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TECHNICAL REPORT

Continuous auditory feedback on the status of adaptive cruise control, lane deviation, and time headway: An acceptable support for truck drivers?

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Abstract: The number of trucks that are equipped with driver assistance systems is increasing. These driver assistance systems typically offer binary auditory warnings or notifications upon lane departure, close headway, or automation (de)activation. Such binary sounds may annoy the driver if presented frequently. Truck drivers are well accustomed to the sound of the engine and wind in the cabin. Based on the premise that continuous sounds are more natural than binary warnings, we propose continuous auditory feedback on the status of adaptive cruise control, lane offset, and headway, which blends with the engine and wind sounds that are already present in the cabin. An on-road study with 23 truck drivers was performed, where participants were presented with the additional sounds in isolation from each other and in combination. Results showed that the sounds were easy to understand and that the lane-offset sound was regarded as somewhat useful. Systems with feedback on the status of adaptive cruise control and headway were seen as not useful. Participants overall preferred a silent cabin and expressed displeasure with the idea of being presented with extra sounds on a continuous basis. Suggestions are provided for designing less intrusive continuous auditory feedback.

Keywords: Sonification, Continuous feedback, Truck driving, Human factors, Driver acceptance

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1. INTRODUCTION

1.1. Auditory Interfaces for Trucks

Trucks are increasingly equipped with advanced driver systems, such as adaptive cruise control (ACC), lane departure warning (LDW), and forward collision warning. Such trucks typically provide binary auditory warnings based upon ACC deactivation, lane departure, and close headway. Auditory signals are attractive as warnings because they are perceivable regardless of the driver's direction of visual attention [1]. People are generally able to distinguish perceptually-related auditory events from each other [2], a phenomenon called 'stream segregation' that may be useful for transmitting multiple types of warnings.

The threshold settings of an auditory warning system must strike a balance between early detection of critical events and the avoidance of false alarms. False alarms are problematic, because they are annoying to the driver, as a result of which the driver may disengage the warning system [3,4]. Some car manufacturers have implemented visual warnings to avoid annoyance. For example, the status of the automation in the Volvo XC90 is shown by means of a green icon on the dashboard. When the automation has no clear picture of the environment, the icon becomes grey, but no auditory warning is provided. The likely reason for having no auditory warnings is that frequent auditory warnings are perceived as annoying. On the other hand, auditory warnings are typically used as imminent warnings, for example as the final stage of a two-stage or graded warning system (e.g., [5,6]).

1.2. Continuous Auditory Feedback

It has been argued that human interaction with the world (e.g., maintaining balance, applying forces, steering, aiming) is essentially continuous [7]. Although discrete triggers do occur in traffic (e.g., another road user suddenly appearing in sight), stimuli in normal driving (car following, lane-keeping) are of continuous nature. Furthermore, as stipulated by Newton's second law of motion, the

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physical movements of road users are necessarily continuous as well; road users cannot change their position, speed, or heading instantaneously. Therefore, continuous feedback may be perceived as more natural than discrete warnings.

Both continuous and binary warning sounds can be spatialized, giving information about the location of the source of the sound. For example, spatialized sound can be beneficial for providing information about surrounding traffic [8]. However, the benefits of spatialized sound are constrained by the angular resolution of the human auditory system [9,10]. Chen *et al.* [8] stated that a number of participants expressed disbelief about the feasibility of using spatialized auditory feedback on the road, despite ranking these stimuli highly during a driving simulator experiment on driver traffic awareness in trucks.

1.3. Aim of the Paper

There is a need for concepts of auditory feedback that yield high acceptance among drivers. It is postulated that truck drivers are sensitive to how their truck sounds like and that they rely on engine noise to infer the state of the vehicle. Accordingly, we aimed to develop a non-annoying functionality that provides continuous feedback, by creating a sound that resembles, and blends with, the natural engine and speed-dependent wind noise inside the truck cabin. Thus, we aimed to deviate from a wealth of research and guidelines on the design of discrete auditory (warning) signals, such as provided in ISO 11429:1996, 7731:2003, ISO 8201:2017, ISO 24500:2010, ISO 24501:2010, and instead test the viability of continuous sound.

By means of an on-road experiment, we tested whether continuous auditory feedback is a possible alternative to standard auditory warnings used in modern production trucks equipped with low-level automation. A real truck was used instead of a driving simulator because we wanted to observe actual truck driving experiences with real cabin noise; simulators may not be able to generate a valid driving experience and may yield biased results.

