A new approach to sound design in automated vehicles

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Abstract

Human-Machine Interfaces (HMIs) aim to support the interaction between automated vehicles and drivers to improve safety and driver experience. With the development of automated vehicles, drivers interact with vehicles in new scenarios. In addition to visual modality, sound is the other modality often used in vehicles. Previously, sounds were mainly used for alarms, but they can be used in other ways in automated vehicles. Therefore, a new approach to sound design is needed. We proposed an interactive approach for sound design to improve driver safety and user experience in automated vehicles. In this study, we suggested that the driver's interaction with automated vehicles should be analyzed based on the user and contextual understanding, and the sound should be designed to consider the appropriateness of situation matching and alert levels. This study showed that the approach supports designing sounds that enhance vehicle and driver interaction.

Introduction

Although alarm sounds remain important in user interface design, sounds offer more possibilities that are currently not used. One of the advantages of sounds is capturing omnidirectional attention (Siwiak & Jame, 2009). The auditory interface can help increase visual attention for potential risk situations on the road (Beattie et al., 2014). At the same time, sound can annoy drivers, which is a significant concern in designing auditory displays (Edworthy, 1998). In addition, sounds in an auditory interface often convey a sense of urgency, which is different from the design intention (Edworthy, 1994). Despite some of these wrong implementations of sounds in user interfaces, sounds have important information capacities and advantages. In conclusion, sounds should not only be designed on their perceptual quality, but more importantly, the interaction of drivers with the vehicle and its context should be the determinant factors in the design of the sounds.

Drivers interact with the vehicle in several situations during driving. As automated driving becomes possible, new scenarios of driver-vehicle interaction have been developed such as a transition of the control. In these scenarios, sounds can be used not only to warn the user about the actual transition but to support the entire transition process.

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In several studies on automated driving, the focus was on the impact of the type of modality. Take-over requests with only sound or sounds combined with visual or tactile modality were compared in reaction time, situational awareness, and acceptance (Politis et al., 2015, Petermeijer et al., 2017, Roche et al., 2019). The function of sounds was evaluated by providing an automation information (König & Neumayr, 2017) or transition-related information (van den Beukel et al., 2016). In addition, the effect of different sounds on ADAS (Advanced driving assist system) function activation (Larsson & Västfjäll, 2013) or take-over requests (Jeon, 2019) were studied. These studies aim to identify the effect of sounds in certain situations and provide important insights into sound design for automated vehicles. Previous studies mainly provided single information in a specific scenario by sound, mainly in the form of beeping. There has been a lack of consideration of the sound design process. Designing sound should be considered how users perceive the context information by sounds or what experiences could be delivered (Özcan & van Egmond, 2008).

We suggest an approach for sound design to provide contextual information during driving. First, designing sounds is based on understanding user interaction and driving situations. Next, to design sounds to match the situation and alert level. This new approach will allow the design sounds to be better accepted and keep their functionality.

Design Methodology

The sound design process consists of two steps as follows. 1. Understanding the driver context and analyzing vehicle-driver interaction, and 2. Designing the sounds

Understanding the driver context and analyzing vehicle-driver interaction

Interaction between drivers and automated vehicles and its context is analyzed, and the situation where the sound should be provided is selected. The abstract sound is difficult to convey narrative information. Speech may be used, but this may quickly increase drivers’ annoyance (Forster et al., 2017). Auditory interfaces in vehicles are commonly used to draw drivers' attention to a visual display. A driver may be aware of sounds and checks the details through the visual interface. When sounds are provided in an integrated way with visual information, sounds do not have to contain information itself. However, only function as means to attract attention. In consideration of the need for interaction, sounds need to be added in essential situations. If the same sounds are overused, the use of sounds becomes counterproductive.

Based on the interactions, the sound can be classified as an Indication or Alert. The indication provides information which is not urgent, such as informing automation state or feedback notification of drivers' input. It helps drivers recognize changes and draws attention to the visual interface. An alert warns drivers to be aware of a situation. If an indication sound is not properly designed, it may evoke a sense of urgency for an alarm sound, and vice versa.

Designing the sounds

Sounds are designed in consideration of the appropriateness of matching and alert level.

