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The Matter of How and When: Comparing Explicit and Implicit Communication Strategies of Automated Vehicles in Bottleneck Scenarios

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ABSTRACT The introduction of automated vehicles (AVs) leads to mixed traffic where the AV should safely and efficiently integrate into established interactions. Since the driving behavior and thus the AV's communication may differ from that of traditional road users, highly comprehensible communication strategies are needed to reliably convey the AV's intention. This work investigates the encounter of an AV and a simultaneously oncoming human driver at bottlenecks due to double-parked vehicles on both sides of the road. Regarding this scenario, we aim to answer how and when the AV should communicate right-of-way to ensure safe and efficient interactions. In a driving simulator study, 31 participants experienced eight different communication strategies in which the AV communicated explicitly via an external human-machine interface simultaneously and separately to an implicit lateral vehicle movement. Furthermore, the AV triggered its communication based on human choice reaction time. Results show that AVs should communicate right-of-way explicitly and implicitly together while not changing their maneuver to ensure safety and increase efficiency. This combined approach was rated highly comprehensible, avoided crashes, and increased participants' passing times by shortening human decision time. In addition, triggering the communication based on human choice reaction time enables the human driver to react appropriately.

INDEX TERMS Automated vehicle movement, communication timing, external human-machine interface, human-automation interaction.

I. INTRODUCTION

ESPECIALLY in urban areas, the implementation of automated vehicles (AVs) leads to mixed traffic consisting of AVs and human road users [1]. Thereby, the automated system performs lateral and longitudinal vehicle guidance [2] that may result in a deviation from human driving behavior. Moreover, the AV's passenger could engage in non-driving related activities [3] and is therefore not available for communication. Both facts change road traffic interaction causing demands on AVs' communication capabilities [4]. Only effective communication enables successful cooperation between road users [5], which is the basis for reaching the goals of traffic automation to increase safety [6] and efficiency [7]–[9].

The modification in AV-human road user interaction is relevant in road bottlenecks (Fig. 1) [10]–[12]. In these scenarios, an AV and a human driver simultaneously approach a bottleneck consisting of one double-parked vehicle on each side of the road. Due to the concurrent arrival, the right-of-way is not regulated by law [13], resulting in one interaction partner taking the defensive part and yielding to the other partner [14]. Although simulations showed that double-parking vehicles increase the probability of incidents and accidents in their surroundings [15], we could not find any real traffic data supporting this statement. A study from Germany even showed that road traffic interactions at constructional bottlenecks are safe and only have an accident

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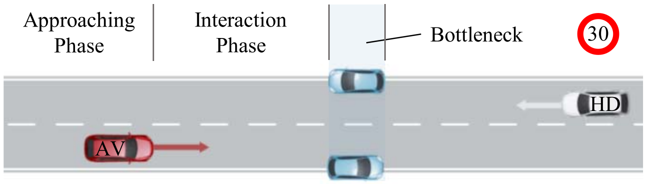

FIGURE 1. Bottleneck scenario caused by two double-parked vehicles. The automated vehicle (AV) and the human driver (HD) arrive simultaneously.

rate of 7.6 accidents/million km [16]. For this reason, the goal should be to maintain the already high safety level in bottleneck scenarios by means of the AV's external communication strategy and to increase traffic efficiency on that basis. To achieve this aim, the AV should communicate its intention to yield the right-of-way or to insist on it during the Interaction Phase [17]. For this purpose, the AV could communicate either explicitly via external human-machine interfaces (eHMIs), implicitly via the AV movement, or via a combination of both approaches [18], [19].

In the bottleneck scenario, explicit communication via eHMIs [20] and implicit communication via a lateral offset to the edge or to the center of the road [21] similarly reduced the human driver's passing times in case the AV yielded the right-of-way and provided safe interactions if the AV insisted on it. Furthermore, an interaction model depending on human choice reaction time [22] showed that the AV should communicate its intention early enough so that the oncoming human driver has sufficient time to react appropriately.

This study differs from the two previous contributions [20], [21] and most of the existing research in the field of AV-human road user interaction by investigating the potential of a redundant explicit and implicit communication strategy. Thereby, we aim to draw the pending comparison between the explicit and implicit communication approaches by analyzing them separately and together since their combination may provide more efficient interactions [23], [24]. Furthermore, the AV's external communication does not follow the distance-based triggering common in existing research, but performs it in a time-based manner. This approach considers the time required by the human driver to interact independently of the relative speeds driven in the scenario and thus incorporates the dynamics of both interaction partners. Moreover, a detailed analysis of the human driver's behavior including the distributions of the sub-task durations extends the mostly literature-based interaction model [22] and allows its pending validation. These aspects lead to the following research questions.

RQ1: Does the combination of explicit and implicit communication result in safe and more efficient passages through the bottleneck scenario than both communication strategies separately?

RQ2: When should the AV communicate to provide the oncoming human driver with sufficient time to react appropriately?

II. COMMUNICATION STRATEGY

A. COMMUNICATION TIMING – THE INTERACTION MODEL

Triggering the communication independently of the human driver's speed in both previous studies [20], [21] provided participants different amounts of time to act according to the AV's communication. To avoid this dissimilarity, we analyzed the latest possible communication timing at which the human driver has sufficient time to detect, process, and appropriately respond to the AV's communication. For this purpose, we performed a mostly literature-based task analysis of the human driver and built an interaction model (Fig. 2) that describes the sequence of tasks that the human driver has to perform in case the AV insists on the right-of-way [22]. We assumed that the communication timing is the same if the AV yields the right-of-way, since the AV's intention is unknown before the communication and thus the human driver might decelerate unnecessarily. The interaction model subdivides the Interaction Phase into the individual parts of Choice Reaction Time (*CRT*) (Detection, Identification, Decision, and Response [25] based on [26]), the vehicle braking distance, the stop distance, and half a bottleneck length. The model describes the bottleneck passage in a time-based manner by quantifying the individual parts of the *CRT* and therefore it applies to all speed ranges. Moreover, human drivers estimate encounters with oncoming vehicles and direct their own driving behavior time-based rather than distance-based [27]–[29]. For these reasons, the communication of the AV was triggered based on the interaction model when the human driver's time to arrival (TTA_{HD}) to the speed dependent braking start X_{brake} fell below $T_{CRT} = 1,338$ ms ($TTA_{HD} \leq T_{CRT}$) [22].

B. HUMAN-MACHINE INTERFACE

1) EXPLICIT COMMUNICATION – EXTERNAL HUMAN-MACHINE INTERFACE

The AV explicitly communicates the right-of-way via a display mounted at its front (Fig. 3–Fig. 5). The eHMI was designed in a user survey and was subsequently evaluated in a driving simulator study [20]. It consists of two lines indicating the roadway and an animated arrow showing in which direction the bottleneck should be passed first. Additional color-coding (*AV yields the right-of-way:* green; *AV insists on the right-of-way:* orange) was used to clarify the AV's intention.

