehicle could be seen from 25 m before the intersection, with medium visibility 10 m before the intersection, and with the lowest visibility only 5 m before the intersection. Each participant saw each of the nine videos in a randomized order. Additionally, six distractor videos were presented, featuring intersections without deadlock situations. Each video was played only once, and after each video, questions were asked about the video just viewed.

Table 1
Description of the sample by group.

	n	gender		Age	Average years holding driver's license
		female	male		
Group 1	38	$n = 22$	$n = 16$	M = 25.05 (SD = 4.91)	M = 7.65 (SD = 4.85)
Group 2	36	$n = 18$	n = 18	M = 24.83 (SD = 4.93)	M = 6.93 (SD = 4.46)
Group 3	33	$n = 12$	$n = 21$	M = 27.61 (SD = 9.56)	M = 9.76 (SD = 9.17)
Group 4	33	$n = 11$	n = 22	M = 26.61 (SD = 9.48)	M = 9.02 (SD = 9.03)

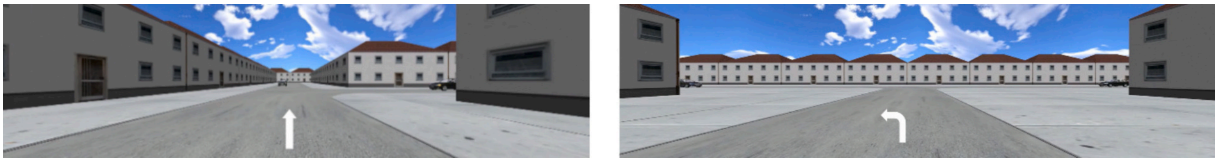

Fig. 2. Screenshot of videos with (a) approach from the left with a narrow sidewalk and (b) approach from the bottom with the widest sidewalk.

2.3. Measures

Participants were randomly assigned to one of four groups. The groups differed in the questions they were asked after each video. All participants from all four groups were asked to indicate how likely they were to be the first to drive through the intersection on a scale from 0 to 100%. Group 1 was asked only this question. Participants in group 2 were additionally asked to indicate in which direction each of the other two vehicles were going through the intersection. Participants in group 3 were asked to indicate which of the traffic participants had the right of way in the situation. As an answer, they could choose between one of the other vehicles, themselves, none of the traffic participants, or that they did not know. Participants in group 4 were asked to indicate how they expected the two vehicles to behave. The two answer options were that the car would brake and come to a stop or that the car would drive through the intersection.

After participants had viewed all the videos, they were presented with four bird's-eye view graphics of a T-intersection, with three vehicles and arrows indicating the direction the vehicles would travel (similar to Fig. 1). One of the four graphics depicted a deadlock situation, while in the other three situations there was one vehicle that had the right of way. They were then asked to indicate who had the right of way in these situations. They could choose between the three vehicles, as well as none of the vehicles, or indicate that they did not know. Finally, participants completed a demographic questionnaire.

2.4. Data analysis

Data analysis was conducted using SPSS 26 and R 4.1.0 with the following R packages: dplyr, ggplot2, multcomp, lmerTest, modelbased, and MuMIn. To analyze the probability to drive first linear mixed models with random intercept were used. While the residuals of these models do not show a normal distribution, linear mixed models are robust to violations of their assumptions and can therefore still be effectively used with a large sample size (Schmidt & Finan, 2018). The differences in behavior examined within the four groups were calculated using non-parametric tests, as the individual subgroups were relatively small.

3. Results

3.1. Perception accuracy and right-of-way-determination in deadlock-situations

3.1.1. Perception of the cooperation vehicles' direction of travel

In Group 2, participants were tasked with detecting the direction in which the other two vehicles would travel through the

Fig. 3. Percentage of correctly and incorrectly identified directions of travel of the cooperation vehicle, depending on its right-of-way relative to the ego vehicle.

intersection. In the majority of situations (77%), participants correctly identified the direction of both vehicles. However, in 23% of situations, the direction of at least one vehicle was misidentified. Descriptively, during approaches from the bottom, the direction of at least one vehicle was more frequently misidentified (28%) compared to approaches from the right (22%) or left (20%). However, this difference was not statistically significant ($\chi^2(2) = 1.788$, $p = .409$). Similarly, in situations with high visibility, fewer misidentifications occurred (19%) compared to situations with medium (24%) or low visibility (28%). However, this difference was also not statistically significant ($\chi^2(2) = 2.613$, $p = .271$). Examining which of the other two vehicles had its direction misidentified more frequently revealed that this occurred more often with the vehicle required to yield to the ego vehicle compared to the vehicle that has the right of way (see Fig. 3).

This effect, that the right-of-way rule relative to the ego vehicle has an influence on the recognition of the direction in which the other vehicles will turn at the intersection, is statistically significant ($\chi^2(1) = 6.554$, $p = .010$). This difference was particularly pronounced for approaches from the bottom. Here, the direction of the yielding vehicle was misidentified in 24% of cases, compared to only 6% misidentification for the vehicle to which the participant must yield to. For approaches from the left and right, the difference was less pronounced (14% vs. 8% and 12% vs. 14%, respectively).

3.1.2. Right-of-way determination

In Group 3, participants were asked to identify which vehicle had the right of way in the observed situations. Across all situations, the right-of-way rule was misidentified in 94% of cases, with only 6% correctly recognizing a deadlock situation. The option "I don't know" was chosen only twice overall. The very low percentage of correct identifications that no vehicle had the right of way did not significantly differ across the three approach directions ($\chi^2(2) = 0.874$, $p = .646$), with 7% correct identifications for approaches from the left, 6% for approaches from the right, and 4% for approaches from the bottom. Visibility also did not have a significant effect on recognizing the right-of-way rule, χ^2 (2) = 0.499, $p = .779$, (low = 5%, medium = 7%, high = 5%). In Table 2, the vehicles indicated by the participants as having the right of way are listed. When approaching from the left, participants equally perceived both the vehicle they had to yield to and the one yielding to the ego vehicle as having the right of way, with approximately the same proportion. However, when approaching from the right or the bottom, there was a significantly higher tendency to indicate that the vehicle the ego-vehicle has to yield to has the right of way, compared to the vehicle that has to yield to the ego-vehicle. This trend was particularly pronounced when approaching from the bottom, where the majority made this assertion. Furthermore, when approaching from the right, there was a relatively high occurrence (32%) of participants indicating that the ego vehicle itself had the right of way in the situation.