Appropriateness of matching
Sounds characteristics should be adjusted to make a sound match the situation. For example, when the pitch rises, something starts, and when the pitch decreases, something is turned off. In urgent situations, a sound is designed to discriminate from other sounds in such a way that the driver should know the situation accurately only by sound. Like in the design of warning symbols, the elements of legibility, conspicuity, discriminability, and urgency mapping are required for users to comprehend symbols (Edworthy, 1998). Analogously, these factors should be considered when designing alarm sounds.

Alert level
Sounds should be designed according to the alert level of a situation. According to ANSI (American National Standards Institute, 1991) standards, there are four stages of alert level: notice, caution, warning, and danger. An alert level is assigned in consideration of the purpose classified in the previous step. In a critical situation, the urgency level can be changed based on a reaction of a driver. For example, the urgency of a take-over request sound can be increased if a driver does not react appropriately. Changes in sound elements such as pulse interval or decibels significantly impact the perceived urgency (Hellier et al., 1993). Unpleasantness can be used to draw the user's attention (Özcan & van Egmond, 2012). Contexts of high alert levels requiring an immediate reaction use the unpleasant parameters as a partial solution. However, sounds of non-critical context consider acceptance, such as pleasantness or appropriateness of matching situations with sounds, rather than drawing immediate attention through sound.

Study 1 - Designing Sounds to Support Visual HMI for Autonomous Truck Drivers

This interactive approach to sound design was applied in a study to inform truck drivers in an autonomous driving situation. Truck drivers are one of the personas within HADRIAN a Horizon, 2020 project. The interaction scenarios developed in Hadrian capture transitions between manual and autonomous driving and driver attention, which are regarded as critical events in automated vehicles (AV).

Truck drivers are professionals and drive longer periods of time than passenger car drivers. (Belman et al., 2004) has indicated that a truck driver on average drives 8.4 hours. (Horberry et al., 2022) have recommended increasing the loudness of the auditory message in trucks in order to prevent them of being masked by background noise. Considering that truck drivers are already exposed to noise over a long period of time it was decided to keep the sound design simple in nature. Sounds normally used in this context are simple beeps. Therefore, we have made sure that the new sound design is inherited from this tradition.

A visual interface wireframe based on the HADRIAN interaction scenarios was first developed in a previous study (Kabbani et al., 2022). This wireframe guided the sound design. A list of the designed sounds is presented in Table 1 indicated by their name. The sounds have two apparent functionalities. First, the sounds indicated in Table 1 by '*Hands-on steering wheel*' and '*Ask attention*' are adaptive to the driver's state. If a driver does not respond to the warning appropriately, then the urgency level increases stepwise. Second, the sounds that support a mode change are *AV available, Driver confirmation* and *AV start* and do not change the urgency level over time.

Table 1. list of designed sounds

Situation	*Sound Names*	*Purpose*	*Expected Alert level*
AV on	AV available	Indication	Notice
	Driver confirmation	Indication	Notice
	AV start	Indication	Caution
AV off	Take-over has started	Alert	Warning
	Hands-on steering wheel	Alert	Warning – Danger
Driver distraction	Ask attention	Alert	Warning - Danger
	Parking maneuver	Indication	Caution

In SAE levels 3, 4 and 5 an automated vehicle has a role in monitoring and controlling. This allows drivers to take their hands off the steering wheel and perform non-driving related tasks (SAE International, 2018). A notification that indicates that the automation mode has changed has a positive effect on usability and safety positively (Nadri et al., 2021). For a transition to autonomous driving ('*AV on*' in Table 1), three sounds are designed to support the steps of this transition. First, a vehicle informs a driver that autonomous driving is possible (*AV available*). Second, when a driver confirms the change to the autonomous driving mode, the vehicle gives a feedback sound (*Driver confirmation*). Thirdly, a sound is provided when AV mode is started (*AV start*).

Several studies (Politis et al., 2015, Petermeijer et al., 2017) have shown that take-over requests using sounds are more advantageous than take-over requests using only a visual interface. (van der Heiden et al., 2017) found that providing a sound before a take-over request made the take-over situations safer. In our study, when a scheduled take-over request occurs from the automation to the manual mode, a driver receives a sound thirty seconds in advance (*Take-over has started*). Fifteen seconds later, another take-over request is provided (*Hands-on steering wheel*). The urgency level will then gradually increase over time if a driver does not react. There is no need for designing an AV deactivation sound, because a driver will notice that manual driving is started when the warning sound is off. In an emergency transition, a '*Take-over request*' is directly provided without the '*Take-over has started*'.