The communication via the eHMI supported the human driver when passing through the bottleneck scenario resulting in safe interactions and significantly shorter passing times compared to encounters without the eHMI. [20]

2) IMPLICIT COMMUNICATION – AUTOMATED VEHICLE MOVEMENT

The AV performs an offset to the edge of the road to yield and an offset to the center to insist on right-of-way since this resulted in more efficient interactions than communicating solely by adjusting the longitudinal driving behavior. The offset is one meter and it is built up over a length of ten

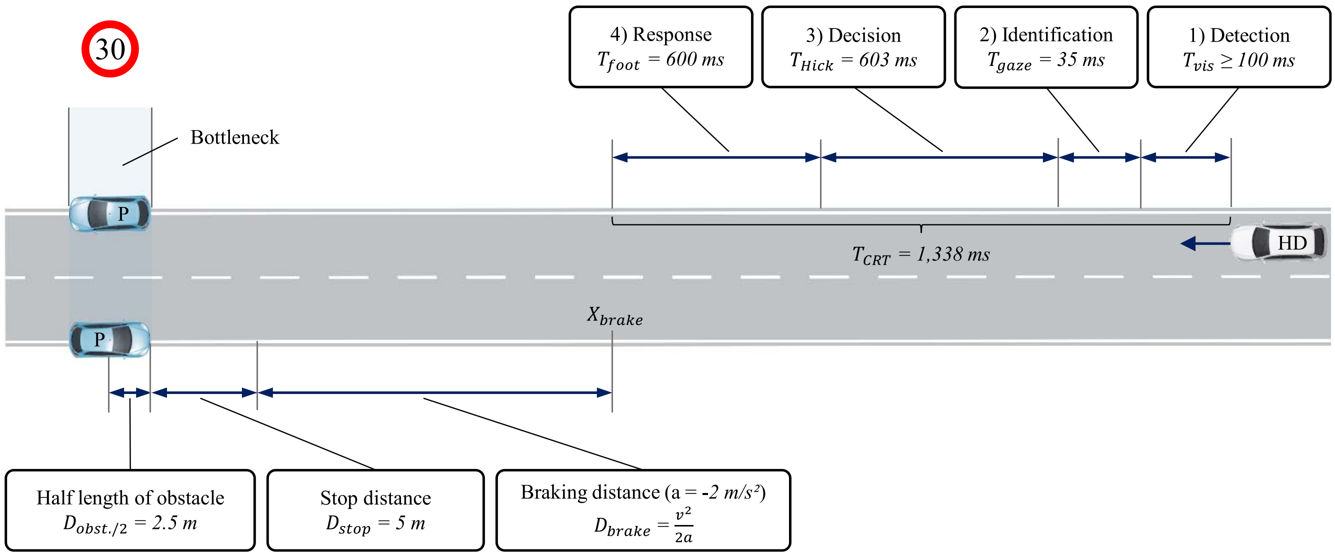

FIGURE 2. Task analysis of the human driver in case the AV insists on the right-of-way. The exact derivation of the interaction model can be found in Rettenmaier and Bengler [20].

TABLE 1. Characteristics of the eight use cases regarding the status of the eHMI, the offset, and the intention of the AV.

	AV yields the right-of-way		AV insists on the right-of-way	
	Two-step deceleration		Maintenance of speed	
	No offset	Offset to edge	No offset	Offset to center
eHMI off	Use case 1	Use case 3	Use case 5	Use case 7
eHMI on	Use case 2	Use case 4	Use case 6	Use case 8

meters. Simultaneously with the offset, the AV yields the right-of-way by decelerating in two steps (decelerating from 30 km/h to 15 km/h, then maintaining speed at 15 km/h until the second deceleration from 15 km/h to 0 km/h) at -2 m/s^2 which is used by human drivers in low speed areas [30], and maintaining speed to insist on the right-of-way. [21]

Since space offering is used to yield the right-of-way in road traffic [31], the lateral offset to the edge of the road resulted in safe interactions and significantly shorter passing times of human drivers compared to AV movements without this offset. [21]

3) FINAL COMMUNICATION STRATEGY

In this study, the AV communicated via the eHMI (Section II-B1) as well as via AV movement (Section II-B2). Furthermore, the start of communication was triggered when $TTA_{HD} \leq T_{CRT}$ was reached (Section II-A). The combination of the factor levels of eHMI (*eHMI on*, *eHMI off*), offset (*offset*, *no offset*), and intention (*AV yields the right-of-way*, *AV insists on the right-of-way*) resulted in eight use cases (Table 1). Fig. 3 and Fig. 4 visualize the eHMI, offset, and speed adjustment regarding the AV yielding right-of-way and insisting on right-of-way, respectively.

In all cases, the AV decelerated in two steps (Dec_{time}) to yield the right-of-way and maintained speed to insist on it. However, if participants reduced speed very early, $TTA_{HD} \leq T_{CRT}$ would not have been reached, resulting in that the communication strategy intended for this encounter would not have been triggered. In these cases, the AV communicated distance-based ($Dec_{dist.}$) at the point (d_{stop}) where it had to start decelerating at -2 m/s^2 from 30 km/h to a standstill in order to come to a stop five meters in front of the bottleneck. This procedure allowed all participants to experience the communication strategies equally often and thus to evaluate and compare them.

4) AUTOMATION FAILURE

In addition to the regular interactions (use cases 1-8), we analyzed an automation failure at a bottleneck narrowed only on the AV's side of the road (Fig. 5). In this scenario, the AV started to yield the right-of-way at a distance of 50 m from the bottleneck in accordance with law. For communication, the AV used the green arrow and a simultaneous lateral offset to the edge. Thirty meters in front of the bottleneck, the AV no longer recognized the oncoming vehicle and started to pass the bottleneck. Therefore, it displayed the orange arrow and performed an offset back to the center of its own lane.

We refrained from time-based triggering of the AV's communication because we intended this scenario to be comparable to the automation failures in previous studies where the crash rates were 95.24% [20] and 97.06% [21]. Building on these findings, this study investigated whether simultaneous explicit and implicit communication renders the automation failure controllable for the human driver and reduces the crash rate.

