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Conceptual Testing of Visual HMIs for Merging of Trucks

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Abstract. Merging sections are challenging for drivers of heavy goods vehicles. Visual support for merging was evaluated in a simulator. Experiment 1 tested HMIs that provided participants (n = 5) driving on the on-ramp with a top view or various forms of speed advice for accelerating behind or in front of a truck platoon on the freeway. Experiment 2 tested HMIs that provided drivers (n = 18) on the acceleration lane with a top view complemented with speed and gap advice for finding a gap to merge in. Experiment 1 showed that speed advice yielded less unnecessary braking compared to unsupported driving. In Experiment 2, speed advice yielded low satisfaction ratings. Our results highlight the potential of visual support and stress the importance of not visually overloading the driver.

Keywords: Heavy goods vehicles · Driver behavior · Visual displays

1 Introduction

In times where almost any product can be purchased online, the logistics sector is vastly expanding. The high demand for freight transport contributes to an increase in the number of heavy goods vehicles (HGVs) on the roads. A transition from manual to fully automated freight transport is not expected before 2025–2030 [1]. Until that time, the driver is in control during complex maneuvers.

Merging onto the freeway is a common yet demanding task. Sen et al. found HGVs to be involved in 42% of all merging crashes [2]. Challenges of merging are related to the restricted field of view and the length of the HGV [3–5]. Six mirrors (class II [2 x] class IV [2 x], class V, class VI) at the HGV provide indirect views to the driver. The class II and class IV mirrors are associated with large blind spots [3–5]. Liao et al. found that HGV drivers would appreciate support while merging, suggesting that current mirrors and assistance systems do not meet their needs [6].

Previous studies among car drivers indicate that the merging maneuver is regarded as cognitively demanding [7, 8] and that the merging decision involves courtesy behavior and is affected by the distance and velocity relative to the approaching freeway traffic [9]. Research on the merging behavior of HGV drivers is relatively sparse.

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Automatic emergency braking (AEB) and lane departure warning (LDW) have become mandatory for HGVs produced after 2015 [10]. Furthermore, the EU has agreed upon 11 mandatory assistance systems by the year 2021 [11]. Lateral assistance systems such as blind spot assistance (BSA) do not aim to ease the merging procedure but warn the driver about the presence of vehicles next to the HGV. Current lane change assistance systems apply different warning strategies depending on the escalation interval. These warnings include yellow or red signs, blinking lights at the mirror or A-pillar, and acoustic signals, in agreement with ISO standard 17387 [12, 13].

The lack of improvements in accident statistics of HGVs [14] might be attributed to multiple factors, including the low presence of BSA and camera-vision systems on the market, as well as a lack of human-centered design of these systems. Current assistance systems offer only limited preview of the road ahead. Warnings are associated with binary decision-making (e.g., changing lanes or not), not acknowledging that merging is a dynamic maneuver consisting of multiple subtasks [15, 16]. Furthermore, the use of warnings rests on the assumption that warnings do not cause an inadvertent startle response or otherwise interfere with driver decision making.

This paper presents alternatives to warnings by providing speed advice and enhanced information about the traffic situation, with the aim to ease the merging decision. Two sets of concepts were tested. The first set of concepts was aimed at letting a driver merge behind or in front of a platoon of trucks driving on the freeway by providing the driver on the on-ramp with information about the platoon. The second set of concepts aimed at easing the gap choice when having to merge in dense traffic. The present study examines whether the developed concepts have the potential for a larger-scale investigation; the concepts are not seen as final or generalizable.

2 Method

Two experiments were conducted in a simulator (Fig. 1). The vehicle model was a semi-trailer truck (40 tonnes, 18.75 m long) [17]. A high-performance actuator (SensoWheel SD-LC) was used to generate realistic force feedback. The driving environment was provided by ST Software [18]. The two experiments were done with different participants. Each experiment took approximately 60 min per participant.

Fig. 1. Left: Setup for Experiment 1 (65- and 49-inch screen). Right: Setup for Experiment 2 (49-inch screen.) The instrument cluster was shown on a 12-inch screen behind the steering wheel.