In the HADRIAN project, a detection system for monitoring a driver state was developed. This system can provide a warning when a driver is distracted. A vehicle will present the sound '*Ask attention*' when the driver is not capable to drive. It also includes situations in which a driver is not adequately responding to a transition request. The Inter-Onset-Intervals between sounds were reduced to generate higher urgency levels. If drivers do not react to the '*Hands-on steering wheel*' and '*Ask attention*' warning, a minimum risk maneuver to protect drivers will be started indicated with the sound (Parking maneuver)

Method

The sounds in Table 1 were validated in a video simulation created by modifying the simulator truck scenario of the Hadrian project, as shown in Figure 1 to confirm whether the design intention matched users' understanding.

Figure 1. Video capture of a driver distraction situation

Participants

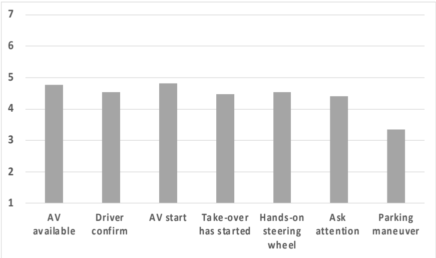
Seventeen drivers participated in the validation test. All subjects were male, and the average age was 41 years. All were professional truck drivers who had 17.1 years of experience in truck driving.

Procedure

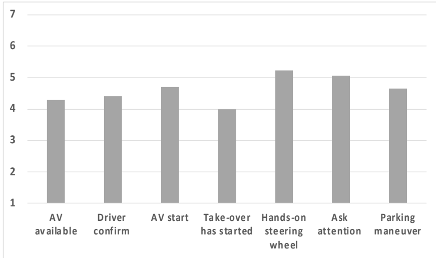
The drivers were explained the purpose of the study and their demographic data were collected. The main procedure consisted of two parts. In the first part, a *pleasantness* rating for each sound without any context was obtained using a 7-point Likert scale. We did not use a context in order to only measure *perceptual pleasantness*. In the second part, a video based on the Hadrian truck driving scenario was used to test the sounds of Table 1 in context. In this part, a participant rated the *alertness* based on the 4-level ANSI (American National Standards Institute, 1991) scale (*Notice, Caution Warning,* and *Danger*) and a 7-point Likert scale questionnaire with terms on *appropriateness*, *annoyance,* and *intention of use*.

Results

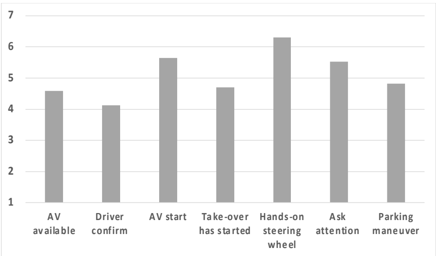
Figure 2 consists of four sub-figures, all addressing the perspective of the driver. In the top left figure, the participants' perception of pleasantness is shown. The overall perceived pleasantness scored more than 4 points. The lowest ranked pleasantness amongst all sounds were '*Parking maneuver'*. Moreover, a t-test indicated that '*AV available*', '*AV start*', and '*Take-over has started*' were rated significantly higher than the midpoint (4, *p*-value <0.05) of the scale. There was no correlation between pleasantness and the other attributes (*appropriateness, annoyance*, and *intention of use*).