We hypothesized that continuous feedback about the system status, headway to the vehicle in front, and deviation of the vehicle from the centre of the lane would receive high acceptance ratings of drivers. The results of the study are intended to be transferable to trucks with higher levels of automation. Acceptance can be regarded as a precondition of usage and performance; if drivers reject a system, it is unlikely they will use it on longer trips. Whether continuous sounds cause improved driving performance was not examined herein.

2. METHOD

2.1. Participants

Twenty-three participants (18 male, 5 female) holding a truck driver's license participated in the experiment. The participants were employees of Volvo Trucks and were between 38 and 65 years old ($M = 49.5$ years; $SD = 6.5$ years). Their mean number of years of having a truck driver's license was 20.8 years ($SD = 11.5$). Thirteen of the participants reported a mileage of 1–1,000 km, 7 participants reported 1,001–5,000 km, 2 participants reported 5,001–15,000 km, and 1 participant reported 15,001–20,000 km of driving in a truck in the past 12 months. One participant reported suffering from a hearing impairment (sensitivity to background sounds). All participants provided written informed consent, and the research complied with the American Psychological Association Code of Ethics.

2.2. Apparatus

The experiment took place on the E6 highway in Gothenburg, Sweden. An FH460 Volvo truck was used. The standard sound setup of the truck was used, where spatialization was achieved by presenting the auditory feedback from the left front/left back loudspeakers or the right front/right back loudspeakers. The speed, lateral position, and use of turn indicators were received from the CAN bus of the truck.

2.3. Continuous Auditory Feedback

Three types of continuous auditory feedback were evaluated: 1) feedback based on the state (on vs. off) of the ACC (ACC-status sound), 2) feedback based on the deviation of the truck from the lane centre (lane-offset sound), and 3) feedback based on the headway time to the vehicle in front (headway sound). All feedback was developed in Pure Data, a visual programming language for multimedia works.

Continuous auditory feedback on the state of ACC informed the driver whether the system was on or off. If ACC was on, sound was generated. When ACC is off, no sound was produced. The sound was created by a white noise generator fed through a second-order bandpass filter. The centre frequency of the filter (in Hz) was adjusted based on the current speed of the truck (in km/h) as follows: $C \times (\text{speed} \times 30.05 + 1054.6)$, with $C = 0.8$. The sound was designed to mimic the speed-dependent sound of the wind, to blend with the intrinsic in-cabin sounds. Figure 1 shows the signal power for the ACC-status sound at 80 km/h.

Continuous auditory feedback on the deviation of the truck from the lane centre is a form of spatial auditory feedback where the driver is informed about the distance from the centre of the truck to the right or left edge of the lane. That is, if the truck deviated towards the right of the centre of the lane, the sound would appear from the right side, and vice versa. This sound level was based on the

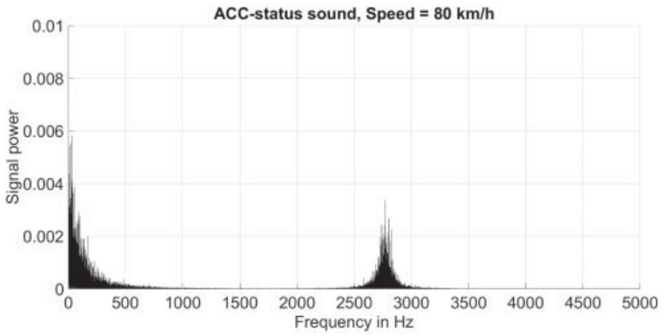

Fig. 1 Signal power (proportional to abs(amplitude^2)) of a discrete Fourier transform (calculated using a fast Fourier transform algorithm) of the ACC-status sound at 80 km/h.

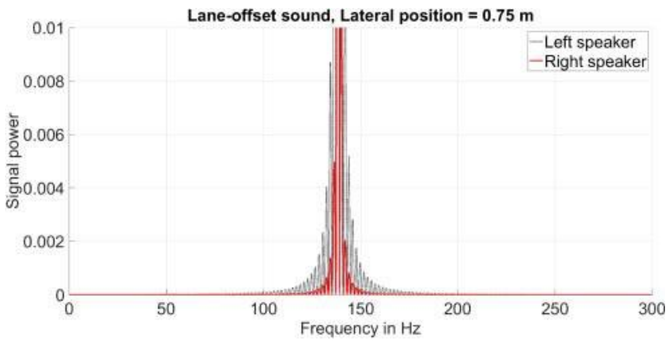

Fig. 2 Signal power (proportional to abs(amplitude^2)) of a discrete Fourier transform (calculated using a fast Fourier transform) for the lane-offset sound for a lateral position of 0.75 m towards the left of the lane center (assuming a 3.5 m wide lane). The speed was set at 80 km/h. The left/right power ratio for this lateral position was 6.1.

distance of the centre of the truck to the left and right lane edges.