III. METHOD

A. SAMPLE

The study includes the data sets of 31 participants with an average age of $M = 32.39$ years ($SD = 12.55$ years). The age range was 23 years to 69 years. Seventeen participants

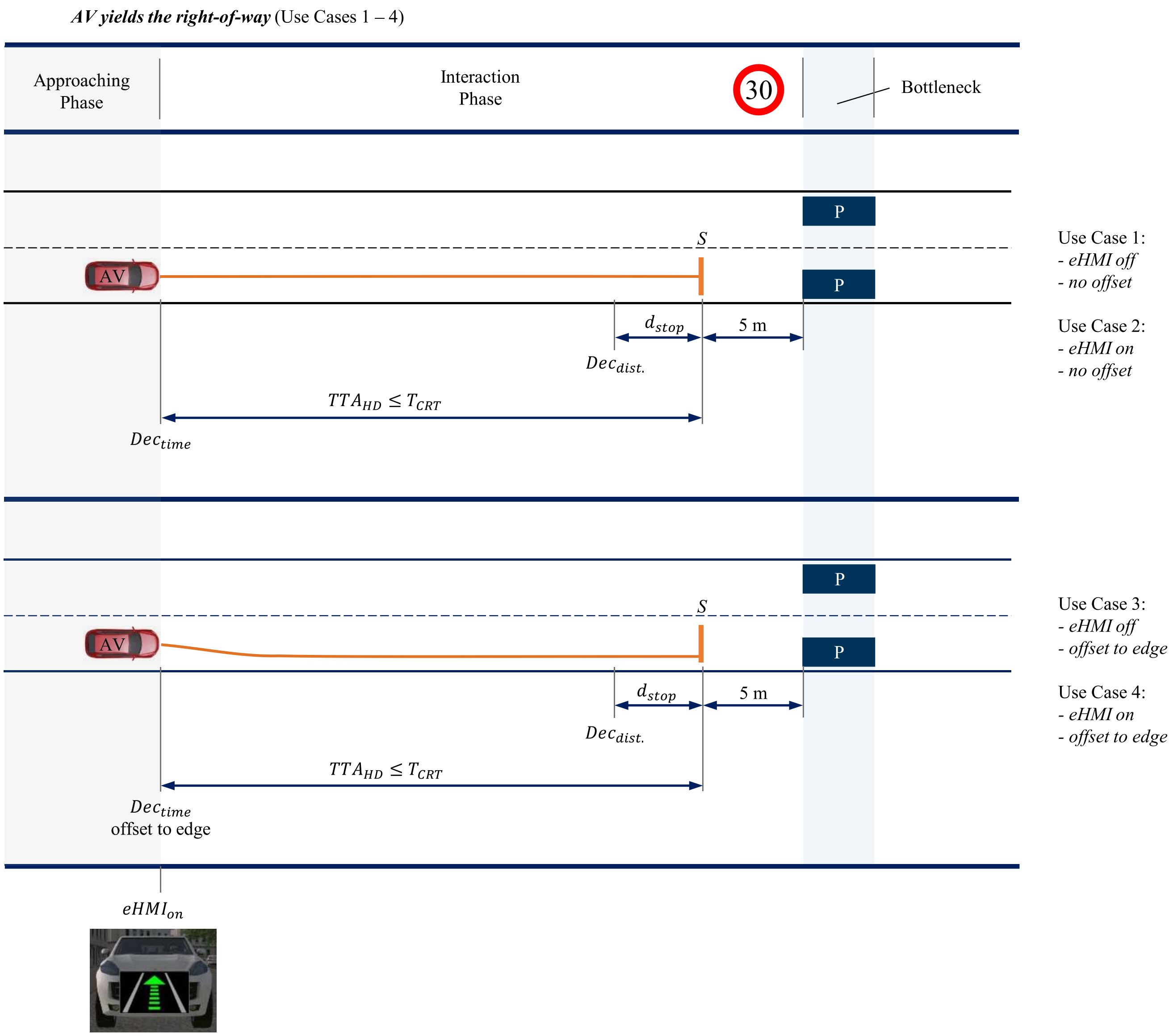

FIGURE 3. Four communication strategies the AV uses to yield the right-of-way.

were male and 14 were female. In order to attend in the study, the participants must have neither participated in the study for explicit communication [20] nor in the study for implicit communication [21]. In addition, the participants had to possess a valid German driver's license. Recruitment was conducted in social networks and on the campus of the university. Participants received an expense allowance of 15 €.

B. DRIVING SIMULATOR

The study took place in the dynamic driving simulator of the Chair of Ergonomics at the Technical University of Munich. The simulator includes a platform on which a driver's seat is installed. Four electrical actuators with a movement range of three inches allow for pitch and roll movements of the driver's seat. The simulation environment was created with the software SILAB 6.0 of the Würzburg Institute for Traffic Sciences GmbH and was displayed on three screens with a resolution of 3,840 x 2,160 pixels. To analyze the human driver's response to the AV's communication, a camera (GoPro Hero6) was mounted in the simulator's footwell. It recorded both the participants' foot movements and the simulation time shown on a display. This approach enabled the synchronization of the foot movements with the simulation data.

C. EXPERIMENTAL DESIGN AND PROCEDURE

At the start of the experiment (Fig. 6), the participants read the experimental information, consented to participate and filled in the demographic survey. The subsequent instructions described that the experiment deals with an AV communicating the right-of-way at road bottlenecks. During an introductory drive, the participants were able to familiarize themselves with the simulator by passing four road bottlenecks without oncoming traffic. Thereafter, the first