Further analysis was conducted to determine which position of the cooperation vehicle was perceived to have the right of way, regardless of the participant's own position. In 43% of cases, participants believed that the cooperation vehicle approaching from the right had the right of way. In contrast, the cooperation vehicle approaching from the left was perceived to have the right of way in 21% of cases, and the vehicle coming from the bottom was perceived to have the right of way in only 17% of cases.

3.1.3. Anticipated behavior of the cooperation vehicles

In group 4, participants were asked to anticipate the behavior of the cooperation vehicle. Overall, participants significantly more often anticipated that the cooperation vehicle would stop (71%) rather than continue driving (29%). Descriptively, participants were more likely to expect the cooperation vehicle to stop in situations with high visibility (74%) compared to medium (72%) or low visibility (68%) conditions. However, this effect was not statistically significant ($\chi^2(2) = 1.527$, $p = .466$). The approach position of the cooperation vehicle had a significant impact on participants' anticipated behavior ($\chi^2(2) = 47.942$, $p < .001$). As can be seen in Fig. 4, participants were considerably more likely to expect a cooperation vehicle approaching the intersection from the bottom to stop compared to those approaching from the left or right. For vehicles approaching from the right, the proportion of participants expecting it to stop versus continue driving was almost evenly balanced. There was no significant difference in participants' anticipated behavior based on whether the cooperation vehicle had the right-of-way relative to the ego vehicle ($\chi^2(1) = 0.821$, $p = .365$). Participants expected the cooperation vehicle to stop in 74% of scenarios where it had the right-of-way compared to 69% when it had to yield to the ego vehicle.

3.2. Probability to drive first

In general, the probability of driving first was relatively low with a mean of 21% ($SD = 31\%$). The following analyses examine the probability of driving first based on approach position, visibility, and the different experimental conditions of the participants.

Table 2
Distribution of participants'judgement of right-of-way in percent.

Perceived right-of-way vehicle	Approach direction of ego vehicle		
	left	right	bottom
The vehicle the participant has to yield to	39%	49%	81%
The vehicle that has to yield to the participant	44%	12%	13%
The ego vehicle	6%	32%	2%
None of the vehicles	7%	6%	4%
Do not know	1%	1%	0%

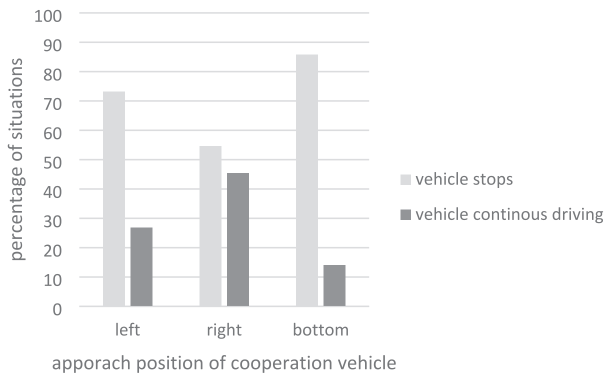

Fig. 4. Anticipated behavior of the cooperation vehicle depending on the approach position of the cooperation vehicle.

3.2.1. *Effects of approach direction and visibility*

To investigate the effect of approach position and visibility on the probability of driving first, linear mixed models with random intercepts for participants were calculated. The approach position at which the ego vehicle arrived at the intersection had a significant influence on the probability that participants would drive first ($F(1, 1116) = 54.39$, $p < .001$), see Fig. 5. When approaching from the right, there was a significantly higher probability that participants would drive first compared to approaching from the left ($p < .001$) or the bottom ($p < .001$). The probability of driving first from the left was also significantly higher than from the bottom ($p < .001$). The visibility did not have a significant effect on the probability to drive first ($F(1, 1116) = 0.273$, $p = .761$) with a mean probability of 20% ($SD = 31\%$) for the low visibility condition, 21% ($SD = 31\%$) for the medium condition and 22% ($SD = 32\%$) for the high visibility condition.

3.2.2. *Effects of perception accuracy on cooperation behavior*

Since participants in each of the four groups were asked about different aspects of the situation, potentially drawing their attention to different elements of the traffic scenario, we investigated whether there was a difference in the reported behavior between these groups. Results revealed a significant difference between the groups ($F(3, 1256) = 10.63$, $p < .001$). As illustrated in Fig. 6, the probability of driving first was higher in group 4 compared to the other three groups. In this group, participants were instructed to indicate the behavior they anticipated from the cooperation vehicles. Bonferroni-corrected post-hoc tests confirmed that these differences were significant for all three comparisons ($p < .05$). Notably, there were no outliers in this group compared to the other three. Additionally, group 2 reported significantly higher values than group 3 ($p < .05$).

Examining the reported probability to drive first within the different groups reveals further distinctions. Participants who correctly identified the direction in which both cooperation vehicles would drive had a slightly lower probability of choosing to drive first ($M = 21\%$, $SD = 31\%$) compared to those who misidentified the direction of at least one cooperation vehicle ($M = 25\%$, $SD = 31\%$). However, this difference is not statistically significant ($z = -1.372$, $p = .170$). Whether participants correctly or incorrectly recognized the right-of-way rule in the presented situations did not significantly influence the probability of driving first ($z = -0.739$, $p = .460$). Nevertheless, a closer examination of incorrect responses (see Fig. 7) reveals that individuals who mistakenly believed they had the

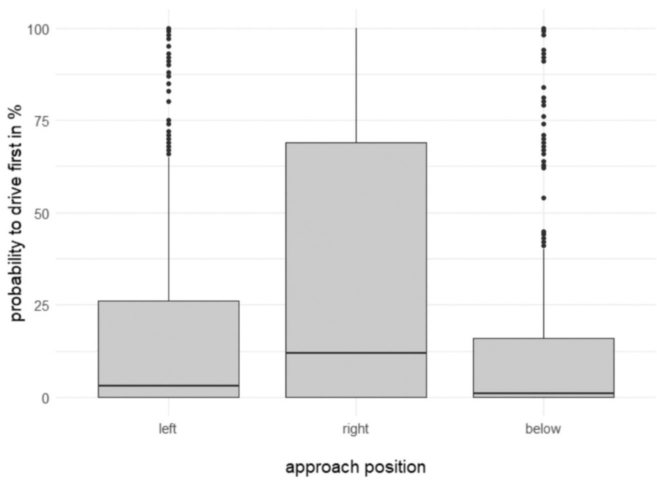

Fig. 5. Probability to drive first depending on the approach position of the ego vehicle.