The sound was generated with a cosine wave oscillator. The frequency (in Hz) of this oscillator was automatically adjusted based on the current speed of the truck (in km/h) as: frequency ¼ speed x 1:732, resulting in a relatively low frequency (e.g., 139 Hz at 80 km/h). The frequency-speed function was based on investigations in a previous project where it was found (through trial-and-error) that it gave a natural sensation of rumble-strip-like road noise. Figure 2 illustrates the signal power emitted from the left and right speaker.

Continuous auditory feedback on the headway time to the vehicle in front informed the driver about the time headway to the vehicle in front. Feedback was given when the headway was smaller than 3.5 seconds; this value was acquired through testing (a headway of 2.0 s is regarded as safe [11], but providing feedback with such a threshold was regarded as annoying). Similar to the feedback on the status of ACC, the base sound mimics the sound of wind.

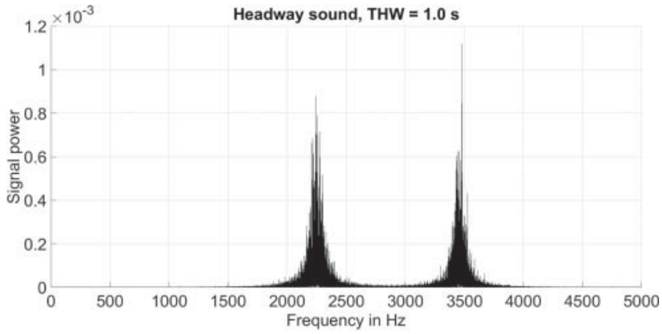

Fig. 3 Signal power (proportional to abs(amplitude^2)) of a discrete Fourier transform (calculated using a fast Fourier transform algorithm) for the headway sound at a THW of 1.0 s.

The headway noise consisted of two noise components: one with a centre frequency of 2,250 Hz and one with a centre frequency as the ACC-status feedback with C ¼ 1. The level of the sound decayed with the time headway to the lead vehicle so that the shorter the time headway, the louder the sound would be. Figure 3 illustrates the frequency distribution of signal power for a THW of 1.0 s.

2.4. Scenario

The participants drove four trials. They started in the garage of Volvo Group Trucks in Lindholmen, Gothenburg, Sweden. Then they drove towards St1 gas station near Kungälv on E6, see Fig. 4.

(1) During the first trial, participants experienced the standard ACC and lane departure warning system available in the truck. The ACC was activated and deactivated a few times voluntarily by the participant. Upon de(activation) of the ACC, a standard sound was produced. After the first trial, the participants stopped near the gas station Preem near Tuve.
(2) During the second trial, the ACC-status sound was played. After the second trial, the participants stopped at the St1 gas station near Kungälv. During the second trial, the ACC was active, and the lane departure warning system was disabled.
(3) During the third trial, continuous auditory feedback on the deviation of the truck from the lane centre and headway time to the vehicle in front was playing. After the third trial, the participants stopped at the Preem gas station near Tuve. ACC and the lane departure warning system were disabled. The presentation order of the second and third trials was counterbalanced.
(4) During the fourth trial, all three types of auditory feedback were played at the same time. The standard lane departure warning system was disabled whereas the ACC was enabled in about half of the trial in terms of distance.