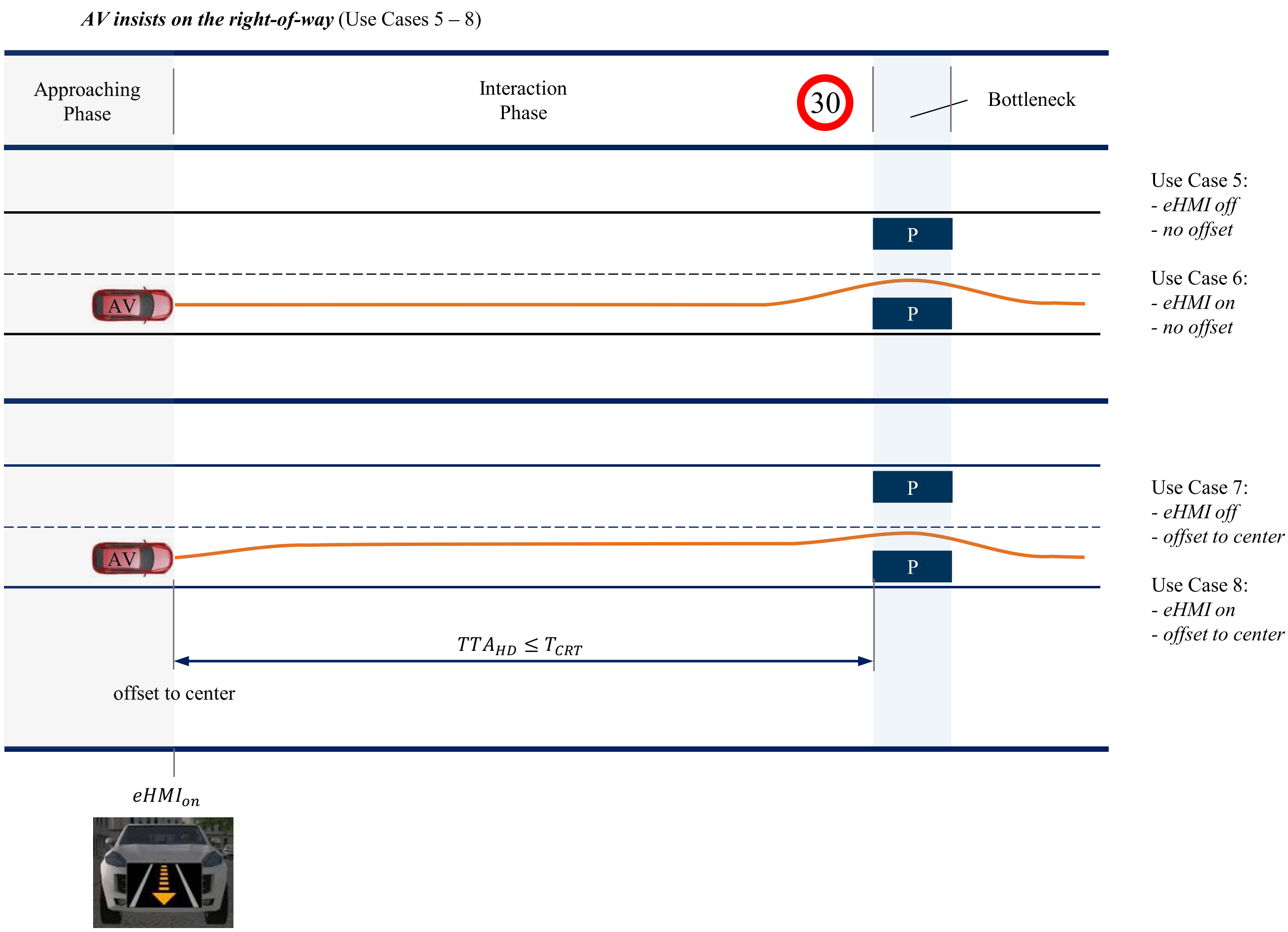

FIGURE 4. **Four communication strategies the AV uses to insist on the right-of-way.**

experimental drive was performed consisting of a repeated measures design with the four factors of intention (*AV yields the right-of-way*, *AV insists on the right-of-way*), offset (*offset*, *no offset*), eHMI (*eHMI on*, *eHMI off*), and contact (*1st*, *2nd*, *3rd*). This resulted in eight use cases, each of which was experienced in randomized order in three consecutive blocks (1A, 1B, 1C) in one continuous drive. Moreover, we integrated a bottleneck narrowed on the AV's side of the road in each block where the AV yielded the right-of-way via the eHMI and the offset to render the automation failure in the end of the experiment less obvious. After the intermediate survey, the second experimental drive was performed consisting of four randomly selected use cases and the automation failure.

D. DEPENDENT VARIABLES

Since the intermediate survey could have influenced participants' driving behavior, all objective data except for the automation failure was measured in the first experimental drive. Safety was evaluated based on the number of crashes and the crash rate of the human driver with the AV during regular encounters (use cases 1-8) as well as during the automation failure. Efficiency was evaluated based on the human drivers' passing times, which we defined as the time period from 50 m before the bottleneck to 10 m after the bottleneck. This definition allows a comparison of the passing times of this study with those of previous studies [20], [21]. For a more detailed analysis, we determined the decision time and the response time if the AV yielded the right-of-way. Decision time was calculated by the time span from the start of the AV's communication until the moment when the human driver's foot started to move towards the accelerator pedal subtracting the detection time ($T_{vis} = 100\ ms$). Response time was defined as the duration of the foot movement towards the accelerator pedal and ended when it touched the pedal. If the AV insisted on the right-of-way, the decision and response time could not be determined because participants could decide to press the brake pedal due to uncertainty before the AV communicated to do so. Additionally, we evaluated the comprehensibility as subjective measure subdivided according to the AV's intention in the intermediate survey, using the item in Table 2.

E. STATISTICAL ANALYSIS

The data were processed with MATLAB and Excel. Statistical analysis was performed with JASP [32]. The significance level was set to $\alpha = 0.05$. We used a 3 (*contact*)

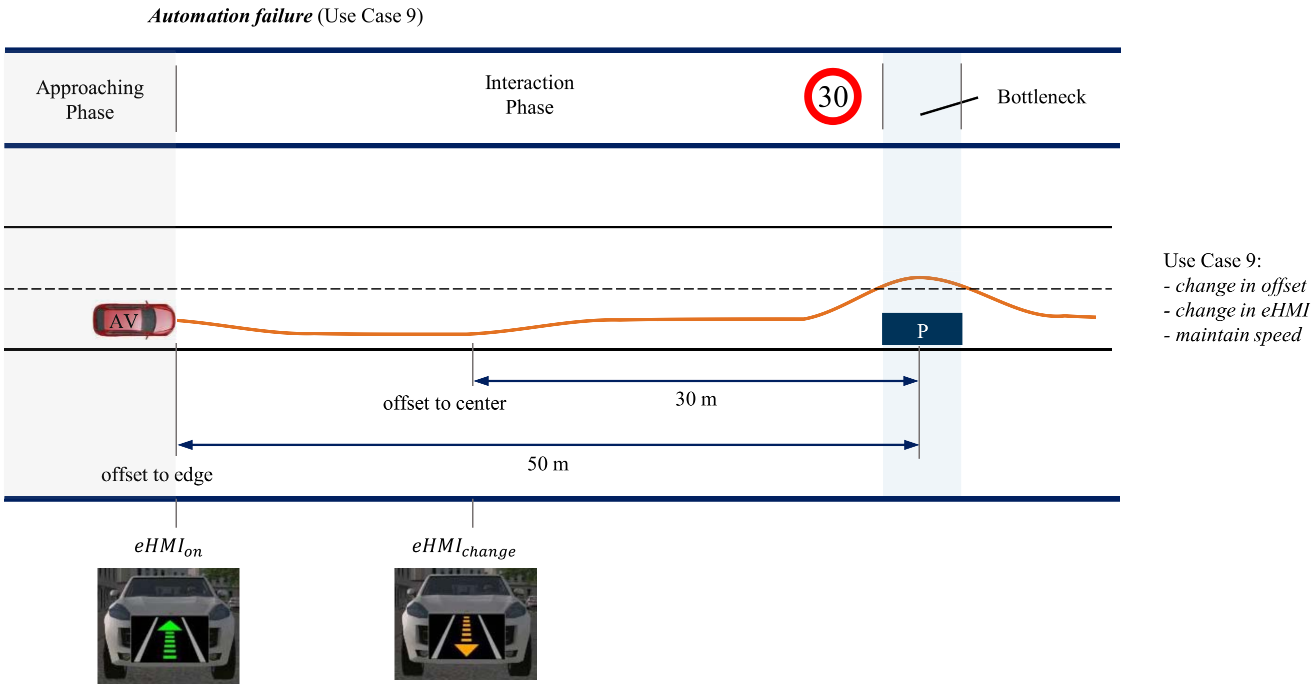

FIGURE 5. The communication strategy of the AV during the automation failure.