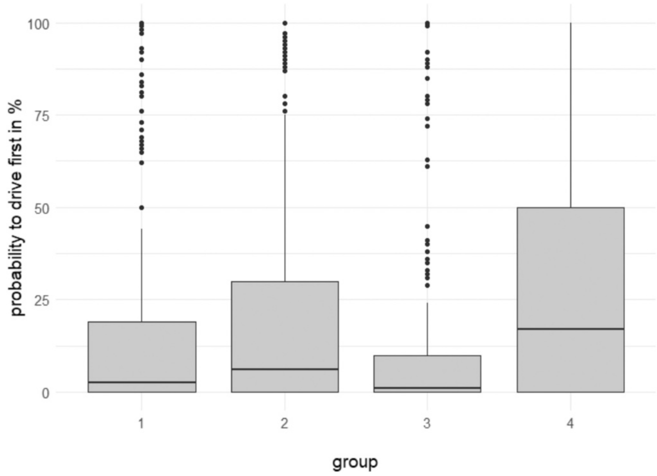

Fig. 6. Probability to drive first for the four different groups. All participants were asked to rate the probability that they would drive first. Additionally, participants were asked in group 2 in which direction the other two vehicles would drive, in group 3 which vehicle has the right of way and in group 4 what behavior they anticipated the other vehicles.

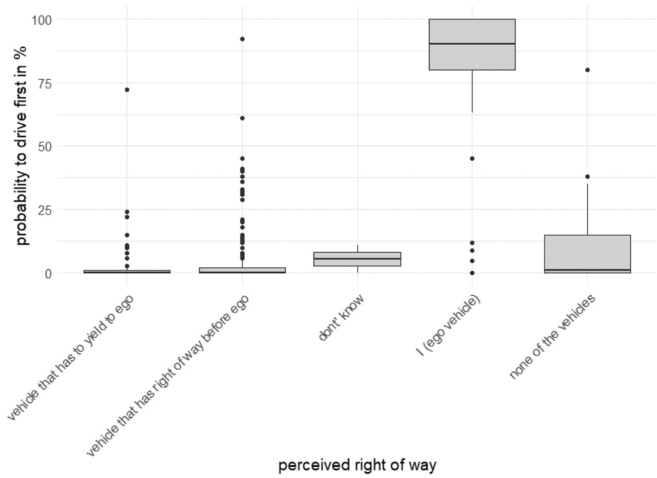

Fig. 7. Probability to drive first in group 3 depending on the right-of-way perception.

right-of-way showed a high probability to drive first. While a similar median was observed for participants who correctly recognized that no road user had the right-of-way compared to those who believed one of the cooperation vehicles had the right-of-way, the interquartile range was noticeably larger for the former group.

The influence of the anticipated behavior of the cooperation vehicles on the probability of driving first was initially examined separately for each cooperation vehicle and its relative right-of-way status compared to the ego vehicle. When participants anticipated that the cooperation vehicle with the right-of-way before the ego vehicle would stop, they exhibited a significantly higher likelihood of driving first (33%) compared to when they expected the vehicle to continue driving (18%), $z = -3.329$, $p < .001$. For the cooperation vehicle that had to yield the right-of-way to the ego vehicle, there was no significant difference in the probability of driving first between the anticipated stopping (30%) and driving (26%) scenarios, $z = -0.378$, $p = .705$.

However, a more differentiated picture emerged when the three different approach directions of the ego vehicle were considered separately (see Figs. 8–10). When participants approached the intersection from the left, there was no significant difference in the probability of them driving first, regardless of whether they expected the vehicle with the right-of-way to stop or continue driving ($z = -1.241$, $p = .215$). However, if they expected the vehicle that must yield to them to stop, they reported a significantly higher probability of driving first compared to when they expected this vehicle to continue driving ($z = -2.799$, $p = .005$).

Conversely, when participants approached the intersection from the right, an opposite pattern emerged. If they expected the vehicle with the right-of-way to stop, they were significantly more likely to drive first compared to when they expected this vehicle to continue driving ($z = 7.739$, $p < .001$). In the case of the vehicle that must yield to them, there was no significant difference in their own driving behavior based on whether they expected this vehicle to stop or continue driving ($z = -0.791$, $p = .429$). It is notable that

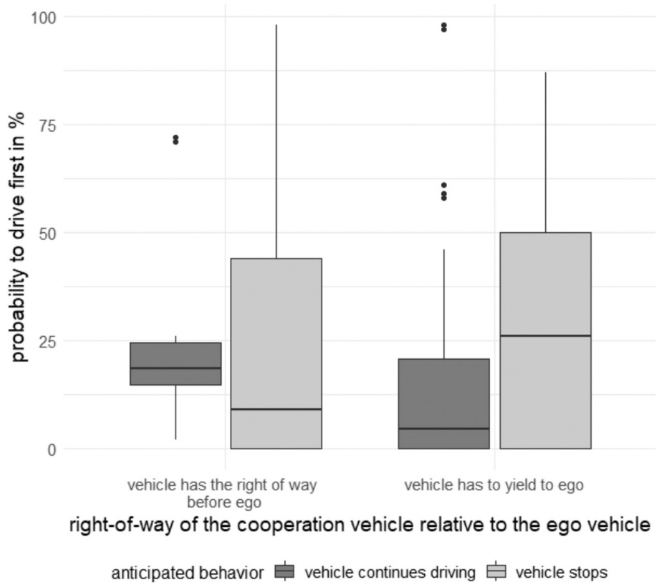

Fig. 8. Probability to drive first depending on right-of-way relative to ego and anticipated behavior when participants approached the intersection from the left.

the reported probabilities of participants driving first were considerably higher when approaching from the right compared to approaching from the left or bottom. Furthermore, the probability of them driving first was relatively high even when they expected the vehicle that must yield to them to continue driving. When approaching from the bottom, participants reported a significantly higher probability of driving first if they expected the vehicle with the right-of-way to stop, compared to when they expected this vehicle to continue driving ($z = -3.182$, $p = .001$). Similarly, they indicated a higher probability of driving first if they expected the vehicle that must yield to them to continue driving, compared to when they expected this vehicle to stop ($z = -3.617$, $p < .001$).