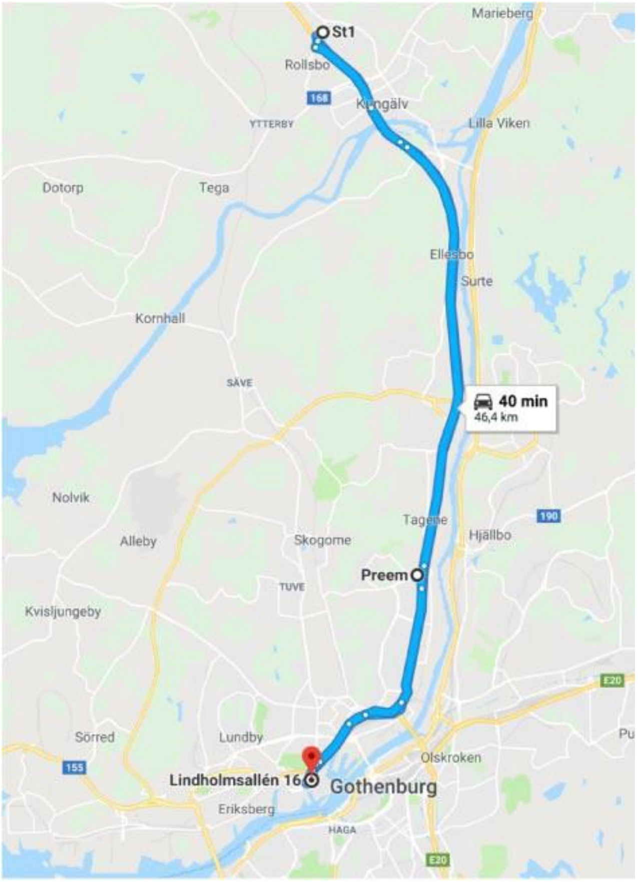

Fig. 4 The route travelled during the experiment. Participants started at the Volvo Trucks garage in Lindholmen, drove towards the Preem gas station for a stop after Trial 1, and then drove towards the St1 gas station in Kungälv for a stop after Trial 2. Trials 3 and 4 were conducted on the way back to the garage with a stop at the Preem gas station after Trial 3.

The participants were asked to complete an introductory questionnaire before the start of the first trial. The questionnaire included questions on demographics, driving behaviour, and opinion on the types of auditory feedback that would be offered in trials 2–4 (i.e., prior to being exposed to the feedback). At different moments during the trials, an unstructured verbal interview on the sound systems was conducted with the driver. Participants were asked to give their general impression on the feedback, how the feedback could be improved, and whether they would like it in a future model of the truck. At the gas stations after trials 2–4, participants completed a questionnaire regarding the auditory feedback experienced in the preceding trial. The questionnaire asked whether the feedback was easy to hear and included a transport telematics acceptance scale [12] as well as the System Usability Scale [13]. The questionnaires can be found in the supplementary material.

Figure 5 illustrates the driving speed of one of the participants. In Trial 2 (9.5–19.5 km) and in the last part of Trial 4 (38–40 km), the ACC was active as can be seen from the constant speed. The breaks between trials can be distinguished by speeds of 0 km/h.

Figure 6 shows the lateral position for the same participant, as shown in Fig. 5. The lane width was about 3.5 m. Considering that the width of the truck is about 2.5 m, an absolute lateral position of 0.5 m or greater corresponds to driving on the lane markers.

Figure 7 shows the sound volume during a trial. Sound was produced when the ACC was active (Trial 2: 8.5–19 km), except for four brief moments where the participant disengaged the ACC or the experimenter disabled the sound feedback. When lane-offset sound was produced (Trial 3: 21–27.5 km), the sound was not equal from the left and right speakers. A lane change to the left can be distinguished around 22.5 km. In Trial 3, between 28.5 and 32.5 km, the participant experienced headway sound. Finally, in Trial 4 (from 33.5 km onward), the participants experienced all sounds together.

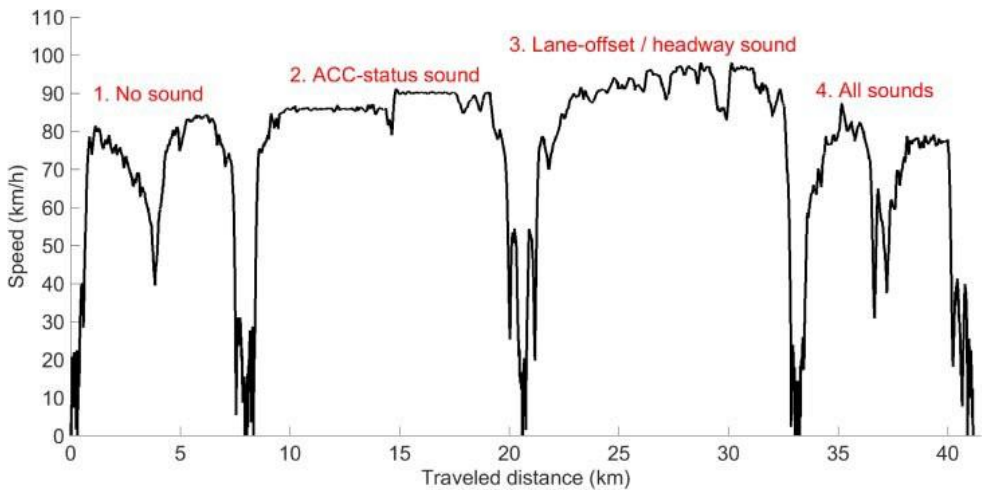

Fig. 5 Driving speed for a selected participant.

