# Sonic Interaction in Intelligent Cars

Public report

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Date: 2021-01-29
Project within FFI - Elektronik, Mjukvara & Kommunikation (EMK)

FFI Fordonsstrategisk Forskning och Innovation

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# 1 Abstract

Highly automated cars (Level 4 or 5) allow their users to become passengers instead of drivers and this means that the interaction between the car and their users will change. This opens up possibilities of creating new, innovative ways of interaction that could help, guide and support car users in their new role. The SIIC project has investigated if and how sound can be used for user interaction in highly automated cars. The project has been carried out by Volvo Car Group (Göteborg), research institute RISE Interactive (Piteå) and computer game sound design firm Pole Position Production (Stockholm). Our general hypotheses have been that sound-based interaction, “auditory displays", can fulfil a number of purposes identified as crucial for the user experience in highly automated cars; it can increase trust, reduce motion sickness, enhance users’ mental model of the automation and enhance their general comfort and wellbeing. Our main approach has been to design auditory displays based on a continuous sonification approach that is more proactive and subtle in comparison to the traditional chimes used in cars today. Furthermore, it has also been the aim to merge ideas from the computer game industry with research and methods from the car industry to be able to innovate this novel research area. The project work has been divided into two phases; the design phase and the main evaluation phase.

In the Design phase, the main design concepts have been established in an iterative fashion. The foundation for this work was built using the impact map methodology which allows for identifying different behaviours that users may have and their corresponding needs. The impact map was based on interviews with potential users both in Göteborg and Piteå and resulted in three main behaviours: The Cautious, The Worker and the Mastering. Sound designs that would meet the needs of these behaviours have then been developed in workshops and through continuous iterations involving the project members as well as potential users. In the design phase, a framework for guiding sound design and research in highly automated cars has also been continuously developed.

In the Main Evaluation phase, four controlled experiments were conducted with 20-40 participants each. A within-subject design was used in all experiments. The studies have used combinations of different subjective measures, such as trust scores, emotional measures, acceptance scales and motion sickness scales. Performance measures were also used in some experiments. In addition, the studies included interview sessions after exposure to the test stimuli.

Evaluation 0 tested the general methodologies and initial framework ideas using recorded video material together with various added sound design concepts. Evaluation 1 tested the hypothesis that our auditory display could increase trust while still being perceived as acceptable and preferred over having no sound. A VR methodology with a HMD-based setup was used in this experiment. The results showed support for the hypothesis. Evaluation 2 tested whether anticipatory sound informing participants of upcoming maneuvers could reduce motion sickness. The experiment methodology involved a real vehicle on a test track where participants rode several laps while reading and rated their motion sickness at regular intervals. Results showed that the sound reduced motion sickness build-up in comparison to when riding without sound and that participants preferred riding with the sound. The third evaluation explored the trust problem further and tested whether the emotional qualities of the sound could affect the level of trust towards an automated vehicle. A VR-based methodology where the visual stimuli was presented on a curved screen was used. A “neutral” sound design was contrasted with a “positive” sound design. No strong support was found for the hypothesis but it was found that a majority of participants preferred the “positive” sound design concept.

In addition, a final event was conducted on a test track where a technical implementation based on the project findings were demonstrated. This demonstrator will be used to further evaluate the feasibility of transferring the project results into product development.

The project has been very successful in pursuing its research agenda and has had an effective collaboration throughout the project. Five scientific publications were produced during the course of the project and one publication is in progress. One of the project’s biggest achievements is the finding that our auditory display can reduce motion sickness and increase trust in AD cars. This solution can potentially become a new customer function that is not only effective but also is highly acceptable and desirable by users. Also, the project is to our knowledge the first one taking a complete approach to sound design for intelligent cars and has established this new field of research on an international level.