The environment consisted of a merging section of a Dutch two-lane freeway (lane width 3.6 m). The on-ramp was about 625 m long and the merging section 300 m long (lane width 3 m). The drivers' view on the freeway was blocked by greenery until 200 m before the start of the acceleration lane (Fig. 2).

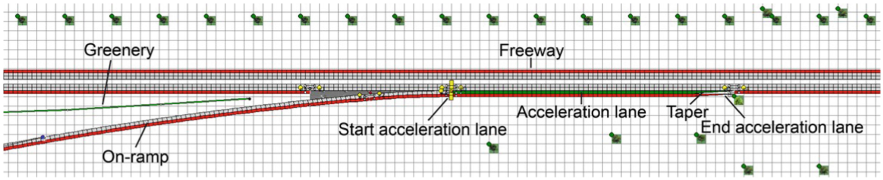

Fig. 2. Road layout.

2.1 Experiment 1

Before the experiment, 15 HMIs were assessed in an online questionnaire with 27 participants. The questionnaire asked for the expected effectiveness in guiding the driver, on a 4-point scale from "very ineffective" to "very effective". Overall, concepts showing lengthy texts or an icon of an accelerator pedal received low ratings. The five HMIs with the highest ratings were implemented in the simulator (Table 1).

The HMIs were active on the on-ramp and not on the acceleration lane. HMI 1 provided a top view, whereas HMI 2–5 provided speed advice to merge either in front or behind the platoon. The advice was determined from the speed of the driver and the platoon (80 km/h) as well as the distance of the driver and platoon to the start of the acceleration lane. The algorithm assessed the minimum speed needed to end up in front of the platoon. If the driver could not get in front, the algorithm calculated the maximum speed to decelerate and merge behind the platoon. The update rate of the calculations was twice per second. A baseline condition with no support was also included.

The participants' drive started on the on-ramp about 625 m before the acceleration lane. Freeway traffic consisted of a platoon of ten HGVs driving at 80 km/h with a time headway (THW) of 0.3 s, making it impossible to merge in the platoon. When the participant had traveled 25 m, the platoon was spawned on the freeway at four distances (575 m, 650 m, 760 m, 900 m) to the acceleration lane. With the 760 m (Front) and 900 m (Far-Ahead) conditions, participants could accelerate and merge in front of the platoon. With the spawning distance of 575 m (Behind), the on-ramp was too short for merging in front, and participants had to reduce speed and merge behind the platoon. With the 650 m distance (Midway), merging in front and behind were both possible.

The experiment was a 4 *meeting location* (Behind, Midway, Ahead, Far-Ahead) x6 *visual interface* (Baseline, HMI 1–5) within-subject design. After receiving instructions to merge safely on the freeway, the participants had a 5-min. familiarization phase without traffic. The participants drove the four distance scenarios per HMI condition in randomized order. The six HMI conditions were also presented in randomized order.

The participants of Experiment 1 were five males with a mean age of 23.0 years (*SD* = 2.8). The participants were four BSc students and 1 PhD student who were familiar with the simulator and the HMIs, as they had designed/programmed them. However, they were not told which meeting location scenario they were given and could not observe this, because the vision was blocked by greenery (Fig. 2). Accordingly, Experiment 1 can be seen as a test of how knowledgeable drivers use the feedback.

We assessed whether participants merged behind or in front of the platoon and the participants' speed while merging. Also, the maximum speed, percentage braking, and the longitudinal control effort (standard deviation of the vehicle's acceleration) from the start of the drive to the moment of merging were assessed.

Table 1. Visual human-machine interfaces (HMIs) to support merging (Experiment 1).

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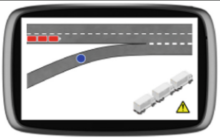
<tr><td></td><td>
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<tr><td>HMI 1: Top view. The blue dot is the ego-vehicle; the red rectangles represent the platoon</td><td>HMI 2: Max. speed in 10 km/h increments (merge behind)</td><td>HMI 2: Min. speed in 10 km/h increments (merge in front)</td></tr>
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<tr><td>HMI 3: Min. speed in 10 km/h increments (merge in front)</td><td>HMI 3: Max. speed in 10 km/h increments (merge behind)</td><td>HMI 4: Advised speed in 1 km/h increments</td></tr>
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<tr><td colspan="3">HMI 5: Recommended speed action, text-based</td></tr>
</table>

2.2 Experiment 2

The participants were recruited from the TU Delft student population and a logistics company. They were 18 males with a mean age of 33.3 years (*SD* = 19.2 years). All drivers were Dutch and had a valid driver's license class B. Six of the 18 drivers (mean age = 57.7 years, *SD* = 13.4) were in possession of an HGV driver's license and were frequently driving HGVs. The participants were naïve to the HMIs.