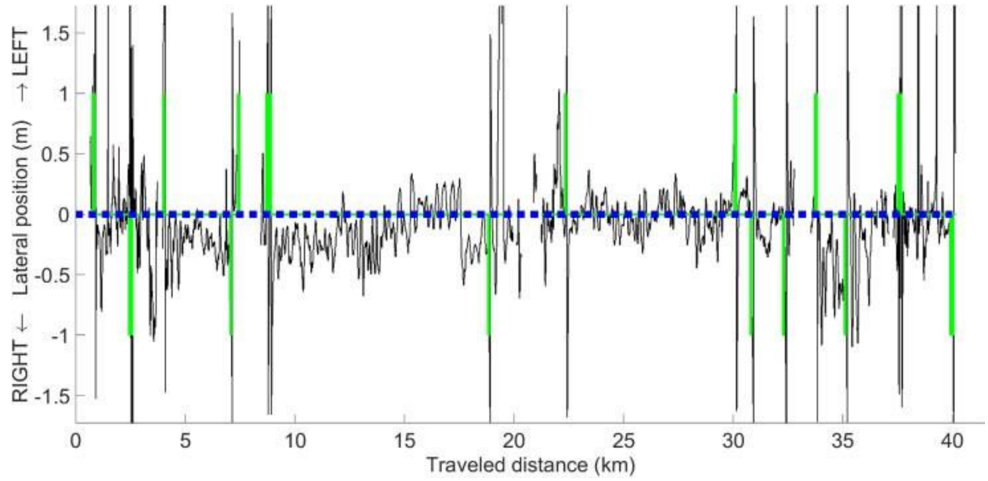

Fig. 6 Lateral position (black) and the use of the turn indicator (green; 1 = left, −1 = right) for the same participant as in Fig. 5. Data are shown only when the driving speed was greater than 50 km/h.

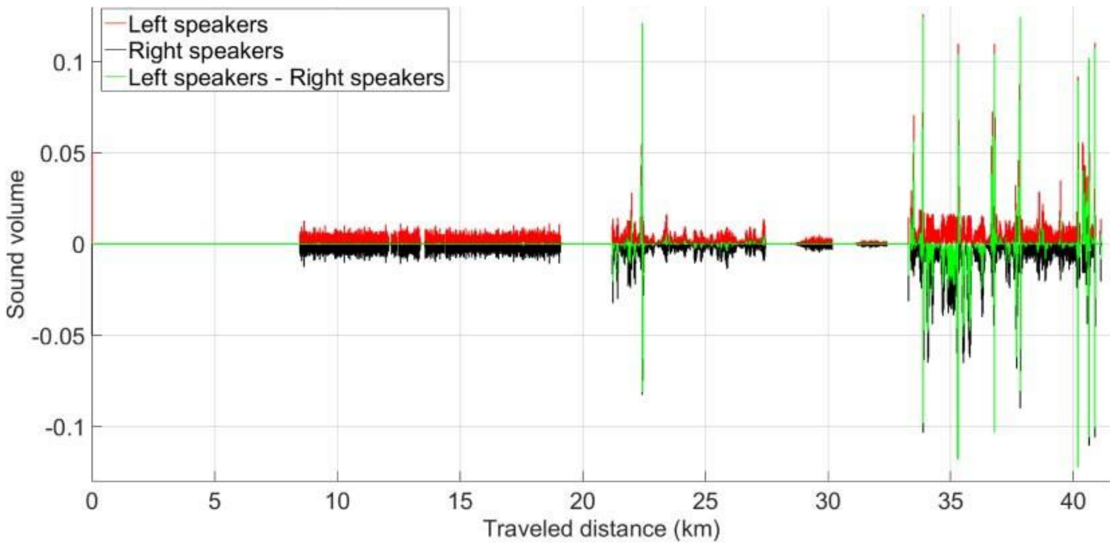

Fig. 7 Sound produced during a trial for the same participant as in Figs. 5 and 6. The signal 'left speakers–right speakers' indicates the difference in volume between the left and right speakers, that is, whether the sound was dominant on the left side (positive values) or on the right side (negative values).