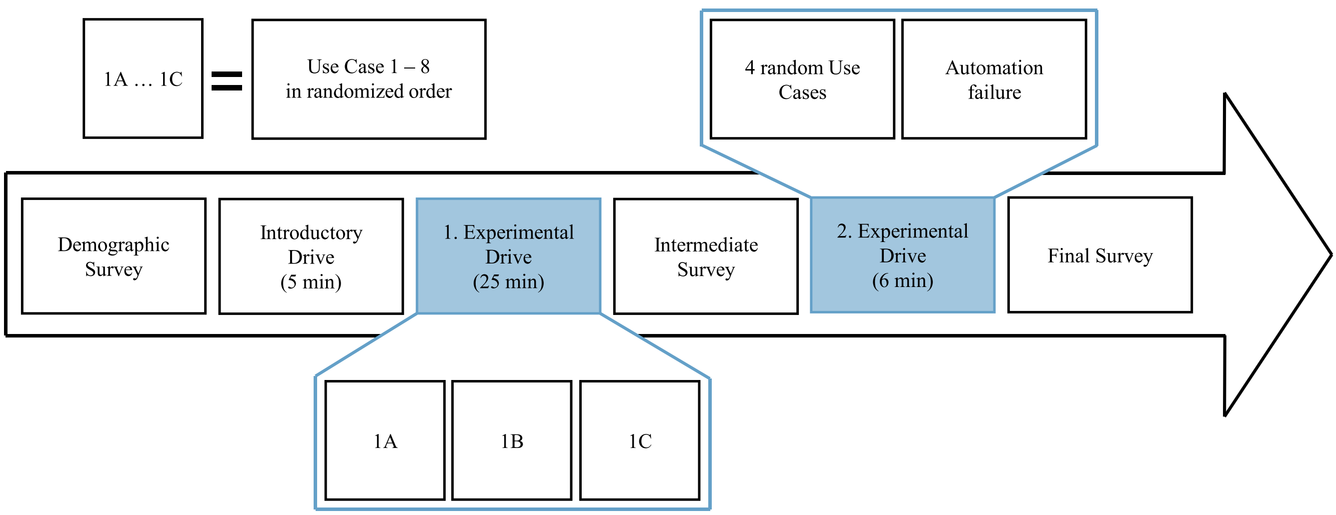

FIGURE 6. Experimental procedure the participants went through during the study.

TABLE 2. Comprehensibility.

How do you rate the comprehensibility of the message "*AV yields the right-of-way*" ("*AV insists on the right-of-way*") using the following communication strategies?	
- *no eHMI + no offset* - *no eHMI + offset* - *eHMI + no offset* - *eHMI + offset*	7-point Likert Scale: Very bad – Very good

x 2 (*eHMI*) x 2 (*offset*) repeated measures ANOVA to analyze the passing times, considering its robustness against a violation of normal distribution [33], [34]. Since sphericity was violated for the contact (Mauchly's test: $p < 0.001$), the data were corrected according to Greenhouse Geisser. In addition, we performed a repeated measures ANOVA to analyze the effect of the communication strategy on decision time and response time at the third contact respectively. Since sphericity was not provided, both data sets were corrected according to Greenhouse Geisser (Mauchly's test: $p < 0.05$). The effect sizes were quantified using Cohen's benchmark (small effect: $d = 0.2$, $\eta_p^2 = 0.01$; medium effect: $d = 0.5$, $\eta_p^2 = 0.06$, large effect: $d = 0.8$, $\eta_p^2 = 0.14$) [35]. For the post-hoc comparisons, we applied a Bonferroni correction to adjust the probability values due to the increased risk of a type I error when multiple statistical tests are conducted.

We performed a non-parametric Friedman test to analyze the ordinal-scaled data of comprehensibility and we

TABLE 3. Absolute number of crashes and crash rate when the AV insisted on right-of-way classified by the AV's communication strategy. ($n = 31$).

contact	no eHMI + no offset	eHMI + no offset	no eHMI + offset	eHMI + offset	automation failure
1	2	1	0	0	-
2	1	0	0	0	-
3	0	0	0	0	-
In total	3 (3.23%)	1 (1.08%)	0 (0%)	0 (0%)	15 (48.39%)

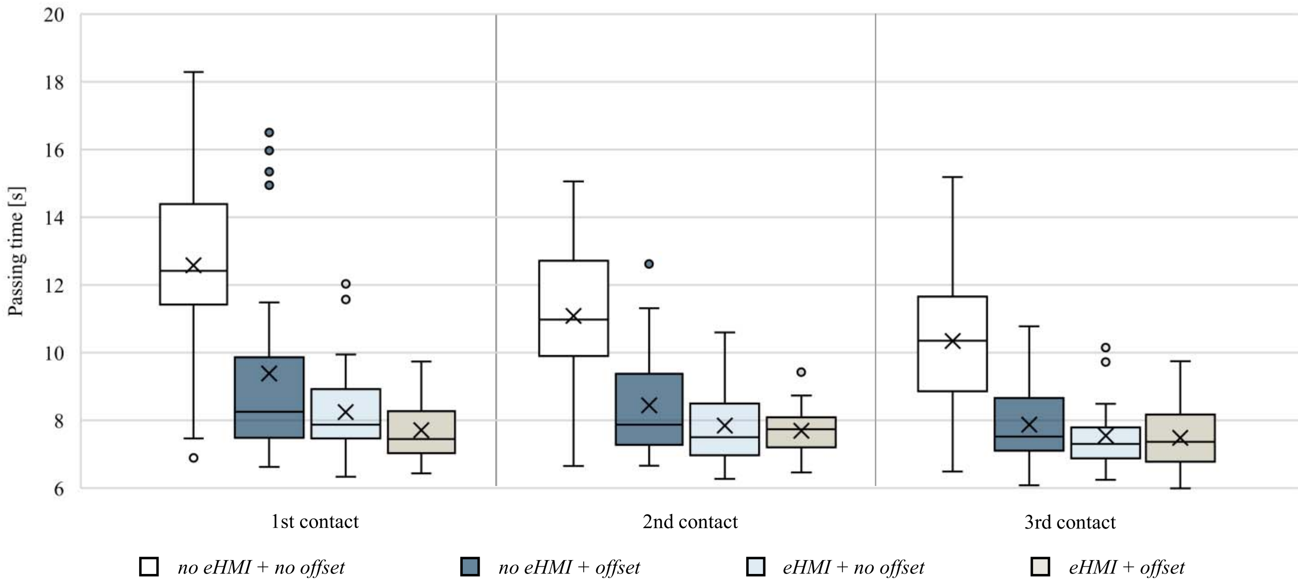

FIGURE 7. Participants' passing times when the AV yielded the right-of-way divided by the AV's communication and by the contact. ($n = 31$).

used Kendall's W (small effect: $W = 0.1$; medium effect: $W = 0.3$; large effect: $W = 0.5$) to evaluate the effect size. Non-parametric Wilcoxon tests were performed as post-hoc comparisons and the significance level was corrected according to Bonferroni. The effect sizes of the Wilcoxon tests were quantified using the Pearson product-moment correlation coefficient r (small effect: $r = 0.1$; medium effect: $r = 0.3$; large effect: $r = 0.5$).