# 2 Executive summary

**Background**
Driving Automation is currently one of the big trends within the automotive industry today along with electrification and new types of mobility services and solutions. With high level automation engaged, the driver no longer has to supervise the automation which means that the user can truly make use of the time freed up by the automation and the user becomes a passenger instead of a driver. The user does not have to pay attention to vehicle/driving-related visual displays anymore and is enabled to freely carry out non-driving tasks which allows for reinventing the user experience (UX) in such cars. For widespread acceptance and adoption of high level Automated Drive (AD) cars to happen, UX research needs to address issues such as perceived trust, comfort, motion sickness, usefulness and enjoyment.

Sound has unique advantages in comparison to visual communication. For instance, since our hearing is omnidirectional, sound can convey information no matter where the user has his/her visual focus. Sound can also evoke emotional responses more efficiently than visual communication which seems to be of importance for creating trust towards the car.
The current project has aimed at exploring how sound, or auditory displays, could play a role in regards to meeting the challenges related to UX in AD cars, to explore new ways of designing sounds for AD and to build a foundation for how auditory displays for these cars should be designed.

**Purpose, research questions**
The objective of SIIC is to examine the potential of sound and the various sonic interaction design approaches described above as a medium for communication during unsupervised AD to support trust, comfort, safe user interaction, acceptance and enjoyment. The work has focused on the following three main research questions:

1. What are the roles of sonic interaction in future unsupervised AD?
2. Can usability and users’ feeling of trust, safety, and comfort in AD cars be influenced by interactive sounds?
3. How do different ways of sound design and sound generation influence people's mood, emotion and general wellbeing in an AD car?

We have focused on three different design application areas believed to be important for the overall AD experience:

- Application 1: Using sound to reduce motion sickness
- Application 2: Using sound to increase trust and acceptance
- Application 3: Using sound to build appropriate mental models to improve usability, understanding and learning
- Application / use case 4: Aesthetically pleasing, mood-inducing, enjoyable sonification

In general, we have hypothesized that a smoother and more continuous sound design (often referred to as continuous sonification) is more effective compared to traditional sound chimes, within all these application areas.

**Methods**
The project has been conducting research in two phases: the Design phase and the Main Evaluation phase which has used different methods for evaluation.
In the design phase, sound design concepts have been created in an iterative manner supported by different methods such as the Impact map method. A framework for communication and idea generation related to sound in AD cars has also been developed.
In the main evaluation phase, four controlled experiments were conducted with 20-40 participants each. The studies were conducted using recorded video material (Evaluation 0), VR with HMD-based setup (Evaluation 1), Real vehicle on test track (Evaluation 2) and VR with screen based setup (Evaluation 3).

**Goals**
The work has focused primarily on raising the level of competence in the development area "User Experience / HMI" as specified in the FFI EMK roadmap. By generating new knowledge in sound design, adaptive HMI, evaluation methodologies as well as concrete design solutions for AD, the project has from start to finish had the goal to support the development of competitive highly automated vehicles.The project has focused on using design approaches and methodologies from the gaming industry combined with the knowledge from sound design principles within the automotive industry.

**Results and achievements**
The project has produced five scientific publications, a functional prototype/demonstrator vehicle for sonic interaction and a set of design methods and the related design framework (see www.siicproject.com). We have also presented the results at a public seminar and by a project movie. The project has also created a platform for collaboration between research, the gaming business and the automotive business. Knowledge regarding sound design from all partners have been brought in and shared through the project platform and helped build a common understanding of users' behaviours and needs and how the gaming sound approach can be utilized in the car context. One of the project's biggest achievements is perhaps the finding that our sonic interaction paradigm can reduce motion sickness and increase trust in AD cars. We see that this solution can potentially become a new customer function that is both effective and highly acceptable and desirable by users.

**Specific results**
Evaluation 0 tested the general methodologies and initial framework ideas using recorded video material together with various added sound design concepts. Evaluation 1 tested the hypothesis that our auditory display could increase trust while still being perceived as acceptable and preferred over having no sound. A VR methodology with a HMD-based setup was used in this experiment. The results showed support for the hypothesis. Evaluation 2 tested whether anticipatory sound informing participants of upcoming maneuvers could reduce motion sickness. The experiment methodology involved a real vehicle on a test track where participants rode several laps while reading and rated their motion sickness at regular intervals. Results showed that the sound reduced motion sickness build-up in comparison to when riding without sound and that participants preferred riding with the sound. The third evaluation explored the trust problem further and tested whether the emotional qualities of the sound could affect the level of trust towards an automated vehicle. A VR-based methodology where the visual stimuli was presented on a screen was used. A "neutral" sound design was contrasted with a "positive" sound design. No strong support was found for the hypothesis but it was found that a majority of participants preferred the "positive" sound design concept.