The participants' drive started 360 m before the start of the acceleration lane. Ten cars or HGVs were spawned on the freeway with short THWs of 1.2 s (26.7 m) and driving at 80 km/h. It was possible yet challenging to merge in these gaps. Freeway traffic after merging would retain a constant THW.

Three visual interfaces were tested (Table 2): a top view (HMI 1), a top view combined with speed advice to reach a target gap at the end of the acceleration lane (HMI 2), and a top view combined with speed advice and colored gap advice (HMI 3; blue = advised gap, green = possible to change lanes). An illustrative video for HMI 3 is available online: https://www.youtube.com/watch?v=03m8gVwwsmo.

The experiment was conducted in a visual interface (Baseline, HMI) x gap closure (cut-in vs. normal) between-within-subjects design. Participants drove the baseline condition followed by one of the three HMI conditions. Six participants (of which two HGV drivers) drove with HMI 1, six participants (two HGV drivers) drove with HMI 2, and six participants (two HGV drivers) drove with HMI 3. Thus, each participant completed 12 drives. Per block, participants experienced four scenarios with a gap closure (a passenger car cut into the target gap) and eight normal scenarios where the participant was expected to merge into the target gap.

After instructions and an explanation of the HMIs, participants completed a questionnaire about demographic data. Next, participants familiarized themselves with the simulator in 5 min. of driving without traffic. The experiment started with six baseline drives (including two gap closure scenarios). Then, the second block with the assigned HMI condition followed. Finally, an acceptance questionnaire [19] was administered. The acceptance questionnaire had a semantic-differential format and consisted of nine items. It comprised two dimensions: usefulness (5 items) and satisfaction (4 items). Each item was measured from −2 to 2 (5 options) with poles on one dimension (e.g., useful-useless). The total was calculated as the mean of items, after reversal of the responses where appropriate.

Lastly, participants completed the System Usability Scale (SUS) [20]. The SUS had ten Likert items with the anchors "Strongly disagree" (1) and "Strongly agree" (5). The usability score was calculated by subtracting 1 from the item response (1 to 5) (for the positively phrased items 1, 3, 5, 7, and 9) or subtracting the item response from 5 (for the negatively phrased items 2, 4, 6, 8, and 10). The sum of the item scores was multiplied by 2.5 to obtain a usability score on a scale from 0 to 100.

We assessed the percentage of drives with crashes with freeway traffic, longitudinal control effort (the standard deviation of the longitudinal acceleration from entering the acceleration lane to the moment of the lane change), and distances with respect to the freeway vehicles in front and behind at the moment of merging.

Table 2. Visual human-machine interfaces (HMIs) to support merging (Experiment 2).

		
Baseline, only showing the speed of the ego-vehicle	HMI 1: Top view	HMI 2: Top view + speed advice
		
	HMI 3: Top view + Speed advice + Colored gap advice	

3 Results

3.1 Experiment 1

All drivers successfully completed all merges within the length of the merging section. The drives with the conditions Far-Ahead and Behind led to 100% of merges in front and behind the platoon, respectively, as intended. For the condition Midway, where the ego-vehicle was expected to meet the center of the platoon at the start of the merging section, the drivers merged behind the platoon in 100% of the drives. The condition Front was designed so that participants would merge closely ahead of the platoon. However, the speed choice of the drivers resulted in 80% of merges behind the platoon. The 20% merges in front occurred while guided by HMI 1 (1 case) and Baseline (5 cases) (Table 3).