3.2.3. Effect of right-of-way assessment in schematic figures on cooperation behavior

After completing the questions following each video, participants were shown a schematic figure of a T-intersection depicting a deadlock-situation. They were asked to indicate which vehicle had the right-of-way according to traffic regulations. Overall, only 16% of all participants answered correctly. In group 4, 24% of participants provided the correct answer, compared to 18% in group 3, 17%

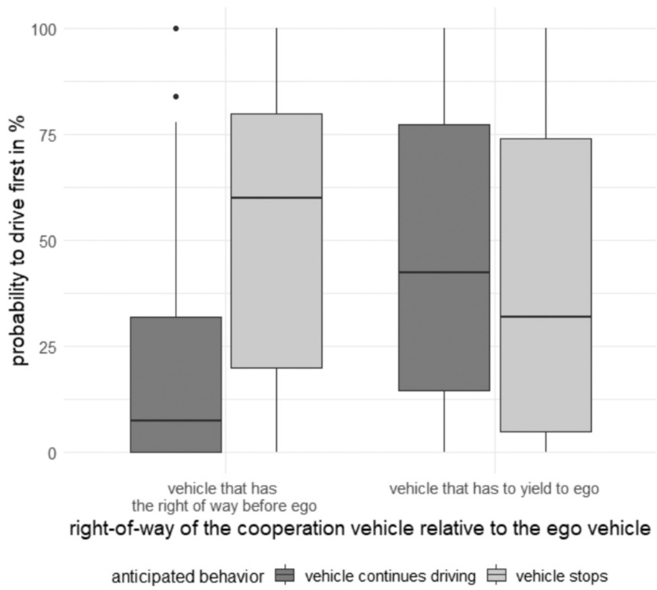

Fig. 9. Probability to drive first depending on right-of-way relative to ego and anticipated behavior when participants approached the intersection from the right.

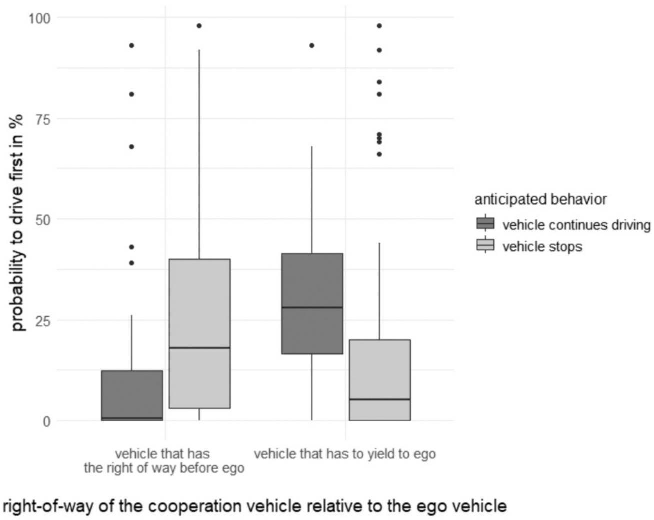

Fig. 10. Probability to drive first depending on right-of-way relative to ego and anticipated behavior when participants approached the intersection from the the bottom.

in group 2, and 5% in group 1. However, these differences are not statistically significant ($\chi2(3) = 5.122$, $p = .163$). Examining the incorrect answers more closely, approximately half of the participants believe that the vehicle approaching from the right has the right-of-way in this situation, and about a quarter think that the vehicle from the left has the right-of-way (see Fig. 11).

However, correctly identifying the right-of-way rule did not significantly influence participants' reported probability to drive first through the intersection, regardless of their approach direction (left: $z = -0.040$, $p = .968$; right: $z = -0.989$, $p = .323$; below: $z = -0.940$, $p = .348$). Even though the difference was not significant, participants approaching from the right who incorrectly identified the right-of-way showed a higher probability of driving first compared to those who correctly recognized that no vehicle had the right-of-way (Table 3).

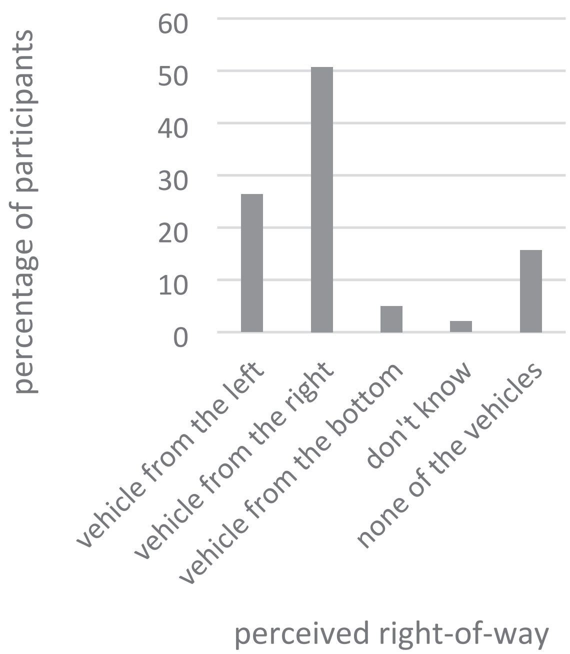

Fig. 11. Participants' perceptions of which vehicle had the right-of-way in the presented schematic figure of the deadlock-situation.

Table 3
Probability to drive first based on approach position and right-of-way identification accuracy (means and standard deviations).

Right-of-Way Identification (correct/incorrect)	Approach direction		
	left	right	bottom
correct	19.45 (27.70)	23.64 (28.94)	15.91 (24.37)
incorrect	19.18 (30.59)	32.75 (37.35)	11.44 (20.99)

4. Discussion

This study investigated how accurately drivers perceive and recognize a deadlock situation at a T-intersection and how this influences their behavior. Specifically, we examined whether drivers correctly identify the intended direction of travel of the two cooperation vehicles, correctly apply the right-of-way rules, and what behavior they anticipate of the cooperation partners. Additionally, we analyzed whether the correct or incorrect recognition of these factors impacts drivers' cooperation behavior in deadlock situation. Furthermore, we explored the influence of different sidewalk widths, which affect the time available to observe the intersection, as well as the effect of approach direction on drivers' perception and behavior.

Overall, participants showed a relatively low likelihood of driving first through the intersection, and the approach position significantly influenced behavior, findings that are consistent with Strelau and Deml (2025). When approaching from the right, participants showed a significantly higher likelihood of driving first compared to when approaching from the left or from the bottom, adding clarity to the mixed results across the three studies reported by Strelau and Deml (2025). Crucially, the approach position not only influenced cooperation behavior but also shaped how participants perceived and interpreted the deadlock situation, aspects that prior work had not examined. The following sections will discuss how these factors can in part explain the different behaviors across approach positions.

4.1. *Direction of travel of the cooperation vehicles*

To understand how drivers interpret right-of-way or decide on their own actions, it is first necessary to examine how accurately they perceive the situation. If the direction of even one vehicle is misjudged, the situation cannot be recognized as a deadlock since different travel directions would result in a clear right-of-way regulation. Correctly perceiving the travel directions is therefore a necessary prerequisite for interpreting the right-of-way relations in the first place, irrespective of whether drivers subsequently apply the rules correctly or act in accordance with them.

