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Equipping vehicles with novel eHMIs potentially changes how pedestrians interact with vehicles without eHMIs*

Daniel Eisele, Carla B. Bubeck, Tibor Petzoldt

Abstract— **Over the last years, there has been a lively discussion whether (automated) vehicles should be equipped with novel external human-machine-interfaces (eHMIs) in order to facilitate communication with nearby vulnerable road users. This exploratory study investigated whether the introduction of eHMI-equipped vehicles to public traffic potentially influences how pedestrians interact with vehicles without eHMIs. To that goal, our participants specified their willingness to cross in front of vehicles that were either equipped with a frontal brake light eHMI or not in a video-based experiment. Between groups, the quota of eHMI-equipped vehicles in simulated traffic was varied. Our findings show that the quota of vehicles with an eHMI did indeed influence street crossing willingness in front of yielding as well as non-yielding vehicles without an eHMI. Notably, the magnitude and direction of the effect was dependent on the distance between vehicle and pedestrian. Future research on eHMIs should take potential unintended side effects of eHMIs into account.**

I. Introduction

In recent years, there has been a huge increase in literature discussing whether novel external human-machine-interfaces (eHMIs) can facilitate how vehicles communicate their state or intention to surrounding road users [1]. This discussion has mainly taken place in the context of automated vehicles. Most of the proposed prototypes are light-emitting displays. They are primarily designed to aid the negotiation of right-of-way with vulnerable road users like pedestrians [1]. Data from vehicle-pedestrian crashes has shown that pedestrians often misunderstand a situation and make an inadequate plan of action as a consequence [2]. While results regarding the effects of eHMIs have been mixed, a consensus has been established that they can influence pedestrians’ subjective perception of AVs and their behavioral responses (e.g., greater willingness to cross, earlier crossing initiation; [3], [4]). It is important to note that most studies so far have focused on the effects of eHMIs when they are activated [1]. Recently, some researchers have extended their focus to include possible effects of non-activated eHMIs in specific traffic situations, e.g., [5]. In one such study, participants watched videos of vehicles that either yielded or maintained their speed [6]. In the experimental group, the vehicles were equipped with a frontal brake light eHMI (FBL). This eHMI activated when the vehicle began braking. When the vehicle did not yield, the eHMI was not activated because the vehicle did not brake. In the control group, vehicles were not equipped with an FBL. The authors report that those participants who knew the brake light reported a lower willingness to cross the street in front of non-yielding vehicles than those that did not know the eHMI. This finding illustrated one way in which eHMIs can influence the interaction with vehicles even if they are not activated. Accordingly, they argued that the existing research gap regarding unintended side effects of non-activated interfaces needs to be addressed in eHMI research. The findings were later replicated by a differently composed team of authors with a sample of children [7]. However, it is important to note that either all or no vehicles were equipped with the eHMIs in these studies. If (possibly automated) vehicles with eHMIs are introduced into public traffic, they would initially constitute only a small percentage of traffic. They would share traffic space with human-driven vehicles without eHMIs. It seems reasonable that the market penetration of vehicles with eHMIs would then gradually increase over a period of several years while legacy vehicles are replaced, cf. [8], [9].

In summary, one has to assume that equipping vehicles with eHMIs changes how pedestrians interact with these vehicles. This is not limited to situations where the eHMIs are activated, but extends to those where they are not activated. The eHMIs should take effect, even when these vehicles represent only a small share of traffic. The question remains unanswered, however, whether they can also influence how pedestrians interact with other vehicles without eHMIs. A subsequent open question is whether the effects depend on the share of vehicles with eHMIs in traffic. In order to explore these issues, we conducted an experimental study.

II. Methods

A. Design

To investigate whether the way pedestrians interact with vehicles can potentially be influenced by different levels of market penetration of vehicles with eHMIs, we conducted a video-based online study with a mixed design featuring five groups. Following prior studies [6], [7], [10], [11], we used an FBL as an exemplary eHMI. Willingness to cross the street in front of a vehicle (WTC) was used as one exemplary indicator for the way pedestrians interact with a vehicle [12]. Participants were shown videos of a vehicle approaching at 30 km/h from the perspective of a pedestrian close to a one-way lane. The videos ended at different points in time when the vehicle’s physical distance from the pedestrian was either 30, 15 or 2.5 m. This approach was based on an earlier study which found that the influence of a vehicle’s appearance on WTC

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All authors are with the chair of traffic and transportation psychology at Technische Universität Dresden, 01069 Dresden, Germany.