Table 3. Percentage of merges behind the platoon or in front of the platoon for all HMIs combined (Experiment 1)

Merge location	Distance condition (spawn distance)			
	Behind (575 m)	Midway (650 m)	Front (760 m)	Far-Ahead (900 m)
Front	0% (0 of 30)	0% (0 of 30)	20% (6 of 30)	100% (30 of 30)
Behind	100% (30 of 30)	100% (30 of 30)	80% (24 of 30)	0% (0 of 30)

Further examination using a repeated-measures ANOVA showed that the speed at the moment of lane change was significantly different between interfaces, $F(5, 20) = 3.17$, $p = .029$. Furthermore, the maximum speed from the start of the drive until the moment of changing lanes was different between conditions, $F(5, 20) = 10.65$, $p < .001$. Post-hoc tests showed that the maximum speed was higher for Baseline compared to all other HMIs. Table 4 shows that the maximum speed was higher than the speed at the moment of lane change for HMI 1, HMI 5, and the Baseline condition, suggesting that participants sped up too much and subsequently decelerated/braked.

Table 4. Means (standard deviations of participants in parentheses) for the speed (m/s) at the moment of the lane change, maximum speed up till the moment of lane change (m/s), percentage braking (%), and standard deviation of acceleration up till the moment of lane change (m/s^2) for each HMI (Experiment 1).

	HMI 1	HMI 2	HMI 3	HMI 4	HMI 5	Baseline
Speed @ lane change	21.09 (1.46)	21.12 (0.44)	21.82 (0.67)	20.96 (0.21)	21.06 (0.77)	22.58 (0.62)
Maximum speed	22.10 (0.91)	22.12 (0.44)	21.82 (0.67)	20.96 (0.21)	21.13 (0.63)	23.51 (0.57)
Mean % braking	1.01 (0.61)	0.02 (0.05)	0.12 (0.14)	0.00 (0.01)	0.51 (0.57)	0.93 (0.44)
SD of acceleration	0.53 (0.07)	0.41 (0.01)	0.42 (0.02)	0.41 (0.02)	0.50 (0.15)	0.51 (0.07)

Furthermore, we analyzed the longitudinal control effort for each HMI. A comparison of the braking input from the start of the drive until the lane change confirmed that participants often braked when driving with HMI 1 (top view), HMI 5 (recommended speed action), and the Baseline condition, see Fig. 3. In line with these findings, the standard deviation of the acceleration was elevated for HMI 1, HMI 5, and the Baseline condition (Table 4). It is noted that a nonzero standard deviation is expected since drivers had to accelerate from standstill; the elevated standard deviation (as observed for HMI 1, HMI 5, and Baseline) can be attributed to *extra* acceleration and braking.

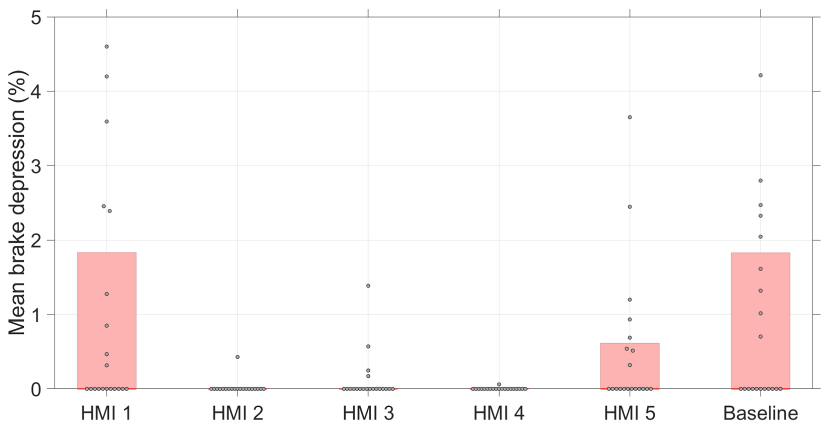

Fig. 3. Braking effort per HMI condition (Experiment 1).

3.2 Experiment 2

The second experiment aimed at guiding the driver until the lane change was completed. We compared the HMIs with respect to merging success (i.e., not crashing), driving performance, and the self-reported system usability and acceptance for the 'normal' scenarios. Note that a crash was defined as virtually hitting another vehicle; crashes did not materialize as participants could drive through other vehicles. Results are based on 66, 24, 17, and 21 drives for the Baseline, HMI 1, HMI 2, and HMI 3 conditions respectively. Due to data recording errors and early merging, data for 6, 0, 7, and 3 drives were missing for these four respective conditions.