IV. RESULTS

A. TRAFFIC SAFETY – CRASHES

Considering all communication strategies and all contacts, only few accidents happened during the regular encounters (Table 3). Provided that a lateral offset was performed, no crash occurred regardless of the eHMI state. For the automation failure, the crash rate (48.39%) was considerably higher than for regular interactions. Although all participants reported noticing the automation failure, half of the sample could not control it.

B. TRAFFIC EFFICIENCY

1) PASSING TIMES

Fig. 7 illustrates that the ranking of the communication strategies regarding the shortest passing times is the same regardless of the number of contacts. When the AV communicates via *no eHMI* + *no offset*, the human drivers need the highest amount of time to pass the bottleneck scenario. If the right-of-way is communicated using the eHMI or the lateral offset separately, the human drivers have shorter passing times when the AV communicates via eHMI. The shortest passing times occur when the AV communicates the right-of-way simultaneously via *eHMI* + *offset*. The respective descriptive data is shown in Table 4. The statistical analysis (Table 5) confirms a significant difference in the passing time due to the eHMI, the offset, as well as the contact, each with a large effect. The post-hoc comparisons (Table 6) show that the passing time significantly decreases for each subsequent contact with a large effect respectively.

TABLE 4. Descriptive data giving the passing times when the AV yielded the right-of-way divided by the AV's communication and by the contact. ($n = 31$).

	1st contact	2nd contact	3rd contact
no eHMI + no offset *M(SD)* [ms]	12577 (2781)	11087 (2075)	10340 (2112)
no eHMI + offset *M(SD)* [ms]	9388 (2785)	8444 (1591)	7877 (1103)
eHMI + no offset *M(SD)* [ms]	8247 (1272)	7848 (1122)	7550 (1075)
eHMI + offset *M(SD)* [ms]	7709 (914)	7695 (793)	7489 (900)

TABLE 5. Repeated measures ANOVA– passing time. ($n = 31$).

	F	df	p	η^2_p
Contact	18.294	1.398	<0.001	0.379
eHMI	67.808	1.000	<0.001	0.693
Offset	64.821	1.000	<0.001	0.684
*Contact*eHMI*	11.374	1.744	<0.001	0.275
*Contact*Offset*	2.898	1.833	0.068	0.088
*eHMI*Offset*	50.117	1.000	<0.001	0.626
*Contact*eHMI*Offset*	0.114	1.506	0.836	0.004

TABLE 6. Post-hoc comparisons – contact. ($n = 31$).

		p_{bonf}	*Cohen's d*
1st contact	*2nd contact*	0.009	0.578
	3rd contact	<0.001	0.924
2nd contact	*3rd contact*	0.001	0.715

TABLE 7. Descriptive data giving the decision and response times when the AV yielded the right-of-way at the third contact divided by the AV's communication. The number of data sets (n) varies because the GoPro failed during some use cases.

	Decision [ms] (T_{Dec})	Response [ms] (T_{Resp})
no eHMI + no offset ($n = 29$)	$M = 3{,}114$ ($SD = 1{,}467$) $Mdn = 2786$	$M = 1{,}051$ ($SD = 917$) $Mdn = 764$
no eHMI + offset ($n = 27$)	$M = 1{,}245$ ($SD = 1{,}187$) $Mdn = 734$	$M = 660$ ($SD = 329$) $Mdn = 598$
eHMI + no offset ($n = 28$)	$M = 570$ ($SD = 387$) $Mdn = 430$	$M = 864$ ($SD = 742$) $Mdn = 658$
eHMI + offset ($n = 29$)	$M = 388$ ($SD = 175$) $Mdn = 342$	$M = 775$ ($SD = 456$) $Mdn = 600$
Interaction Model [20]	$T = 603$	$T = 600$

TABLE 8. Post-hoc comparisons – decision time. ($n = 25$).

		p_{bonf}	*Cohen's d*
no eHMI + no offset	*no eHMI + offset*	< 0.001	1.176
	eHMI + no offset	< 0.001	1.711
	eHMI + offset	< 0.001	1.914
no eHMI + offset	*eHMI + no offset*	0.085	-
	eHMI + offset	0.010	0.706
eHMI + no offset	*eHMI + offset*	0.467	-

TABLE 9. Post-hoc comparisons – response time. ($n = 25$).

		p_{bonf}	*Cohen's d*
no eHMI + no offset	*no eHMI + offset*	0.063	-
	eHMI + no offset	0.467	-
	eHMI + offset	0.350	-
no eHMI + offset	*eHMI + no offset*	1.000	-
	eHMI + offset	1.000	-
eHMI + no offset	*eHMI + offset*	1.000	-

2) DECISION AND RESPONSE

In order to minimize the influence of the learning effect during the first encounters, we focus our consideration with each communication strategy on the third contact. The order of the decision time (Table 7) regarding the shortest durations corresponds to that of the passing times. The participants had the shortest decision time when the AV communicated simultaneously via the eHMI and lateral offset. This duration was even lower than the decision time of the interaction model [22]. In addition, the communication strategy significantly affects the decision time with a large effect, $F(2.08, 49.79) = 46.552$, $p = <0.001$, $\eta^2_p = 0.660$. The post-hoc analyses (Table 8) indicate that all comparisons except the comparisons *no eHMI + offset* with *eHMI + no offset* and *eHMI + offset* with *eHMI + no offset* result in significant differences with large effect sizes.

The response times (Table 7) do not follow the same trend as the decision times and the passing times with regard to the shortest time spans. The participants had the shortest response times when the AV communicated via *no eHMI+offset*. The communication strategy results in a significant difference of the response time, $F(1.30, 31.13) = 4.368$, $p = 0.036$, $\eta^2_p = 0.154$. However, the post-hoc comparisons show no significant results (Table 9).

C. INTERACTION SEQUENCE

We examined the interaction sequence in more detail to validate the interaction model and to derive an optimal communication timing. In the following, we restrict ourselves to the third contact with the most efficient communication strategy *eHMI + offset* when the AV yielded the right-of-way. This approach allows it to determine the minimum communication requirements from the human driver's perspective. Fig. 8 illustrates the interaction sequence and describes the last two seconds of the Approaching Phase and the entire Interaction Phase in detail.

In the Approaching Phase, all data from all passages of the third contact ($n = 248$) were analyzed because participants could not infer the AV communication before its start (T_{Start}). Half of the sample ($n = 126$, 50.81%) did not brake before T_{Start}, thus they reached $TTA_{HD} \leq T_{CRT}$ and reacted to the AV's communication. The other half ($n = 122$, 49.19%) applied the brakes before T_{Start}. This group can be subdivided into participants ($n_1 = 53$, 21.37%) who braked late enough ($M_1 = -799$ ms; $Mdn_1 = -417$ ms; $SD_1 = 924$ ms) to reach $TTA_{HD} \leq T_{CRT}$ and participants ($n_2 = 69$, 27.82%) who were braking so early ($M_2 = -4373$ ms; $Mdn_2 = -4150$ ms; $SD_2 = 2239$ ms) that they did not reach $TTA_{HD} \leq T_{CRT}$ and thus experienced the distance-based communication start. Fig. 8 does not show the data of this last mentioned group, since we did not consider it for optimizing the communication timing due to the broadly spread and very early braking onsets.