D. Eisele (corresponding author; phone: +49 351 463-36702; e-mail: daniel.eisele@tu-dresden.de).

C. B. Bubeck (e-mail: carla_bernadette.bubeck@tu-dresden.de)

T. Petzoldt (e-mail: tibor.petzoldt@tu-dresden.de)

varied across distances [12]. The participants' task was to specify their willingness to cross on a Likert scale ranging from 1 (very low) to 10 (very high) at the moment the video ended. Within groups, we varied the vehicle's behavior (non-yielding/yielding). In non-yielding conditions, the approach speed was maintained until the vehicle passed the observer's position. In yielding conditions, the vehicle started decelerating at a distance of either 45 m or 35 m from the pedestrian and came to a standstill 2 m from the pedestrian's position. We refer to this variable as *braking onset*. Between groups, the proportion of vehicles equipped with an FBL was varied. This was done to simulate a specific point in time during a period with increasing market penetration of vehicles with eHMIs in each group. In the baseline-condition, vehicles were not equipped with an FBL and participants were neither introduced nor exposed to it. In the remaining four experimental groups, either a minority (17%), half (50%), a majority (83%) or all vehicles (100%) were equipped with an FBL. The exact percentages were chosen because they were convenient to implement in the experimental design.

Table I provides an overview over the factors and factor levels. To get a feel for the quota of vehicles with eHMIs in traffic, the participants completed 14 practice trials featuring two trials in which the vehicle did not yield (no FBL) and 12 trials in which the vehicle yielded. In these yielding trials either 0, 2, 6, 10 or 12 vehicles were equipped with an FBL, depending on the participant's group. Each participant then completed a total of 54 experimental trials. In 18 of these trials, the vehicle did not yield (no FBL). It did yield in the remaining 36 trials. In these, either 0, 6, 18, 30 or 36 vehicles were equipped with an FBL. The order of the trials was randomized for every participant. Table II lists the exact number of times each stimulus was shown in the respective groups.

B. *Participants*

265 German residents (131 f, 1 d, 133 m) between 18 and 72 years of age (M = 29.3, SD = 8.1) took part in the study. They were recruited through Prolific, an online platform, which distributes online experiments to paid research participants for a service fee [13]. Our participants received 2.3 GBP as compensation. The experimental software [14] randomly assigned them to the groups ($n_{0\%}$ = 53, $n_{17\%}$ = 52, $n_{50\%}$ = 51, $n_{83\%}$ = 54, $n_{100\%}$ = 55).

TABLE I. OVERVIEW OVER FACTORS AND FACTOR LEVELS

Between Subjects	**Within Subjects**	
Proportion of vehicles with FBL	Yielding behavior	Remaining distance from pedestrian when video ended
0%	no yielding, approach speed maintained	2.5 m
17%	yielding, braking onset 45 m from pedestrian	15 m
83%	yielding, braking onset 35 m from pedestrian	35 m
100%		

TABLE II. NUMBER OF TIMES EACH STIMULUS WAS SHOWN IN THE RESPECTIVE GROUPS.

Stimulus Combination			**Group**				
Yielding behavior	Distance from pedestrian	FBL activates	0%	17%	50%	83%	100%
no yielding	2.5	no	6	6	6	6	6
	15	no	6	6	6	6	6
	30	no	6	6	6	6	6
35 m	2.5	yes	0	1	3	5	6
		no	6	5	3	1	0
	15	yes	0	1	3	5	6
		no	6	5	3	1	0
	30	yes	0	1	3	5	6
		no	6	5	3	1	0
45 m	2.5	yes	0	1	3	5	6
		no	6	5	3	1	0
	15	yes	0	1	3	5	6
		no	6	5	3	1	0
	30	yes	0	1	3	5	6
		no	6	5	3	1	0

Note. Stimuli in which the FBL activated are highlighted.

C. *Material*

The videos of a vehicle approaching the camera perspective were rendered using the VICOM Editor Software [15]. The FBL was added using DaVinci Resolve [16]. The FBL's color (magenta; RGB 225, 0, 225) was chosen for pragmatic reasons as it is unusual in German traffic and well visible [17]. The FBL was not visible when it was not activated. The setting resembled a so-called informal street in a shared space [18]. A shared space is an urban design approach in which the usual segregation between different types of road users is minimized, for example by removing curbs [19], [20]. In shared spaces, different road users are supposed to show consideration for each other and need to cooperate. This made it plausible that vehicles yield to the pedestrian. Every clip started when the vehicle was 70 m away from the pedestrian. The combination of the factor levels resulted in 15 unique variations. Fig. 1 shows screenshots of the setting and the vehicle with and without an FBL. The stimuli were purely visual; there was no audio track. The clips were presented at 50 fps and a maximum resolution of 1920 x 1080 px. The videos can be downloaded from osf (see appendix).