**Dissemination and publications**
The project has increased knowledge in the area with its publications and webpage. The work regarding motion sickness will also be continued in an advanced engineering / research project (Echo2). There are no established plans for product development or market introduction as of yet, but we see high potential for it to happen. The publications from the project are listed on the website www.siicproject.com.

**Conclusions and further research**
The SIIC project has been very successful in pursuing its research agenda and has had an effective collaboration throughout the project. Ideas from the computer game industry and automotive development and research have been merged and formed principles and concepts that have the potential of solving some of the user experience challenges related to highly automated cars. In turn, this may directly facilitate large-scale acceptance and adoption of automated vehicle products and services. One of the project's most important findings is that our auditory display principles can reduce motion sickness and increase trust in AD cars.

There are a number of possibilities for further research:

- Investigating the effectiveness of the auditory display solution in a more realistic setting (such as a field test trial using a robot taxi vehicle) and during longer exposures.
- Investigate what degree of auditory display information consistency and reliability is necessary not to counteract the trust induced by the same display.
- Investigate how the driving situation and behaviour should interact with auditory saliency in such a way as to reduce unnecessary information whenever possible but still give a consistent impression to the user.
- Considering the whole automated ride journey from start to finish including car-external scenarios such as: ordering a robotaxi trip, locating the vehicle, providing feedback for door unlocking/welcoming etc.

# 3 Background

Driving Automation is currently one of the big trends within the automotive industry today along with electrification and new types of mobility services and solutions. A range of car manufacturers currently offer SAE (Society of Automotive Engineers - an automotive standardization body) Level 1-2 automation functions in their cars. With these functions, the driver still has the responsibility to supervise the automation and take over driving when needed [1]. In other words, the driver cannot perform tasks such as reading - or even take their eyes off the road - while this type of low level automation is active. The next generation of automated cars aimed at reaching higher levels of automation [1] are currently being developed. With Level 4 or 5 (L4-5) automation engaged, the driver no longer has to supervise the automation which means that the user can truly make use of the time freed up by the automation [2].
L4-5 automation or “unsupervised AD” (as we will refer to it hereafter) provides new ways of interacting with cars and the entire experience of them may be drastically different compared to that of a traditional, manually-driven car (or an L1-2 car).This situation introduces a lot of freedom and calls for new ways of designing the user experience of the car [3]. The user does not have to pay attention to vehicle/driving-related visual displays anymore and is enabled to freely carry out non-driving tasks [4].

However, even if unsupervised AD cars are brought to the market, their success is contingent on that users are willing to use and adopt this new technology [5]. Users need to feel that they can trust the AD technology [6,7], they need to feel that it is comfortable and safe to use it, they need to perceive it as being more useful than their current mode of transportation [6], and they need to enjoy using it, in order for them to accept unsupervised AD and eventually adopt it [7]. This stresses the importance of performing user centred research and development in the area of unsupervised AD. Previous research on user experience of automated vehicles have focused mainly on supervised AD, while there is a lack of work focusing on the possibilities and challenges involved in unsupervised AD.