3. RESULTS

3.1. Interview Responses and Responses to Open-ended Questions

In the interviews, participants expressed that they did not appreciate the idea of having additional sounds in the cabin. They indicated that significant research funds are directed to the reduction of noise in the cabin. During the second trial, multiple participants said that they would rather have auditory feedback when the ACC is turned off, instead of having it when the system is on. The idea of adding auditory feedback when no action was needed was not well accepted. On multiple occasions, it was stated that a driver should be able to change the type of sound, its volume, and frequency to have personalized feedback.

In each post-trial questionnaire, the participants were given an open question '*What did you think of the feedback in the last trial? Is it useful and satisfactory?*' After Trial 1, 13 participants provided a response. It was mentioned by 9 participants that the standard lane keeping support warnings were annoying or could be improved, and 5 mentioned that the feedback was useful.

After Trial 2, 18 of 23 participants noted something down. For example, one participant expressed his opinion that auditory feedback when ACC was turned on is not needed as 'You should get 'rewarded' when using for example ACC so there should be sound when it is off

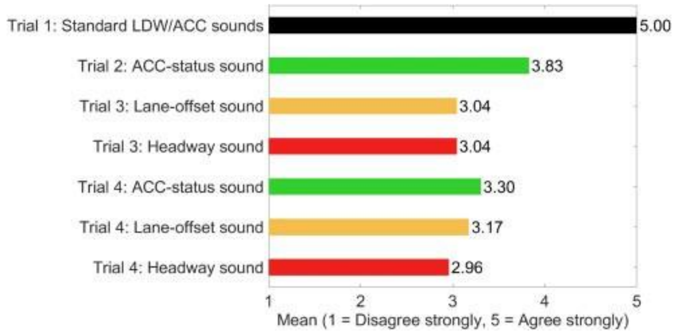

Fig. 8 Mean responses regarding whether the sound was easy to hear. The numbers represent the mean values of participants.

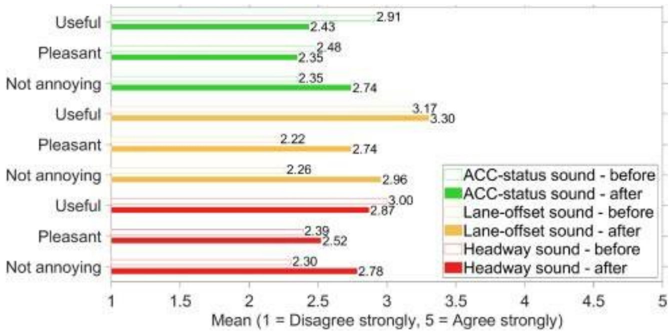

Fig. 9 Acceptance of feedback before the experiment (i.e., before Trial 1) and after the experiment (i.e., after Trial 4). The numbers represent the mean values of participants. The standard deviations of the 18 values range between 0.95 and 1.55 (N ¼ 23).

instead.' Another participant reported that the ACC-status feedback sounded like a 'malfunctioning fan.'

After Trial 3, 19 of 23 participants provided their feedback on the lane-offset sound. One person said 'Much better than standard function. It supports me instead of dismissing my capability.' A number of people said that such feedback is helpful and can be used especially by novice drivers. However, many participants were displeased with the system or found it hard to distinguish.

After Trial 4, 18 of 23 participants provided feedback on the headway sound. This sound was given mixed reviews. It was reported that such feedback was difficult to hear and may not be useful in dense traffic. One participant stated that the lane-offset sound and the headway sound were not useful when the driver is focused but would be useful during automated driving. Feedback on the combination of all three systems received after Trial 4 was mostly negative, where participants reported not being able to distinguish between the components of the sound.

3.2. Responses to Closed-ended Questions

The mean scores for whether it was easy to hear feedback are shown in Fig. 8. The existing lane keeping system was easy to hear, with unanimous agreement among participants. All three wind-based sounds were hard to perceive, especially the headway sound. This may be because short headways were not often experienced, resulting in low overall volume.

Figure 9 shows the self-reported acceptance of the feedback before the experiment as was reported in the introductory questionnaire, and after the experiment. Participants saw some merit in the lane-offset sound, with a mean usefulness score of 3.30 on a scale from 1 to 5. However, the ACC-status sound was seen as unpleasant and irritating.