The results showed that drivers supported by HMIs 3 and 4 merged within the length of the acceleration lane in 53% and 62% of the drives, respectively. In drives without support (Baseline) and drives supported by HMI 1, drivers merged within the length of the acceleration lane in 38% and 46% of the drives, respectively. The largest number of crashes occurred in the Baseline condition (53%) and while supported by HMI 1 (46%) and the lowest while supported by HMI 3 (38%). Rear crashes occurred with all HMIs; however, front crashes occurred only with HMIs 1 and 2 (Fig. 4).

Higher longitudinal control effort was observed for HMI 1 (M = 0.36 m/s^2), HMI 2 (M = 0.34 m/s^2), and HMI 3 (M = 0.32 m/s^2) as compared to Baseline (M = 0.24 m/s^2) drives (Fig. 5).

We analyzed the temporal distance to the lead and following vehicle at the time of merging as additional performance indicators. Overall, participants merged right behind the lead vehicle (on the right freeway lane), with median THWs between 0.25 s and 0.38 s. Safety margins on the rear were even smaller; especially in the Baseline condition, participants often collided with the following vehicle (see Figs. 6 and 4).

Participants with HGV driving experience (n = 6) and non-HGV drivers (n = 12) participated in the experiment. Their merging patterns were highly similar (Fig. 7).

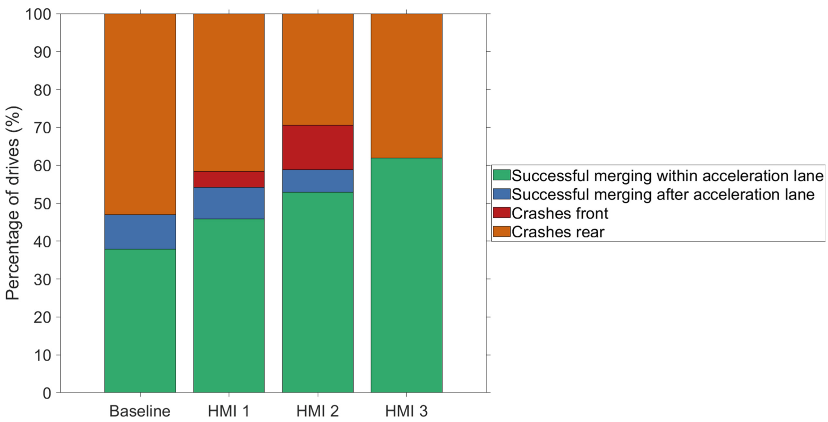

Fig. 4. Frequency of crashes and successful merges (Experiment 2).

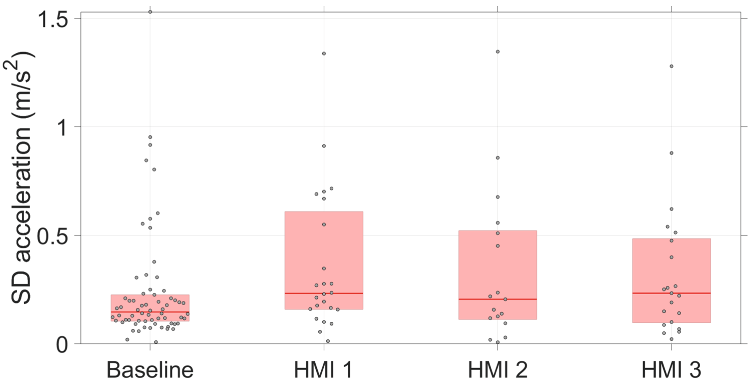

Fig. 5. Standard deviation of acceleration on the acceleration lane (Experiment 2).