In 23% of situations, at least one vehicle's direction was misidentified. This means that almost a quarter of drivers were, solely due to misperception, not in a position to identify the situation as a deadlock. A closer examination of which vehicle's direction was more frequently misidentified revealed that participants were more likely to misidentify the direction of the vehicle that had to yield to them compared to the vehicle they had to yield to. This could be due to differences in attentional focus: drivers may prioritize observing the vehicle with the right of way relative to them, as they may find it more relevant to them, increasing the likelihood of correctly perceiving its travel direction.

Notably, when approaching the intersection from the bottom, participants misidentified the direction of the yielding vehicle even more frequently compared to the vehicle with the right of way. This could be due to limited observation time: unlike approaches from left or right, where one of the cooperation vehicles is visible throughout the whole approach, both cooperation vehicles become visible relatively late when approaching from the bottom. Another factor that may contribute to misidentifications is the salience of the travel direction. A turn signal is a highly salient cue that draws attention and is easy to interpret. In contrast, a vehicle traveling straight does not provide an explicit visual cue; rather, the absence of a turn signal serves as an implicit indicator of its intended direction. When approaching from below, this lack of a salient visual cue may explain why the travel direction of the vehicle driving straight ahead was more frequently misidentified. When approaching from the right, however, the turning and straight-traveling vehicles were recognized with similar accuracy. The combination of observation time, the salience of cues indicating travel direction, and the prioritization of the vehicle with the right-of-way appears to influence the accuracy with which drivers identify the travel directions of the cooperation vehicles. This is consistent with the observation that fewer misidentifications occurred when the sidewalk was wider, allowing earlier visibility into the intersection. Although not statistically significant, this pattern supports the interpretation that increased visibility or observation time helps drivers better distribute their attention between both vehicles, leading to fewer errors in identifying the direction of the yielding vehicle.

Future research could benefit from eye-tracking studies to examine whether drivers primarily focus on only one vehicle and whether there are differences between drivers who correctly identify the deadlock situation and those who do not, in terms of their attention to both cooperation vehicles.

4.2. *Right-of-way determination*

To investigate the extent to which drivers correctly recognize right-of-way in deadlock situations, two approaches were employed. In the first approach, participants in group 3 were asked after each video to indicate which vehicle they believed held the right-of-way in the given scenario. In the second approach, after viewing all the videos, participants of all groups were shown schematic figures of the deadlock situation at the T-intersection (similar to Fig. 1).

Based on the finding that 77% of drivers correctly identified the travel directions of both vehicles, a similar proportion of participants could have recognized the deadlock situation. However, only a very small percentage of participants actually recognized that no vehicle had the right-of-way. When asked immediately after each video, only 6% of participants provided the correct response. When presented with the schematic figures at the end of the study, 16% of all participants and 18% of those in group 3 correctly identified the deadlock situation. The failure to correctly identify travel directions alone does not fully account for the lower rate of correct right-of-way identification after each video. If we assume that 77% of participants in group 3 accurately recognized the travel directions of both vehicles, as observed in group 2, and consider that 18% correctly identified right-of-way in the schematic images, one would expect approximately 14% to do so after watching the videos—roughly twice the observed rate.

One possible explanation for the difference between responses to the videos and the schematic images is the time available for analysis. In the schematic images, participants could carefully examine the situation for as long as needed, with all vehicle directions clearly indicated. In contrast, the videos were only shown once, meaning participants had only a brief moment to perceive the traffic situation before making their decision. This time constraint may have made it more difficult to fully process all relevant information. Differences in observation time within the videos due to sidewalk width did not, however, significantly affect the accuracy of recognizing right-of-way. These findings indicate that insufficient observation times may contribute to drivers misinterpreting traffic rules, while only substantially longer observation times facilitates an accurate understanding of the situation.

However, overall, the majority of drivers simply do not know or correctly apply the relevant traffic rules in this situation and fail to recognize the deadlock as such. In a deadlock situation, two traffic rules must be recognized, which are equally relevant. First, the right-before-left rule requires that vehicles approaching from the left and bottom yield to the vehicle to their right. Second, vehicles that are turning and crossing another vehicle's path (in our case the vehicle approaching from the right) must yield to that vehicle. Approximately half of the participants indicated that the vehicle approaching from the right had priority, while roughly one-quarter believed that the vehicle approaching from the left did. Although the percentages were slightly lower in direct video responses, the overall pattern remained consistent.

The finding that a notable proportion of drivers assigned priority to the left vehicle aligns with results from Björklund and Åberg (2005), who observed that drivers sometimes interpret intersections based on assumed road hierarchies rather than official traffic rules. In their study, some drivers treated the straight road as a main road and did not yield to vehicles approaching from the intersecting road, even though traffic regulations required them to do so. A similar tendency might explain why some participants in our study believed that the left vehicle had the right-of-way. However, the present study extends this finding in two important ways. First, whereas Björklund and Åberg (2005) examined two-vehicle interactions at intersections with clearly defined right-of-way rules, the present study measures priority assignment in a three-vehicle deadlock scenario where right-of-way is not clearly regulated. Second, in contrast to Björklund and Åberg's findings, an even larger proportion of our participants assigned priority to the vehicle approaching the intersection from the right. This suggests that drivers rely more strongly on the right-before-left rule, even when another equally relevant rule also applies. Assuming that drivers principally know the rule that left-turning vehicles must yield to oncoming traffic, the question arises why this rule was not taken into account in the deadlock situation. One possible explanation is that drivers, while knowing the rule in principle, may believe it does not apply in this specific situation involving three vehicles. This would indicate not a general lack of knowledge, but rather a situation-specific misunderstanding or misapplication of the rule.

Another explanation is that drivers do not consciously dismiss the left-turning rule, but instead resort to heuristic information processing in a complex and ambiguous situation which requires less mental work. When individuals do not have enough knowledge or time to carefully evaluate a situation, they are more likely to rely on simple and easily accessible decision rules than systematically analyzing all relevant information. In such cases, they focus on cues that are easily noticed or understood (Chaiken & Ledgerwood, 2012). The right-before-left rule may serve as such a heuristic, as it is a well-known and frequently applied rule in everyday traffic, and may be more present for drivers than the left-turning rule. This tendency to resort to basic heuristics in ambiguous situations is consistent with previous results by Strelau and Deml (2025), who found that drivers in deadlock situations tend to follow a vehicle that enters the intersection shortly before them. This behavior was interpreted as a form of social conformity shown in ambiguous situations. The present study extends this pattern to the level of rule interpretation: In more complex situations with multiple road users or where multiple traffic rules apply, drivers appear to use simple heuristics such as imitating the behavior of other drivers or applying the most familiar rule.