Following the literally determined detection time (T_{vis}), the Interaction Phase continues with the decision time and response time that are represented by their left-skewed distributions describing the end of the respective time span and by their mean values (T_{Dec}, T_{Resp}). Furthermore, the diagram

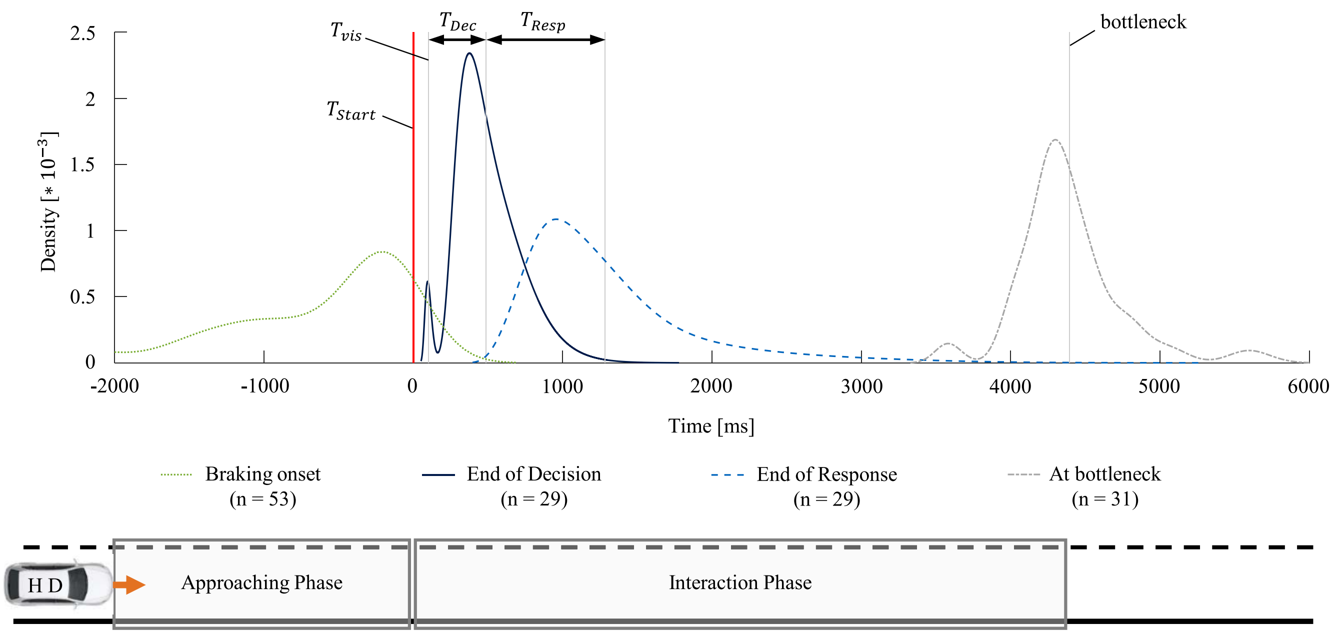

FIGURE 8. Interaction sequence of the AV and the human driver. Except for the distribution of the braking times, the figure refers exclusively to the third contact with the AV when it yielded the right-of-way via eHMI + offset.

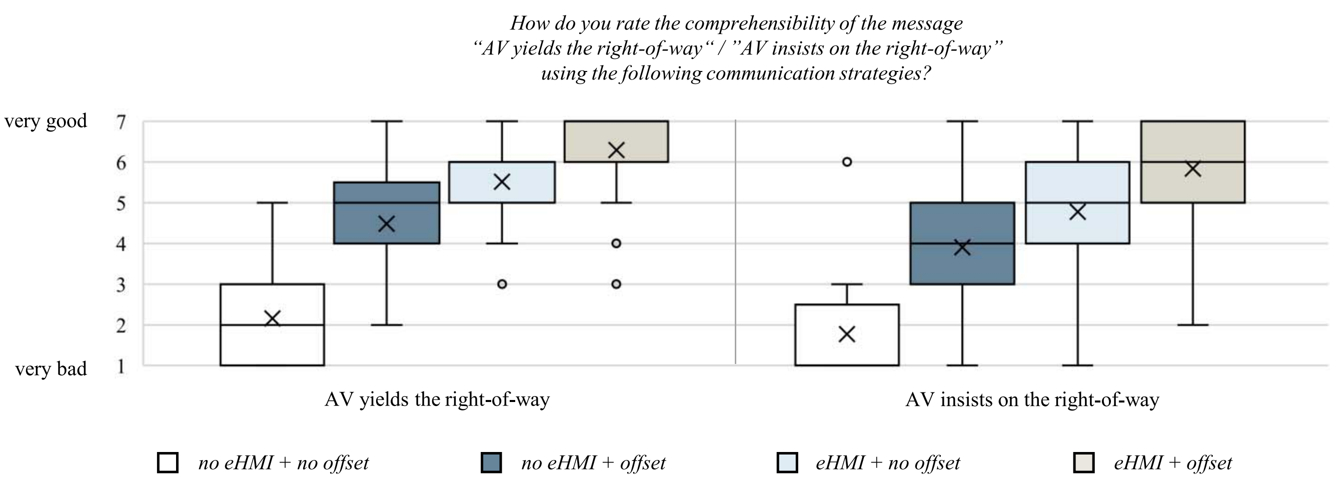

FIGURE 9. Participants' comprehensibility rating regarding the AV's communication strategies.

shows the time distribution when the participants reached the bottleneck.

D. SUBJECTIVE DATA – COMPREHENSIBILITY

The order of the communication strategies regarding best comprehensibility is equal for the AV yielding the right-of-way and insisting on it (Fig. 9, Table 10). In both cases, the communication strategy results in a significant difference in comprehensibility of the AV's intention (AV yields right-of-way: $X^2 2 = 71.979$, $p = <0.001$, *Kendall's* $W = 0.391$; AV insists on right-of-way: $X^2 2 = 59.234$, $p = <0.001$, *Kendall's* $W = 0.507$). The participants rated the communication *no eHMI + no offset* as the lowest in comprehensibility. The most comprehensible communication was *eHMI + offset*. The Wilcoxon tests for *AV yields right-of-way* (Table 11) and *AV insists on right-of-way* (Table 7) show significant differences in comprehensibility with large effect sizes for all comparisons except for the comparison *no eHMI + offset* with *eHMI + no offset.*

V. DISCUSSION

A. HOW TO ENSURE TRAFFIC SAFETY?

Since no crashes occurred with lateral offset, its performance ensures traffic safety regardless of the eHMI status, thus meeting a prerequisite for AV-human driver interaction in the bottleneck scenario. This positive finding can be explained by the fact that a lateral offset is already used by human drivers in today's traffic to communicate the

TABLE 10. Descriptive data – comprehensibility classified by the AV's communication. ($n = 31$).

	no eHMI + no offset	*no eHMI + offset*	*eHMI + no offset*	*eHMI + offset*
AV yields the right-of-way (*Mdn*)	2	5	6	7
AV insists on the right-of-way (*Mdn*)	2	4	5	7

TABLE 11. Post-hoc comparisons – comprehensibility of communication strategies when the AV yielded the right-of-way. ($n = 31$).