D. *Procedure*

Participants used their own hardware to take part. Smartphones and devices with a screen resolution lower than 1280 × 720 pixels were excluded from participation. After they gave informed consent, they were familiarized with the traffic situation. They were told to imagine that they are a pedestrian close to a one-way driving lane on a shared space; they want to get to the cinema on the other side of the square because they have reserved tickets for a movie and need to pick them

Figure 1. Screenshots of the yielding vehicle at a distance of 2.5 m from the observer without (top) and with an FBL (bottom).

up in time. The participants in the experimental groups were then introduced to the FBL. They were told that it activates as soon as the vehicle begins to decelerate, remains activated during the deceleration and deactivates as soon as the vehicle stops decelerating. It therefore works similar to brake lights at the back of motorized vehicles. Depending on their group, the participants were instructed to imagine that either some, half, most or all vehicles are equipped with an FBL. Vehicle automation was not mentioned in order to avoid confounding effects, as we were purely interested in the effects of the eHMI. After they had seen an example video and passed attention and comprehension tests, they were introduced to their tasks. Then they got accustomed to the task and proportion of vehicles with an FBL in practice trials after which the experimental trials would follow without notice.

The stimuli were presented in random order. After the participants finished all trials, they provided information on their age and gender. Those in the experimental groups rated their user experience regarding the FBL with the UEQ-S questionnaire [21]. The UEQ-S measures user experience on a pragmatic and hedonic dimension and provides an overall score. After finishing, they had the opportunity to read additional information on the background of the study. On average, it took 16 minutes to complete the experiment.

E. Analysis

We calculated three Mixed RMANOVAs in Jasp [22] in order to analyze the influence of the FBL quotas and vehicle behavior in (1) the yielding conditions with activated FBL, (2) the yielding conditions without an FBL, and (3) the non-yielding conditions. The proportion of FBLs was the between-subjects factor. In the yielding conditions, the within-subject factors were the braking onset and the vehicle's physical distance from the pedestrian at the time the video ended. In the non-yielding conditions, the distance at which the video ended was the single within factor, as there was no braking onset. Willingness to cross was the dependent variable. The F-tests were considered robust to possible violations of normality and homoscedasticity due to the relatively large group sizes and the fact that the five groups were almost equal in size [23]. When sphericity was violated, Huynh-Feldt corrected values are reported. Post-hoc tests were Tukey corrected. The respective WTC scores of those stimuli that were presented more than once were averaged within participants.

III. Results

A. Yielding vehicles with FBL

The left box in Fig. 2 shows that there were small unsystematic between-groups differences in WTC when the vehicle yielded and the FBL was activated. The RMANOVA showed that these differences were barely significant with a small effect size ($F(3, 208) = 2.6$, $p = 0.05$, $\eta_p^2 = 0.04$). Simple main effects showed that the difference was only significant at