Figure 10 shows the results of the van der Laan acceptance questionnaire. The results confirm the above

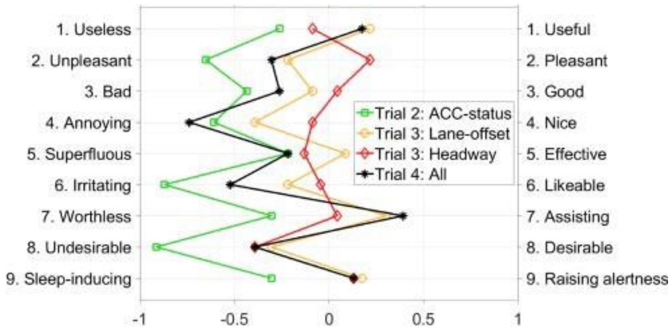

Fig. 10 Mean scores on the van der Laan questionnaire (minimum possible is −2, maximum possible is +2). The standard deviations of the 36 values range between 0.77 and 1.31 (N ¼ 23).

observations, where the lane-offset sound was regarded as somewhat useful, whereas the ACC-status sound and all sounds in combination received low acceptance ratings. The mean usefulness ratings (average of items 1, 3, 5, 7, and 9 in Fig. 10) were −0:30, 0.14, 0.00, and 0.04 for the ACC-status sound, lane-offset sound, headway sound, and all sounds, respectively. A repeated-measures ANOVA showed no significant difference, Fð3;66Þ ¼ 1:24, p ¼ 0:303. The mean satisfaction ratings (average of items 2, 4, 6, and 8 in Fig. 10) were −0:76, −0:28, −0:08, and −0:49 for the ACC-status sound, lane-offset sound, headway sound, and all sounds, respectively. A repeated-measures ANOVA showed a significant difference, Fð3;66Þ ¼ 3:51, p ¼ 0:020.

Figure 11 shows the results of the System Usability Scale (SUS). The results indicate that all systems were regarded as easy to use and learn (Items 3 & 7). Furthermore, on average, participants indicated that they would not like using the systems frequently; the ACC-status sound received particularly low ratings (see Item 1). The mean usability scores were 60.9%, 64.6%, 62.9%, and 55.5% for the ACC-status sound, lane-offset sound,

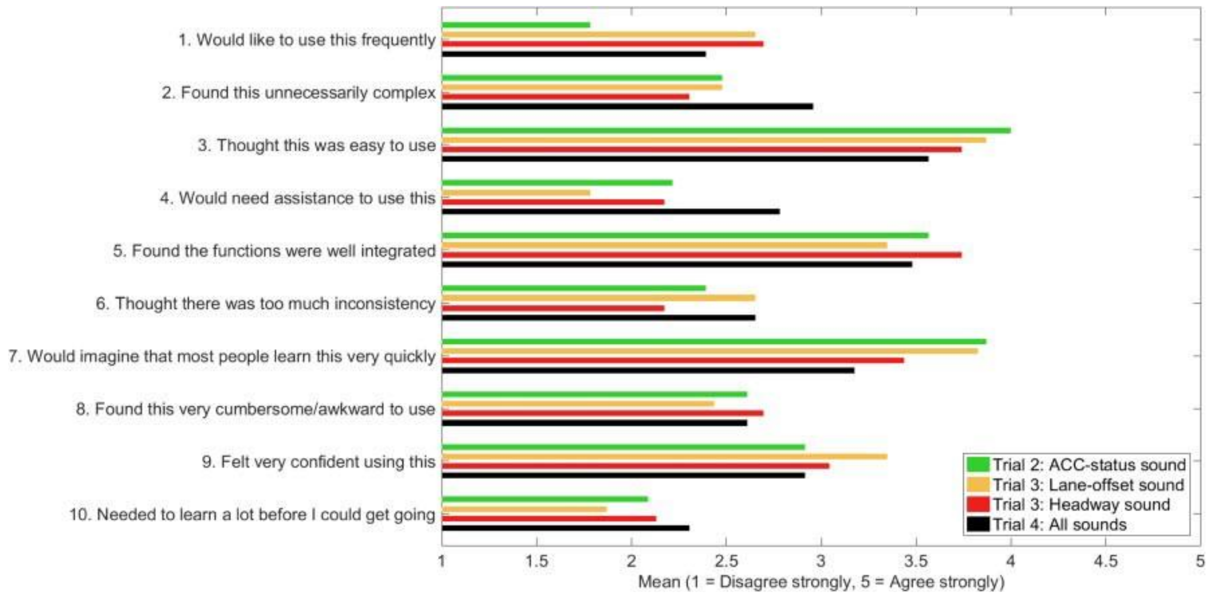

Fig. 11 Mean scores on the System Usability Scale as reported after Trials 2–4.

headway sound, and all sounds, respectively. A repeated-measures ANOVA showed no significant effect, $F(3, 66) = 1.29$, $p = 0.286$. These scores represent the average of the 10 items, with sign reversals for items 2, 4, 6, 8, and 10, and transformed to a percentage from 0% (lowest possible scores on all 10 items) to 100% (highest possible scores on all items).