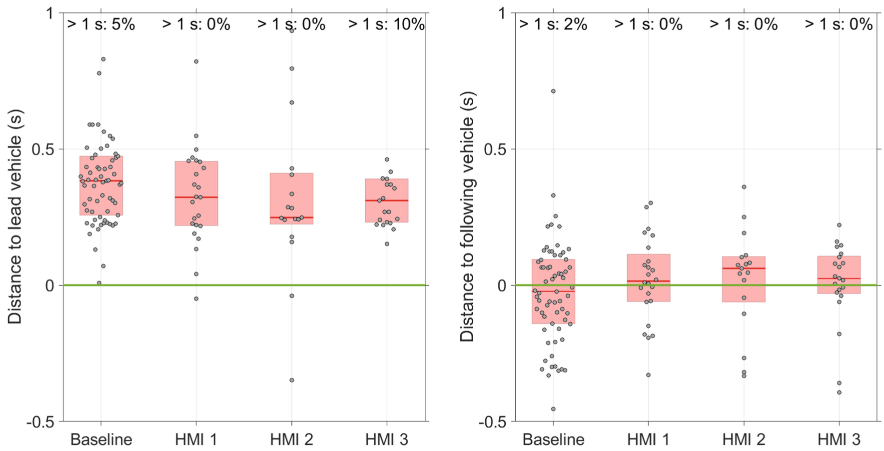

Fig. 6. Distance to lead and following vehicle at the moment of merging (Experiment 2).

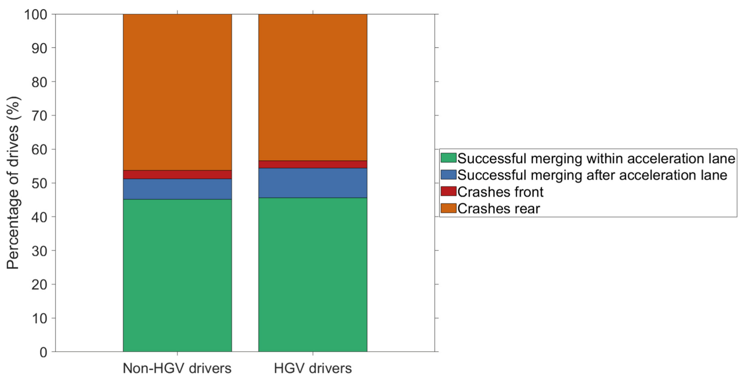

Fig. 7. Frequency of rear crashes, front crashes, and successful merges within and after the acceleration lane, for non-HGV drivers and HGV drivers (Experiment 2).

Participants rated the usefulness and satisfaction of the HMIs. A one-way ANOVA indicated that the satisfaction ratings were significantly different between the HMIs, $F(2, 15) = 4.52$, $p = .029$. The mean satisfaction score for HMI 2 ($M = 0.04$) was lower than for HMI 1 ($M = 1.29$) and HMI 3 ($M = 1.17$), see Fig. 8.

Additionally, the HMIs were evaluated by means of the SUS. The usability scores showed that HMI 1 yielded the highest evaluation with an average of 80 ('good' to 'excellent'), and HMI 2 the lowest score with an average of 51 ('OK'). HMI 3 received an average rating of 65 ('OK' to 'good'), interpreted according to [21] (Fig. 9).

Participants had the opportunity to provide comments in a free-response item. For HMI 1, no meaningful responses were provided. For HMI 2 and 3, 5 of 12 participants provided a critical remark. Three of them recommended simplification of the HMI: "I received a bit too much input; speed advice could be removed", "Good concept, the projection of the image can be simplified, and the desired speed is not reliable considering the sluggishness of the vehicle and the length of the acceleration lane", "Could round the speed advice to 5 km/h, for more simplicity".

4 Discussion

By means of two experiments, we aimed to investigate how drivers avoid conflicts with freeway traffic at a merging section while receiving support from different visual HMIs.

In Experiment 1, all drivers successfully avoided a platoon of trucks and merged within the range of the acceleration lane. The experiment revealed differences between the HMIs regarding longitudinal performance: the lowest amount of braking was found for the minimum/maximum speed advice and the numerical speed advice. Action recommendations based on text and a top view of the driving situation led to relatively high control effort, similar to unsupported driving. Thus, using the terminology of information processing stages [22], information acquisition support (top view) and action implementation support (text-based advice) did not ensure fluent driving. The minimum/maximum speed advice may have yielded low control effort because this HMI resembles the well-learned driving task of adhering to speed limits. Additionally, the speed advice HMIs do not provide explicit commands to speed up or slow down.