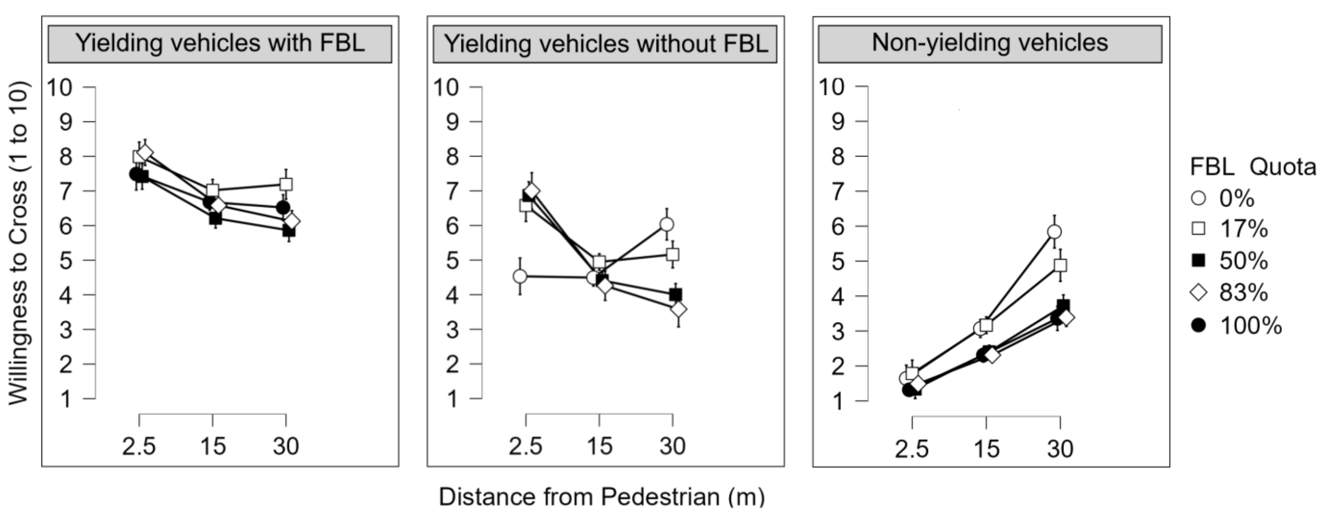

Figure 2. Willingness to cross in front of vehicles relative to physical distance between vehicle and pedestrian, split by groups.
Note. Error bars display the 95% confidence interval. Left box: The baseline group is not included because there were no FBLs; Middle box: The 100% group is not included because there were no vehicles without an FBL; Right box: As the vehicles were not braking, the FBL was inactive in these trials.

a distance of 30 m ($p = 0.005$). As one would expect, the WTC was higher when the vehicle was close to standstill (i.e., at the smallest distance) than when it had just started braking ($F(1.3, 264.9) = 45.5$, $p < 0.001$, $\eta_p^2 = .18$). The braking onset (and simultaneously the onset of the FBL) explained most of the observed variance. WTC was higher for the earlier braking onset ($F(1, 208) = 120.7$, $p < 0.001$, $\eta_p^2 = .37$).

B. Yielding vehicles without FBL

Comparing the middle and left box in Fig. 2 shows that the FBL quota had a more pronounced effect on WTC in front of yielding vehicles without an FBL than vehicles with an FBL. There was no main effect of FBL quota but a conspicuous interaction of quota and distance from pedestrian ($F(4, 276.8) = 18.4$, $p < 0.001$, $\eta_p^2 = .21$). In the baseline group without any FBLs, WTC was highest at the furthest distance and lower at closer distances. In the other groups however, one can identify the same pattern we observed for vehicles with an FBL. In these groups, WTC was higher at a close distance when the vehicle was close to standstill and lower at the furthest distance. Post-hoc tests showed that the difference between the baseline group and the others was significant at 2.5 m (all $p < 0.001$). At 30 m, it was only significant compared to 50% and 83% ($p < 0.001$). The 17% group differed significantly from the 83% group ($p = 0.01$) but non-significantly from the 50% group.

Interestingly, there were no significant between-groups differences at a distance of 15 m when the vehicle had been braking for some time but was still comparatively fast. Again, braking onset had a significant large effect on WTC ($F(1, 206) = 41.7$ $p < 0.001$, $\eta_p^2 = .17$). The effect size was noticeably smaller compared to vehicles with an FBL. There was no braking onset*FBL quota interaction.

C. Non-yielding vehicles

The right box in Fig. 2 shows that WTC in front of vehicles that maintained their speed was highest at the furthest distance and then decreased to a minimum when the vehicle was very close. The difference between distances was significant ($F(2, 389) = 372.8$, $p < 0.001$, $\eta_p^2 = .59$). The figure further shows that there were distinct between-groups differences ($F(4, 260) = 9.4$, $p < 0.001$, $\eta_p^2 = .13$). WTC was lower in the groups with a high quota of vehicles with an FBL. As one would expect, the between-group differences were very small at a close distance, where most participants were not willing to cross. With increasing distance, they became more pronounced. This interaction was significant ($F(8, 389) = 9.8$, $p < 0.001$, $\eta_p^2 = .13$). Notably, two groups can be distinguished. All participants in the groups with an FBL quota of 50% or more reported a nearly identically low WTC compared to the 0% and 17% group. Post-hoc tests showed that there were indeed no statistically significant differences within these two clusters at any distance (including the descriptively large difference between 0% and 17% at 30 m).

D. Subjective ratings of the FBL

With regards to user experience, participants in the experimental groups rated the FBL positively. Scores can range from -3 (horribly bad) to +3 (extremely good) [24]. The pragmatic quality received an average rating of 2.1 ($SD = 1.0$), which is labeled "excellent" on the UEQ-S benchmark. The hedonic quality was 1.1 ($SD = 1.1$), which corresponds to "above average". This amounts to an "excellent" overall rating of 1.6 ($SD = 0.8$). There were no significant between-groups differences.