While the pattern shows that many drivers assign priority to the vehicle approaching from the right, a slightly different picture emerges when considering responses based on their own approach direction. When participants themselves approached the intersection from the right, only about one-third indicated that they had the right-of-way. This is a notable difference from the roughly 50% who had assigned priority to the right vehicle when they were **not** in that position themselves. A similar shift is observed when participants approached from the left. In this case, only 6% believed they had the right-of-way compared to about a quarter of participants who thought the vehicle from the left had the right-of-way when the participants themselves were not approaching from the left. These differences show that drivers' perceptions of right-of-way can shift depending on their own approach direction and that they are more likely to attribute priority to other vehicles than to themselves, even when they are in the exact same intersection position.

4.3. Anticipated behavior of the cooperation vehicles

Since driver behavior is influenced not only by traffic rules but also by the actions of other road users, this study examined how participants anticipated the behavior of the two cooperation vehicles in the deadlock scenario. Since the videos were cut just before the vehicles would have fully stopped, participants did not see the moment when the vehicles came to a complete halt. The majority of participants expected the cooperation vehicles to stop, which was the actual behavior of the vehicles. However, in nearly 30% of situations participants anticipated that the vehicles would continue driving.

The anticipated behavior appears to be influenced by both the time available to observe the cooperation vehicles and their approach direction. Participants were more likely to correctly anticipate the behavior of the cooperation vehicles when they had more time to observe them (due to a wider sidewalk). This pattern is similar to the one observed in the recognition of driving direction of the cooperation vehicles, where longer observation time also seemed to aid accuracy. Additionally, the approach position of the cooperation vehicles significantly impacted participants' expectations. When the cooperation vehicle approached from the left or bottom of the intersection, most participants expected it to stop. In contrast, when the cooperation vehicle approached from the right, almost half expected the vehicle to continue moving. This aligns with result that about half of the participants believed that the vehicle approaching from the right has the right-of-way. Interestingly, the right-of-way relative to the ego vehicle (e.g. whether the cooperation vehicle had to yield to the ego or vice versa) did not significantly influence participants' expectations of the cooperation vehicles' behavior. This indicates that the driver's own approach direction had little direct effect on how the behavior of the other vehicles was anticipated.

Overall, the results show that participants' expectations regarding the cooperation vehicles' behavior were influenced by both observed behaviors and their interpretations of right-of-way rules.

4.4. Effects on driving behavior

As the previous sections demonstrated, drivers do not have a uniform understanding of the deadlock situation. The following section therefore examines how these diffenrences in rule interpretation an expectation of others' behavior influence drivers' own behavior.

Drivers who believed they had the right-of-way reported a very high likelihood of driving first themselves compared to those who did not think they had the right-of-way. This suggests that drivers' behavior, especially driving first in an intersection, is at least partially influenced by rule interpretation. As the cooperation vehicles slowed down, a defensive behavior that increases others' tendency to drive first (Imbsweiler et al., 2018), the combination of this behavior with the belief of having priority likely reinforced drivers' confidence to drive first.

In contrast, there was no difference in the likelihood of driving first when comparing participants who believed that one of the cooperation vehicles had the right-of-way with those who correctly identified that none of the vehicles had priority. In both cases, participants tended to let one of the other vehicles go first. For those drivers who correctly interpreteted the traffic regulations, future research could explore whether this behavior stems from uncertainty in their interpretation of the rule, from an expectation that the other vehicles would eventually proceed first, or from a cooperative intention to yield to the other vehicles. This question is particularly intriguing given that most participants correctly anticipated that the cooperation vehicles would stop.

The anticipated behavior of the cooperation vehicles also influenced participants' own behavior, and which of the two vehicles played a greater role depended on the participant's approach direction. For participants approaching from the left, the anticipated behavior of the vehicle with right-of-way relative to the ego (approaching from the bottom) had no significant influence on their own behavior. In contrast, participants were more likely to report driving first when they expected the vehicle that had to yield to them (approaching from the right) to stop rather than continue driving. For participants approaching from the right, the opposite pattern was observed. Here, the anticipated behavior of the vehicle that was required to yield to the ego (approaching from the bottom) had no effect, whereas the anticipated behavior of the vehicle with right-of-way relative to the ego (approaching from the left) did influence participants' decisions. For both approach directions, participants therefore seemed to focus primarily on the behavior of the vehicle located opposite their own approach rather than on the vehicle approaching from the bottom.

These results show that participants do not merely respond to the anticipated behavior of the cooperation vehicles alone, but rather to the combination of the anticipated behavior and approach direction. The approach direction and the associated relative right-of-way to the ego vehicle not only influences how the behavior of the cooperation vehicles is anticipated, but also shapes how participants respond to the anticipated behavior. This finding extends the results of Imbsweiler (2019), who demonstrated that cooperation vehicles' behavior could be categorized into defensive and offensive behaviors, which significantly influence how drivers behave in deadlock situations. However, his study did not differentiate between the three approach directions. Our findings suggest that, while the behavior of cooperation vehicles does have an impact, the approach direction must also be taken into account, as it influences the way participants perceive and respond to the cooperation vehicles' behavior. Specifically, the behavior of vehicles approaching from the left and right plays a crucial role in participants' decisions. When combined, the results of our study and Imbsweiler's work offer a more complete picture of cooperation behavior at T-intersections in deadlock situations, with the approach direction playing a key role in drivers' behavior.

From a rule-based perspective, the observed pattern reveals an interesting asymmetry: when approaching from the right, participants reacted to the vehicle that could formally grant them priority in the deadlock situation. When approaching from the left, however, they responded to the “incorrect” vehicle, i.e. the one that, according to traffic rules, must yield to them and therefore cannot formally grant the right-of-way. This aspect may also make cooperation less effective if drivers attempt to explicitly grant priority to another driver, for instance by flashing their headlight. Without a shared mental model of the situation and its right-of-way relations, such signals can be misinterpreted, directed at or understood by the wrong interaction partner, leading to confusion rather than cooperation.

4.5. Differences between the groups

Since participants were asked different questions after each video, it is possible that directing their attention to specific aspects of the traffic situation also influenced their recognition of the deadlock scenario. Participants in the groups that answered additional questions about travel direction, right-of-way, or expected behavior demonstrated a higher accuracy in identifying the correct priority rule compared to those who were only asked about their own behavior. Drawing attention to specific aspects of the situation may have led to more systematic information processing and in turn to a more accurate mental representation of the intersection. Moreover, participants who evaluated the anticipated behavior of the cooperation vehicles reported a higher likelihood of driving first, possibly because focusing on this aspect made them more aware of the cooperation vehicles' stopping behavior.