Within supervised AD, it has been found that trust, feeling of safety and acceptance can be influenced by the users’ interaction with and experience of the car via its human-machine interfaces and it is likely that this will be possible also for unsupervised AD [8,9]. An as of yet rather unexplored area of research is to use sound, or sonic interaction, as a means of communication between the user and the AD car. Sound has unique advantages in comparison to e.g. pure visual communication. For instance, since our hearing is omnidirectional, sound can convey information no matter where the user has his/her visual focus. This feature of sonic interaction may prove to be especially useful in an unsupervised AD context where the user might have his/her visual focus anywhere (he/she might be e.g. reading a book or looking at the passing landscape) and not at the vehicle’s visual displays [10].
Also, it is well-known that sound can easily catch users’ attention and change the emotional and physiological state of the driver [11]. These properties make sound suitable as warning signals and alarms, which is one of the most common types of sonic interactions in cars today (e.g. collision alerts, belt reminder etc.). Sound design requires a lot of consideration especially when it comes to such warning sounds, which should result in appropriate and sometimes quick reactions [11-15]. For unsupervised AD, these types of attention-grabbing sounds triggered by

discrete events may not be anywhere as useful as for manual driving and supervised AD since quick reactions are not likely to be requested by the AD system. The traditional type of discrete sounds (“chimes”) may also be too intrusive and annoying - and especially so when the user is really not involved in driving the car.

An alternative type of sonic interaction design is continuous sonic interaction, which possibly can build a more proactive interaction between a car and a user, rather than just presenting information in a reactive manner. Continuous sonic interaction - sonification - refers to an auditory display that, based on continuous data signals, provides concurrent auditory information about the state or response of the system [16]. In the current project, we have assumed that datastreams from e.g. vehicle sensors could be used to render sonfications for the cars’ users, possibly making the AD system more transparent, intuitive, useful and engaging. An example of this type of auditory display from the AD domain was previously suggested by Bazilinskyy, Larsson & de Winter [17] who in an on road study explored using a subtle, continuous sound for which the level was mapped to the distance to other, leading vehicles and another sound which was in similar manner continuously informing about the ego vehicle’s lateral position in the lane.

As opposed to the traditional discrete auditory signals, a sonification-based auditory display is believed to be better matched to humans who have evolved to act and control their environment in continuous fashion, and the auditory responses in everyday interactions tend to involve nuanced feedback depending subtly on human actions [16]. Sonification also promotes closed-loop relationships which creates a higher level of perceived cooperation between human and machine, which can improve the understanding of the machine and have the potential to increase a user’s sense of engagement [16]. Still, despite having these potential benefits, this type of sonic interaction likely needs to be carefully designed in order for it to be perceived as pleasant and enjoyable - in turn a prerequisite for its perceived usefulness and user acceptance and adoption.

It has been the aim of the current project to explore how auditory displays could play a role in regards to meeting the challenges related to user experience in AD cars, to explore new ways of designing sounds for AD and to build a foundation for how auditory displays for these cars should be designed.

# 4 Purpose, research questions and methods

## Purpose and research questions

The SIIC project addresses the need of knowledge on how sound could be utilized to shape the user experience during unsupervised, L4-5 AD. The objective of SIIC is to examine the potential of sound and the various sonic interaction design approaches described above as a medium for communication during unsupervised AD to support trust, comfort, safe user interaction, acceptance and enjoyment. The project has also aimed at building knowledge regarding sound-related design and test methodologies and to propose concrete design solutions which can guide the development of technology and desirable future vehicles. The work has focused on the following three main research questions:

1. What are the roles of sonic interaction in future unsupervised AD?
In today’s cars, interactive sounds are used to provide feedback, notifications and warnings to the users, typically in the form of short chimes or beeps. In an AD scenario, the user will likely not need similar types of information and warnings since the car normally performs the driving task and does not require users to behave like drivers. Moreover, when users are not required to look anymore at the road and even may have their eyes closed, hearing has the potential of

becoming an even more important channel of communication between the users and AD cars. This new situation brings new needs and opens up the auditory environment for new interactions. The SIIC project has investigated the different AD-related use cases where interactive sound can play an important role in the user-car interaction.

2. Can usability and users' feeling of trust, safety, and comfort in AD cars be influenced by interactive sounds?
As mentioned in the background, there are user-related aspects of AD cars that may prevent widespread AD acceptance and adoption, such as lack of usability, and lack of trust, feeling of safety and comfort of AD cars. The auditory space available for building seamless interaction between the users and the AD car may be a very valuable but as of yet rather unexplored medium to reduce these problems. RQ 2 has concerned investigating if and how this can be achieved, e.g. through portraying the AD ride by using sound, informing about the car and the ride status or comforting the user through sound.