		W	*p*	*r*
no eHMI + no offset	*no eHMI + offset*	0.000	< .001	1.000
	eHMI + no offset	6.000	< .001	0.974
	eHMI + offset	0.000	< .001	1.000
no eHMI + offset	*eHMI + no offset*	83.000	0.154	0.344
	eHMI + offset	21.500	< .001	0.877
eHMI + no offset	*eHMI + offset*	0.000	< .001	1.000

Note: We applied a Bonferroni correction. The corrected level of significance was adjusted to $\alpha = 0.0167$.

TABLE 12. Post-hoc comparisons – comprehensibility of communication strategies when the AV insisted the right-of-way. ($n = 31$).

		W	*p*	*r*
no eHMI + no offset	*no eHMI + offset*	0.000	< 0.001	1.000
	eHMI + no offset	9.500	< 0.001	0.956
	eHMI + offset	2.000	< 0.001	0.991
no eHMI + offset	*eHMI + no offset*	124.000	0.070	0.389
	eHMI + offset	18.000	< 0.001	0.911
eHMI + no offset	*eHMI + offset*	0.000	< 0.001	1.000

Note: We applied a Bonferroni correction. The corrected level of significance was adjusted to $\alpha = 0.0167$.

right-of-way [20], [21]. Participants' direct understanding of the AV's intention comes with a higher predictability of the AV's future behavior, leading to non-critical and safe interactions.

However, as soon as there are communication irregularities, such as a maneuver change during the automation failure, traffic safety is no longer provided even though there was theoretically sufficient time to avoid a crash. Although displaying the changed intention via the eHMI reduced the crash rate substantially compared to both previous studies (95.24% [20], 97.06% [21]), the situation was still not controllable for the participants and even an intervention of the passenger in the AV would not defuse the situation [36].

B. HOW TO INCREASE TRAFFIC EFFICIENCY?

With traffic safety assured, we propose that the AV should communicate via eHMI and lateral offset since this strategy was the most effective in reducing human drivers' passing times (*RQ1*). The difference in passing times derived from the communication strategies improves the human decision time to different extents. This finding confirms the assumption that decision time is the only parameter of the interaction model that can be improved by communication design [22].

During interactions, humans seek information that quickly decreases their uncertainty [37] and thus increases the predictability of the interaction partner's behavior [38]. For the AV-human driver interaction, this means that a communication strategy reduces human uncertainty and makes the AV's future behavior predictable. The more comprehensible the communication of the AV was and the faster it could be perceived by the human driver, the quicker the uncertainty was reduced, which in turn improved the decision time and thus reduced the passing times.

In cases where the AV only communicated via the speed adjustment, its intention was poorly perceivable due to the small visual angle change in straight-approach scenarios [39], and consequently the decision time was extended. In contrast, the lateral offset increased the visual angle change and the communication was therefore more perceptible to the human driver [40]. However, the time it took building up the offset prolonged human decision time. During interactions where the AV communicated via the eHMI, the visual stimulus built up immediately, attracting human attention [41] and shortening the human reaction times [42]. The consistent meaning of the simultaneous lateral offset supported the message of the eHMI and additionally reduced the uncertainty of the human driver resulting in the fastest decision times and passing times.

A further advantage of communicating via eHMI and offset is that the interaction was very efficient from first contact. The eHMI was designed to be comprehensible due to its human-centered iterative development and the lateral offset has been used by human drivers themselves to insist on right-of-way [20], [21]. This familiarity shortens the decision time, because human drivers were able to react to the communication of the AV already rule-based [43] at first contact.

C. WHEN TO COMMUNICATE?

For a validation of the interaction model, we focused on the two main components of decision and response, since detection ($T_{vis} = 100$ ms) is given by human neural conduction speed [44] and identification ($T_{gaze} = 35$ ms) was not measurable (see Section V-D.) and proportionally negligible. The proposed decision time in the interaction model could be undercut on average in this study, at least when the AV communicated via eHMI. The foot movement to the accelerator pedal was on average slightly slower than the response time in the interaction model ($T_{foot} = 600$ ms) [45]–[47], but the median was equal to this time span. Overall, the previously modeled *CRT* ($T_{CRT} = 1{,}338$ ms) in the interaction model and the *CRT* ($T_{CRT} = 1{,}298$ ms) determined in the interaction sequence in this experiment were almost identical when communicating via *eHMI + offset*. After the *CRT* had elapsed, we calculated a human deceleration of -2 m/s^2, which we derived from real driving data [30] and we therefore consider this to be reasonable. Since T_{vis} and T_{gaze} are not controllable by participants, all human-affected parameters were either confirmed in this study or are based on real data. We therefore state that the interaction model could be validated by the interaction sequence of this study.

Before the AV's communication, half of the sample decelerated unnecessarily, resulting in efficiency losses. As a result, we suggest communicating earlier to avoid these unnecessary braking interventions (*RQ2*). If human drivers brake even before this earlier communication start, the AV could insist on the right-of-way in the future.

D. LIMITATIONS

Projecting the simulation environment on screens may have caused deviations from reality regarding distance perception [48], due to a lacking depth perception [49] which might have affected participants' actions. Furthermore, the sample was on average young and rather technically experienced due to recruitment at the Technical University of Munich, which might have influenced the absolute results.

Furthermore, the AV did not react to the behavior of the human driver after communicating the right-of-way explaining the few crashes in this study. For this reason, the external validity of the crash rate is limited and we discuss these results regarding comprehensibility of the respective communication strategy.

The identification time (T_{gaze}) could not be measured in this study because the participants had already fixated the AV before its communication so that no gaze transition was necessary. Moreover, its short time span (35 ms) could not be evaluated with the frequency of the available eye tracking system (60 Hz). Given the small contribution to the total time of the *CRT,* the interaction model could still be validated.

VI. CONCLUSION AND FUTURE WORK

The AV should communicate the right-of-way via eHMI and a simultaneous lateral offset, and it should strictly refrain from changing its intended maneuver. This strategy ensures a safe AV-human driver interaction and leads to the most efficient passages through the bottleneck scenario. Moreover, the communication could be triggered time-based considering the time required for human information processing. This approach would provide the human driver with enough time to detect, process, and respond to the AV's communication before reaching the speed-dependent, last possible, comfortable deceleration start. Starting the communication even earlier could additionally reduce efficiency losses due to unnecessary braking operations. With these findings applied, human drivers may have sufficient time to react to the AV's message. For the remaining passively acting drivers, the AV could insist on the right-of-way.

In the future, the focus should be on more complex scenarios with several surrounding road users. It should be investigated how the proposed communication strategy influences the behavior of all participants and whether it ensures safety and improves efficiency to the same extent in these scenarios.

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