4.6. Limitations

The findings of this study offer valuable insight in the perception of deadlock-situations and its influence on cooperation behavior. However, certain limitations must be acknowledged that may affect the interpretation of the results. Participants were presented with videos rather than experiencing the situations in real-life driving conditions. This introduces several differences that could influence their decision-making. The decisions made in the study carried no real-world consequences unlike in actual traffic, where misjudgments could result in accidents. This lack of real consequences could have influenced their willingness to drive first in the given scenarios. Additionally, participants had time to consciously think about their decisions. This additional time for deliberation may have led to responses that do not fully reflect actual driving behavior, where decisions often have to be made instantly. The ability to correctly assess the right-of-way rules and, consequently, to recognize the deadlock situation may also differ in real traffic. The study showed that participants were better at identifying the correct right-of-way rules for the schematic figures, where they could analyze the situation as long as needed, than after watching each video, where they could only see the situation for the limited duration of the video. This suggests that in real traffic, where drivers must process information quickly and cannot pause to analyze the situation, correctly recognizing a deadlock situation may be even more challenging. It is possible that even more drivers would incorrectly interpret the right-of-way or would only realize they are in a deadlock after all vehicles have remained stationary for some time. The videos also depicted only one type of defensive behavior for all cooperation vehicles. Different behaviors while approaching the intersection, such as more offensive or defensive actions, could alter how drivers perceive the situation and react to it. The ego vehicle, which also showed the same defensive behavior, may likewise have shaped participants' judgments. Furthermore, the videos were cut one second before all vehicles came to a complete stop, thus excluding the later stages of behavioral negotiation which might have also affected behavior.

However, the standardized video-based design offers an important methological advantage for the research questions addressed here: it ensures that all participants were exposed to identical situations, including the same timing of vehicle arrivals and the same observation time for the cooperation vehicles, which would not be possible in real traffic or a driving simulator. This was particulary relevant given that our results suggest that observation time influences drivers' perception of the situation.

In addition, the findings are likely transferable to real-world traffic situations. Previous studies have shown that research using video-based methods can produce patterns and results that are consistent to those observed in real traffic and that self-reported behavior often aligns with observed behavior (Imbsweiler, 2019; Lee & Sheppard, 2016). Nevertheless, future research should examine cooperation behavior in deadlock situations in real traffic or driving simulators to gain a deeper understanding of driver behavior. Additionally, eye-tracking studies would be valuable in determining which cooperation partners drivers actively observe in such situations.

4.7. Conclusion

The results of the study show that deadlock situations are complex scenarios for which drivers do not share a uniform mental model. Drivers' behavior cannot be explained by rule knowledge alone but arises from the interaction of perceptual accuracy, subjective rule interpretation, and expectations about others' actions.

A considerable share of drivers misperceived at least one vehicle's travel direction, limiting their ability to correctly recognize the deadlock situation. This misperception appears to stem from a combination of limited observation time, the salience of directional cues, and the assumed priority of the vehicles. Even when the situation was perceived accurately, many drivers did not interpret right-of-way rules correctly or applied only one of the two relevant traffic rules. Priority was most often attributed to the vehicle approaching from the right and, to a lesser extent, from the left, while drivers tended to ascribe less priority to themselves than to vehicles approaching from the same position. Drivers who believed they had priority were more likely to drive first and when they expected the cooperation vehicle to stop. Participants' expectations of others' behavior were influenced by the actual defensive behavior of the cooperation vehicles, their approach direction, and the participants' interpretation of right-of-way rules.

Together, these findings emphasize that behavior at T-intersections in deadlock situations cannot be examined in isolation from the context of approach position, as it significantly shapes drivers' perception and, consequently, their decision-making in these situations.

For autonomous vehicles, these results provide guidance for cooperative decision-making at T-intersections, refining previous work. Imbsweiler et al. (2018) recommended that AVs should generally attempt to drive first in deadlock situations, without differentiating between approach positions. Strelau and Deml (2025) refined this recommendation by demonstrating that approach position significantly influences cooperation behvavior and recommended that AVs approaching the intersection from the bottom should stop. Due to mixed results across their studies, they could not give recommendations regarding the approach position left and right. The present study is able to further refine these recommendations by providing explanation for the observed behavioral patterns. Drivers approaching from the right most frequently perceived themselves as having priority compared to the other two positons and are most often expected to drive first. The right-approaching vehicle therefore appears best positioned to resolve the deadlock by proceeding first, while vehciles approaching from the left or below appear less suitable for this role. For the right-approaching vehicle, a moderately offensive approach, e.g. slowing down while still rolling forward at reduced speed (Imbsweiler, 2019), can communicate intent without compromising safety.

It should be noted that these recommendations are derived from the behavior and perceptions of manual drivers and have not been directly tested from the perspective of AV passengers. However, based on drivers' rule interpretations, behavioral expectations, and self-reported behavior, the right approach position appears most suitable for an AV to resolve the deadlock by driving first.

Beyond the question of which vehicle should drive first, the present findings have further implications for how AVs should interact with human drivers in deadlock situations at T-intersections. The results show that drivers do not share a uniform mental model of the situation and may draw different conclusions from the same situational cues, which complicates mutual understanding. Moreover, drivers tend to respond primarily to the vehicle located opposite their own approach, which does not always corredpond to the vehicle that can formally grant them priority. This makes explicit communication signals, such as flashing headlights to yield, potentially unreliable, as such cues might be interpreted by the wrong driver or directed at the wrong vehicle. Therefore, an AV must be able to reliably predict the intentions of other drivers. While this can be based on observable behavior, approach direction could also serve as a strong contextual predictor, as it systematically influenced drivers' perception and interpretation of the deadlock situation and, consequently, their actions.

CRediT authorship contribution statement

Nadine-Rebecca Strelau: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Barbara Deml:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve translations and the readability of certain sections of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

Acknowledgments

This project has been funded within the priority program 1835 “Cooperatively Interacting Automobiles” by the German Research Foundation (DFG).

Data availability

The authors do not have permission to share data.

References

ADAC. (2022). Nur Halbwissen bei vielen Autofahrern. https://presse.adac.de/meldungen/adac-ev/tests/nur-halbwissen-bei-vielen-autofahrern.html.

ADAC Unfallforschung. (2023). *Abbiege- und Kreuzenunfälle im Ländervergleich 2022*.