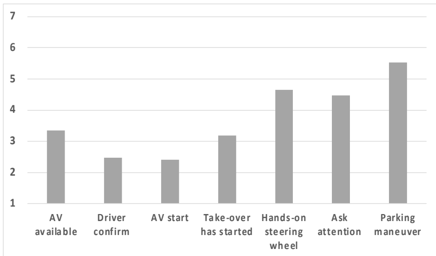
(1) Mean *pleasantness* ratings as a function of Sound Type (ratings were obtained without visual context)



(2) Mean *appropriateness* ratings as a function of Sound Type



(3) Mean *intention of use* ratings as a function of Sound Type



(4) Mean *annoyance* ratings as a function of Sound Type

Figure 2. Bar chart of the mean ratings for (1) *Pleasantness*, (2) *Appropriateness, (3) Intention of use,* and (4) *Annoyance*

The top right figure shows the appropriateness level of how well a sound matches a certain situation. Participants answered more than 4 points in all events, although only the *'Take-over has started', 'Hands-on steering wheel',* and *'Ask attention'* were rated significantly higher than 4 points from the t-test (p-value <0.05). In the bottom left figure, how necessary a sound is in a certain situation is shown. Participants also rated more than 4 points in all events, especially the average of *'AV start', 'Hands-on steering wheel',* and *'Ask attention'* were significantly higher than 4 points from the t-test (p-value <0.05). In the bottom right figures, an answer of annoyance level is shown. The '*Parking maneuver*' was rated with the highest annoyance points.

In Figure 3 the proportion of choice for the ANSI alert levels as a function of *Sound Name* is shown. More than 80% of participants responded that the sounds '*AV* *available'*, '*Driver confirmation'*, and '*AV start'* evoked the alertness levels *notice* or *caution*. These sounds were designed to function as an indication. Thus, this finding corresponds to the designed intention. However, around 80% of the participants indicated that the '*Take-over has started*' sound was a *notice* or a *caution* sound, although it was designed as a higher-level alert sound. No participant indicated that the alert level of the sound was dangerous. More than 60% of the participants indicated that the sounds '*Hands-on steering wheel'* and '*Ask attention'* were '*warning* or *danger'* alarms. This finding corresponds to the designed intention of the alert level. More than 60% of the participants indicated *Parking maneuver* sound was a *warning* or *danger*. However, the sound was designed for the function of indication.

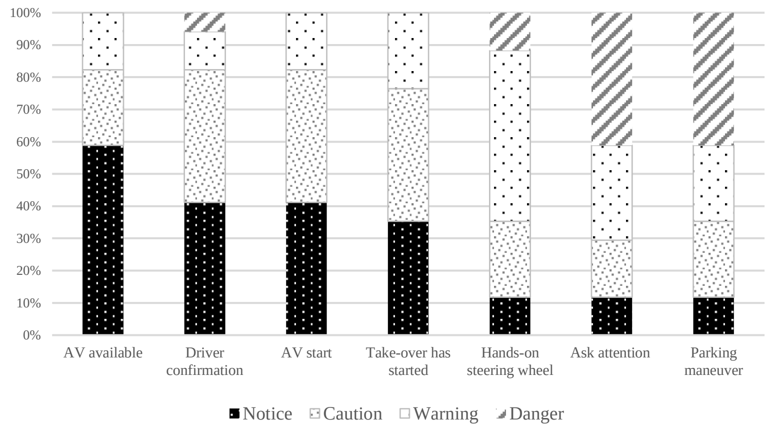


Figure 3. *Alert level responses*

Discussion

Our main finding is that it is possible to design sounds that are pleasant and of which the designed intention for a specific context matches their function and proper corresponding alert level. Seven sounds indicated in Table 1 were designed for interaction in an autonomous truck. Based on the validation results, five sounds (*'AV availble', "driving confirmation', 'AV start', 'Hands-on steering wheel',* and *'Ask attention'*) were appropriately designed for their driving context. The *'take-over has started'* and *'parking maneuver'* sounds were revised. The '*take-over has started'* sound was modified to raise the alert level, and the '*parking maneuver'* sound was modified to reduce the urgency for less annoyance and lower the alert level. The remaining sounds and the newly designed sounds will be applied in a FORD truck and evaluated in a road demonstration for the Hadrian project. This research has to be conducted.

Study 2 - Exploratory Study to Design Ambient Sounds for Highly Automated Vehicles

The above-described sound design methodology was used in a Master course, Interactive Audio Design, at the Faculty of Industrial Design Engineering. The study purpose is to design context-relevant soundscapes including feedback sounds, with the aim of creating a better user experience. A soundscape is an acoustic environment perceived by listeners in contexts (Schafer, 1976), and it can provide context information (Aletta et al., 2016). Soundscape should orally describe the context in which a driver is and what kinds of actions are to be expected.