4. DISCUSSION

4.1. Main Findings and Interpretation

Before the experiment, we hypothesized that because our world is essentially continuous and discrete triggers are rare in nature, continuous feedback would be perceived as pleasant and natural. In this study, we investigated whether continuous auditory feedback on the status of a truck equipped with ADAS is beneficial for the user experience. The experiment showed that our hypothesis might not be true since truck drivers were not favourable to adding auditory feedback that was intended to blend with the engine and wind noise inside the cabin.

The presented concepts were easy to understand for most participants. The lane-offset sound was the most accepted type of feedback presented; a number of participants said that such feedback was helpful. The volume level of the headway sound was reported to be too low. The ACC-status sound was not accepted well. Most participants would prefer to have it off, instead of receiving it when the system is on. The presentation of all three sounds together was also regarded as annoying. The combination of all three concepts yielded a sound consisting of different frequencies, which was not tolerated well.

Our results can be explained by the fact that truck drivers are usually confined to their cabin for extensive periods [14] and therefore may not tolerate extra sounds. In fact, much research has been conducted on the cancellation of noise in the cabin [15–18]. Truck drivers have a risk of hearing loss due to the noise in the working environment [19]. Annoyance due to environmental noise has been shown to be largely determined by overall loudness [20,21]. Low-frequency noise with a dominating frequency spectrum of up to 200 Hz was shown to be perceived as more annoying than noises with higher frequency [22].

It is our impression that the truck drivers were markedly open and critical; they expressed no social desirability but provided honest feedback on both existing systems and new concepts. Our findings confirm the importance of conducting on-road experiments when developing in-vehicle feedback systems. The present results serve as a useful reminder that end users may reject theoretically interesting ideas (e.g., the use of continuous auditory feedback) that are proposed in the academic realm.

4.2. Implications and Recommendations

The offered concepts, as they were presented in this study, are not ready to be alternatives to auditory warnings used in modern production trucks equipped with advanced driver-assistance systems. However, they may have future, especially the lane-offset sound, which received positive comments from some of the participants in the experiment. Accordingly, we recommend testing continuous lane-offset sound in future experiments. The lane offset sound was provided from the left and right speakers at the same time with a weighting factor depending on the deviation from the centre of the lane (see Fig. 7). In future experiments, the effects of providing such feedback solely from the side of the deviation from the trajectory could be investigated. An improvement may be to disable the sounds when the driver enables the turn indicators. The continuous feedback on the status of ACC or automation of a vehicle may be tested further with reversed feedback, where the sound is on when the system is turned on. Headway sound should be tested in a more controlled environment with well-managed headway to the vehicle in front.

Are the present results generalizable to higher levels of automated truck driving? The truck industry is one of the early adopters of automated driving. In 2017, MIT's Technology Review considered automated trucks as one of top 10 Breakthrough Technologies of the year and speculated that the introduction of such trucks would happen in the next 5 to 10 years [23]. Automation in trucks could bring substantial benefits, because drivers may be able to use the periods when the truck is driving automatically to have their mandatory breaks. More revolutionarily, trucks may drive without any drivers on the highway. Truck platooning could be the first commercially successful application of automated driving, where one or multiple trucks within a platoon are automated [24,25]. It is important that drivers of automated trucks are aware of the automation mode because, as with other applications, mode confusions are an important contributor to accidents [26]. Drivers need to be informed about upcoming mode changes, as well as situations where the system limits are reached, such as when a collision or lane departure is about to occur. It may be interesting to use continuous auditory feedback for presenting the automation mode of the automated truck in a continuous manner, akin to how we presented the ACC mode in the present study.

We showed that many truck drivers believe that adding in-cabin auditory feedback is not beneficial. However, it is still possible that other types of continuous auditory feedback may be less annoying than the ones tested in our experiment. Our study focused on the subjective acceptance of sounds in the cabin. Future research could investigate the effects of continuous sounds on driving performance and safety. For example, it would be interesting to examine whether continuous tones would yield more accurate lane keeping than a regular lane departure warning system. Whether continuous sounds could counteract fatigue or vigilance decrements would also be a worthy topic of research.

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SUPPLEMENTARY MATERIAL

Samples of sounds and questionnaires used in the experiment are available at: https://doi.org/10.4121/uuid:6f781c05-c696-4d0e-9fc6-bbfb7247a19e

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