IV. Discussion

The aim of this study was to explore whether introducing novel eHMIs on (automated) vehicles into public traffic can change how pedestrians interact with legacy vehicles without eHMIs. So far, most studies investigated the effects of eHMIs on the very vehicles that are equipped with the respective eHMI [1]. In line with the majority of studies conducted over the last years, a frontal brake light eHMI (FBL) increased our participants' willingness to cross in front of yielding vehicles [3], [4]. This study further corroborates recent findings that eHMIs do not only influence how we interact with vehicles when their eHMIs are activated but also when they are not [6], [7].

We extended the scope of present research by providing evidence that novel eHMIs on vehicles in traffic can indeed influence the interaction with legacy vehicles. We further showed that the interaction with vehicles without eHMIs possibly changes depending on the market penetration of vehicles with eHMIs. Interestingly, we observed that the effect of different eHMI quotas on interactions in which the eHMI was activated (i.e., when our vehicles with an FBL yielded) was negligible. However, when the eHMI was not activated (either because a vehicle was not equipped with an eHMI or the vehicle did not yield and therefore the eHMI did not light up), the effects were more pronounced. Notably, the effect of eHMI quotas was dependent on the respective distance between the approaching vehicle and pedestrian. When the vehicle did not yield, we observed an intuitively plausible pattern. The eHMI quota in traffic had no influence at a close distance. This is intuitive as the vehicle was very close to the pedestrian and had maintained its approach speed. Consequently, our participants were not willing to cross regardless of eHMI quota. When a non-yielding vehicle was still comparatively distant, willingness to cross was overall higher. Still, it was conspicuously lower when one was used to an eHMI quota of 50 percent or more.

Additionally, we replicated the prior observation that street crossing willingness in front of non-yielding vehicles diminishes when participants have been subjected to vehicles with an FBL [6], [7]. It seems like our participants incorporated the activation of the eHMI into their repertoire of decision strategies when deciding whether to cross. Such simple rules of thumb are called heuristics [25]. They allow pedestrians to make quick decisions [26]. One well-known heuristic in street crossing concerns the distance of an approaching vehicle ("when the vehicle is distant, I can cross"/"when the vehicle is close, I cannot cross"). While our participants still used this heuristic, a new rule concerning the eHMI seems to have taken effect for those that were subjected to the FBL (i.e., "when the FBL activates, I can cross"/"when the FBL does not activate, I cannot cross"). Consequently, they were less willing to cross in front of the vehicle when the eHMI did not light up than those who did not know about a frontal brake light. Our findings further show that this effect seems to depend on the quota of eHMIs in traffic, as street crossing willingness did not diminish when only few vehicles were equipped with an FBL. The same goes for vehicles that did yield, but were not equipped with an eHMI. Although they had been decelerating for either 15 or 5 meters and were still distant, willingness to cross was again lower when at least half of the vehicles were equipped with an FBL. Compared to the far distance, the FBL quota had the opposite effect at a very close distance when the vehicles were close to standstill. Those that were used to (any quota) of eHMIs were significantly more willing to cross the street than those who did not know of the eHMI (although there was no eHMI in this particular situation). While the effect is pronounced (street crossing willingness was similarly high in front of vehicles with and without the eHMI shortly before standstill), we cannot conclusively explain this effect at this point. Interestingly, the eHMI quota had no effect at a (seemingly ambiguous; see [12]) midway distance.

Some limitations of our experiment should be noted. While we simulated different points in time to draw conclusions about possible changes during an increasing market penetration of eHMIs, our study was cross-sectional and consisted of one single experimental session. Each participant was exposed to one single eHMI quota. Possible future efforts to model the changing interactions in more detail should employ a longitudinal design. Besides that, the study's external validity is somewhat limited. Lastly, as mentioned above, we deliberately designed the eHMI in such a way that it was not possible to tell whether a car was equipped with the FBL until it was activated. Of course, alternative designs are conceivable that would make it possible to tell at a glance whether a car is equipped with a particular eHMI. It seems plausible that this design feature would increase the differences in pedestrian interaction between cars with and without an eHMI (e.g. lower WTC in front of a car with FBL that is not activated compared to a car without FBL). However, the present study did not address this issue. This is a task for future research.

Nevertheless, within the scope of this study, we were able to provide first insights into the effects of novel eHMIs on vehicles without eHMIs. In a broad sense, our results imply that the introduction of (automated) vehicles with novel features can change the way we interact with current vehicles. Future research on eHMIs should consider such possible behavioral changes in the interaction with legacy vehicles. A deeper understanding of possible behavioral changes could help to prevent possible undesirable consequences. They are one factor that needs to be considered in the ongoing discussion on the introduction of eHMIs.

Appendix

The stimulus material used in this study can be downloaded from osf: https://osf.io/pygq5/

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