Al-Rukaibi, F., Ali, M. A., & Aljassar, A. H. (2006). Traffic safety attitudes and driving behavior of university students. *Transportation Research Record: Journal of the Transportation Research Board, 1969*(1), 65–71. https://doi.org/10.1177/0361198106196900109

Björklund, G. M., & Åberg, L. (2005). Driver behaviour in intersections: Formal and informal traffic rules. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(3), 239–253. https://doi.org/10.1016/j.trf.2005.04.006

Chaiken, S., & Ledgerwood, A. (2012). A theory of heuristic and systematic information processing. In *Handbook of theories of social psychology: Volume 1* (pp. 246–266). SAGE Publications Ltd. https://doi.org/10.4135/9781446249215.n13.

Chandrasekaran, L., Crookes, A., & Lansdown, T. C. (2019). Driver situation awareness – Investigating the effect of passenger experience. *Transportation Research Part F: Traffic Psychology and Behaviour, 61*, 152–162. https://doi.org/10.1016/j.trf.2017.12.007

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 37*(1), 32–64. https://doi.org/10.1518/001872095779049543

Fuller, R. (2011). Driver control theory: From task difficulty Homeostatis to risk Allostasis. In B. E. Porter (Ed.), *Handbook of traffic psychology* (pp. 13–26). Elsevier. https://doi.org/10.1016/B978-0-12-381984-0.10002-5.

Hasan, T., & Al-Bar, H. O. (2009). *Assessment of driver understanding of traffic control devices in Saudi Arabia. Transportation research board 88th annual MeetingTransportation research board, 2009*.

Imbsweiler, J. (2019). *Kooperation im Straßenverkehr in innerstädtischen Pattsituationen [Dissertation, Karlsruher Institut für Technologie]. (RIS.)*.

Imbsweiler, J., Palyafári, R., Deml, B., & Puente León, F. (2016). *Entwicklung einer Beobachtungsmethode von Verhaltensströmen in kooperativen Situationen im innerstädtischen Verkehr. In 32. VDI/VW-Gemeinschaftstagung Fahrerassistenzsysteme und automatisiertes Fahren, Wolfsburg*.

Imbsweiler, J., Ruesch, M., Weinreuter, H., Puente León, F., & Deml, B. (2018). Cooperation behaviour of road users in t-intersections during deadlock situations. *Transportation Research Part F: Traffic Psychology and Behaviour, 58*, 665–677. https://doi.org/10.1016/j.trf.2018.07.006

Jeon, M., Walker, B. N., & Gable, T. M. (2014). Anger effects on driver situation awareness and driving performance. *Presence Teleoperators and Virtual Environments, 23*(1), 71–89. https://doi.org/10.1162/PRES_a_00169

Jeon, M., Walker, B. N., & Gable, T. M. (2015). The effects of social interactions with in-vehicle agents on a driver's anger level, driving performance, situation awareness, and perceived workload. *Applied Ergonomics, 50*, 185–199. https://doi.org/10.1016/j.apergo.2015.03.015

Kaber, D., Jin, S., Zahabi, M., & Pankok, C. (2016). The effect of driver cognitive abilities and distractions on situation awareness and performance under hazard conditions. *Transportation Research Part F: Traffic Psychology and Behaviour, 42*, 177–194. https://doi.org/10.1016/j.trf.2016.07.014

Kass, S. J., Cole, K. S., & Stanny, C. J. (2007). Effects of distraction and experience on situation awareness and simulated driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 10*(4), 321–329. https://doi.org/10.1016/j.trf.2006.12.002

Kulkarni, V., Kanchan, T., Palanivel, C., Papanna, M. K., Kumar, N., & Unnikrishnan, B. (2013). Awareness and practice of road safety measures among undergraduate medical students in a south indian state. *Journal of Forensic and Legal Medicine, 20*(4), 226–229. https://doi.org/10.1016/j.jflm.2012.09.022

Lee, Y. M., & Sheppard, E. (2016). The effect of motion and signalling on drivers' ability to predict intentions of other road users. *Accident Analysis and Prevention, 95* (Pt A), 202–208. https://doi.org/10.1016/j.aap.2016.07.011

Lu, Z., Coster, X., & de Winter, J. (2017). How much time do drivers need to obtain situation awareness? A laboratory-based study of automated driving. *Applied Ergonomics, 60*, 293–304. https://doi.org/10.1016/j.apergo.2016.12.003

Ma, R., & Kaber, D. B. (2007). Situation awareness and driving performance in a simulated navigation task. *Ergonomics, 50*(8), 1351–1364. https://doi.org/10.1080/00140130701318913

McKerral, A., & Pammer, K. (2021). Identifying objective behavioural measures of expert driver situation awareness. *Accident; Analysis and Prevention, 163*, Article 106465. https://doi.org/10.1016/j.aap.2021.106465

Schmidt, A. F., & Finan, C. (2018). Linear regression and the normality assumption. *Journal of Clinical Epidemiology, 98*, 146–151. https://doi.org/10.1016/j.jclinepi.2017.12.006

Statistisches Bundesamt. (2024a). Fehlverhalten der fahrer bei unfällen mit personenschaden. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Verkehrsunfaelle/Tabellen/fehlverhalten-fahrzeugfuehrer.html.

Statistisches Bundesamt. (2024b). Straßenverkehrsunfälle nach unfallkategorie*,* Ortslage. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Verkehrsunfaelle/Tabellen/polizeilich-erfasste-unfaelle.html.

Strelau, N.-R., & Deml, B. (2025). Drive first or yield? Effect of complexity on cooperation behavior at deadlock-situations at t-intersections. *Transportation Research Part F: Traffic Psychology and Behaviour, 109*, 754–769. https://doi.org/10.1016/j.trf.2024.12.035

Tinga, A. M., Cleij, D., Jansen, R. J., van der Kint, S., & van Nes, N. (2022). Human machine interface design for continuous support of mode awareness during automated driving: An online simulation. *Transportation Research Part F: Traffic Psychology and Behaviour, 87*, 102–119. https://doi.org/10.1016/j.trf.2022.03.020

Wijayanto, T., Marcillia, S. R., Lufityanto, G., Wisnugraha, B. B., Alma, T. G., & Abdianto, R. U. (2021). The effect of situation awareness on driving performance in young sleep-deprived drivers. *IATSS Research, 45*(2), 218–225. https://doi.org/10.1016/j.iatssr.2020.10.002

Yang, Y., Karakaya, B., Dominioni, G. C., Kawabe, K., & Bengler, K. (2018). *An HMI Concept to Improve Driver's Visual Behavior and Situation Awareness in Automated Vehicle. In 2018 21st international conference on intelligent transportation systems (ITSC)*. IEEE. https://doi.org/10.1109/itsc.2018.8569986