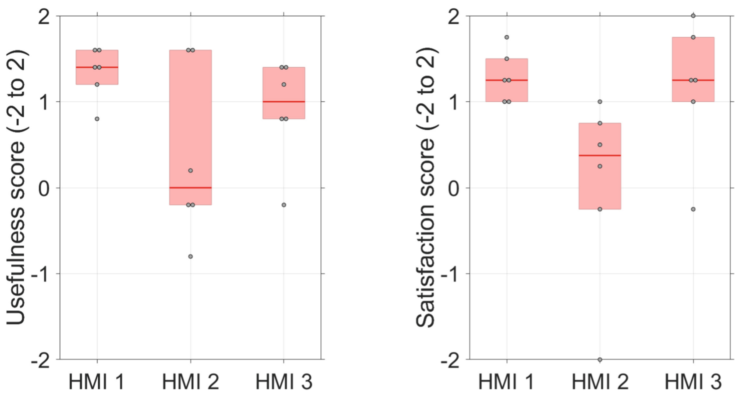

Fig. 8. Usefulness (left) and satisfaction (right) ratings of the acceptance scale

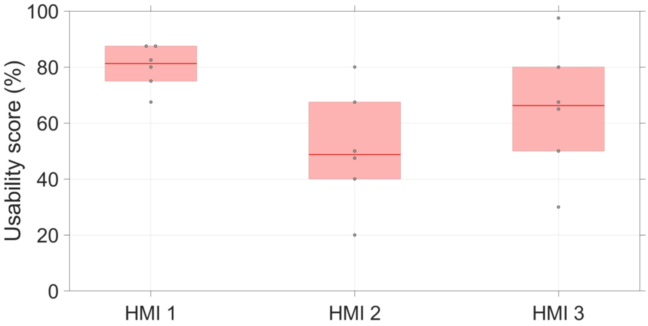

Fig. 9. Scores on the System Usability Scale (SUS)

In Experiment 2, we used a top view, numerical speed advice, and colored gap cues to guide drivers to a suitable gap. The high amount of crashes in all conditions indicates that the merging task was challenging.

Drivers subjectively evaluated the top view as positive, whereas the speed advice yielded the lowest satisfaction ratings. Although the speed advice may have helped participants to position the vehicle next to the gap, it was not designed to support the gap search and the action of changing lanes. Furthermore, the speed advice may have come across as visually demanding or irrelevant/invalid to the task of finding a gap. In Experiment 1, the HMIs provided information that was otherwise unavailable to the drivers, due to the greenery blocking the view on the freeway. In Experiment 2, however, participants had to rely on the forward view in order to merge; additional visual information may therefore come across as too demanding. The cueing of the desired gap (HMI 3) may have compensated for the shortcomings of the speed advice (HMI 2), as the gap cues supported the decision-making process [22] of the merging task.

It would be interesting to examine whether the top view could be further improved. Bateman et al. [23] found that a third-person view (i.e., a bird's-eye view from behind the vehicle) yielded better driving performance as compared to a top view, independent of the provided preview. However, we considered a third-person view inappropriate for merging because rear traffic needs to be assessed in merging. Additionally, it would be interesting to examine the effectiveness of in-vehicle interfaces compared to variable message signs [24] or shared control approaches [25] in merging tasks.

This study provided insights into the design of visual support for the merging task. The limited sample sizes and the fact that only six HGV drivers participated need to be considered when interpreting the results. Moreover, the benefits after longer use need to be considered, and the effects of training need to be assessed. Also, the fidelity of the virtual traffic could be enhanced. Lastly, the design of the speed advice may be improved by incorporating a better predictive model of the vehicle's longitudinal dynamics. It appears that the information provided by the HMIs resulted in increased control effort exerted by the drivers. The lag in the drivers' and vehicle's response may have made the prior advice obsolete, possibly resulting in inadequate driver actions.

For future merging support systems, we recommended keeping the visual load low. This could be achieved by providing support sequentially over the course of the merging maneuver (e.g., speed advice at the on-ramp, gap cueing on the acceleration lane).

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