Students received the following scenario description on which they had to base their sound design: “The vehicle is a B-segment-sized vehicle, commonly described as a small car and the largest segment volume in Europe (i.e., Toyota Yaris, Renault Clio). The driver is around 35 years old and runs a startup company. The vehicle is highly automated, allowing the driver to work such as sending an email or writing a document during the automated driving mode". A final deliverable was a movie clip including sounds and their context. Students made a persona based on the scenario description. Next, a theme of sounds was decided based on the persona’s characteristics in a conceptualisation phase. After, they analysed driver-automated vehicle scenarios where sounds would be provided as shown in Figure 4. Next, students designed sounds using a sound design tool. Six groups of twenty-five students created movies, including at least two automation mode transition situations, and three experts evaluated the movies.

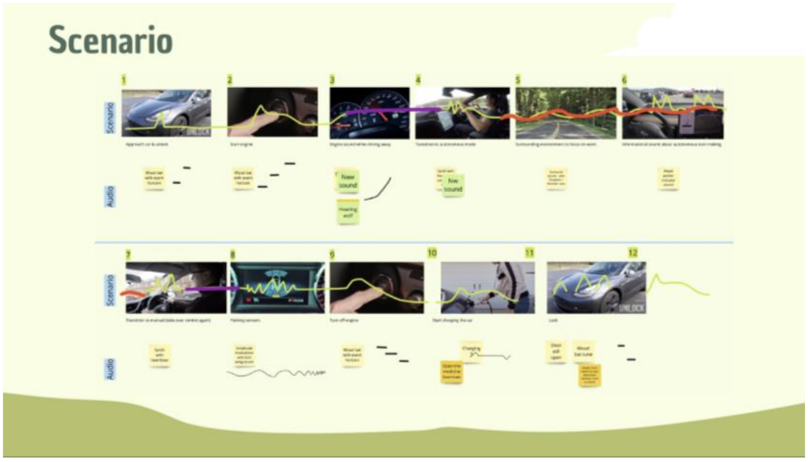


Figure 4. Analyzing interaction scenarios example of one group

The soundscape has been designed to enhance user experience and provide information to a driver with less perceived annoyance. The deliverables were evaluated by two experts in sound design and one expert in UI design. The evaluation was based on whether a sound was appropriate for a context, applicable for interaction, and highly completable. Although the soundscapes were not evaluated in a rigid experimental setting the deliverables showed that soundscape could be used in various ways in highly automated vehicles. For example, it is possible to provide automation system information using a soundscape, such as the external vehicle information (Gang, et al., 2018), lane-keeping or a round-about maneuver of an ego-vehicle (Beattie et al., 2014). In addition, soundscapes may allow drivers to be aware of scheduled take-over situations.

Discussion

Our first findings are somewhat at an informal level. However, the design brought forward the possibility of informing drivers about contextual information and the ego-vehicle actions without having to look at the road. This is one of the strengths of the use of sound in a more advanced way that enables situation awareness of the driver. This may be an essential factor in the increase of safety when a car is in SAE levels 4 and 5. Furthermore, driver-vehicle interaction through soundscapes can provide a new way of designing user experiences to drivers. Further research will be conducted on the impact of soundscape on drivers' trust, situational awareness and safety, as well as user experience.

General Discussion

This study suggested a new approach to sound design and contributed to improving drivers' experience. In Study 1, sounds were designed considering several interaction scenarios that were validated with the purpose of enhancing functionality and user experience. Study 2 showed that soundscape could be used in automated vehicles, contributing to less perceived annoyance, and therefore enhancing the user experience.

However, the limitations of the design approach need to be taken into consideration. First, it is important to note that the outcome is dependent on the capability of the interaction designer. The interaction designer needs to understand the driving context and consider the driving experience in its design. In addition, the interaction designer is required to have adequate technical sound design skills or work in close collaboration with a sound engineer to produce the sounds. Furthermore, a validation phase does require an investment in both time and cost.

In future research, there is a need to evaluate the designed sound's impact on situational awareness, trust, workload as well as user experience in the automated vehicle context.

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