3. How do different ways of sound design and sound generation influence people's mood, emotion and general wellbeing in an AD car?
While building the knowledge on what is useful and desired to be presented through sound, it is also necessary to understand how we can make the sound aesthetically pleasing so the users will enjoy using the proposed sound interaction over an extended period of time.

The SIIC project has addressed these main research questions within four application areas where sonic interaction may become especially helpful in unsupervised AD: 1. Motion sickness, 2. Trust/acceptance, 3. Usability/learnability and 4. Emotional response. These application areas are more or less overlapping. For example, if a user has a correct mental model of the AD system, he/she may also trust the AD system to greater extent, an aesthetically pleasing design may be crucial in order to get acceptance and so on. In our research, we have worked across these application areas to be able to test hypotheses in an efficient manner and also to be able to evaluate possible interaction effects. In the next sections, we explain the respective application area in more depth. It should be noted that the research questions and hypotheses presented in this section are on a high level. During the project, research questions and hypotheses more specific to each experiment have also been formulated, see section "Specific results".

*Application 1: Using sound to reduce motion sickness*
One of the main arguments for autonomous vehicles is that they will allow users to spend their time in a more productive way. For example, the Concept 26 by Volvo Cars [2] suggest that the driver should, when having delegated the driving task to the autonomous driving function, be able to either relax or "create" (meaning: make calls, write emails or watch films and TV shows, etc.). However, there is a growing concern that the possibilities for performing non-driving-related activities in AD cars will be limited due to the risk of motion sickness (kinetosis) [16, 17]. Solutions to the motion sickness problem have been suggested, e.g. using specific visual displays and motion cues. While these types of stimuli could be efficient in reducing the visual/vestibular conflict that may lead to motion sickness, the required displays would likely be quite expensive and cumbersome to integrate in a production vehicle. Using sound reproduced by an audio system, readily available in most production cars today, would be a more practical display. The general hypothesis for Application 1 has been:

Hypothesis 1: In comparison to silence and/or event-based sound design, sonification of motion patterns and car's decisions reduces motion sickness when the user has his/her eyes off road.

*Application 2: Using sound to increase trust and acceptance*
It is key that the user trusts the automation since a lack of trust likely leads to rejection and disuse of the related product or service. Recent studies have found that many people would be afraid of riding in an automated vehicle [18], and a way to increase trust is by the design of the vehicle itself and its user interface. A high level automation vehicle may be perceived to be

more capable of driving by itself when it seems able to think and sense its surroundings than when it just gives an impression of “mindless machinery” [19]. Visualisations of what the car “sees” and where it is about to go are therefore often shown on displays facing the backseat passengers in todays’ driverless shuttle services, e.g. [20].
Speech feedback could provide rich information and also give anthropomorphic features to the automation which has shown to increase trust in automation [19]. This type of information, especially when presented regularly, may be too intrusive. We therefore hypothesize that a more continuous and subtle sonification of the car movements, intentions and abilities would be more efficient in inducing the appropriate degree of trust in the user:

Hypothesis 2: In comparison to silence or/and events-based sound design, continuous sonification of motion patterns increases trust and feeling of safety.

Trust can be seen as part of the wider scope of user acceptance – naturally also crucial for user adoption of automated vehicles [6]. Among many things, acceptance is contingent on ease of use, usefulness and enjoyment [6] and we believe that sound can play a role in increasing acceptance of autonomous vehicles by making them more useful and comfortable. Consider for example the use case of stop-and-go traffic (low speed queueing) or other situations where the vehicle brakes and/or accelerates frequently which may cause the user to look up to see what is happening. If sonification would provide subtle information to the user on what is going on in traffic, the user would not be triggered to look up each time he/she experiences sudden motion cues. Therefore, e.g. performing eyes-off-road visual tasks may be perceived as more comfortable and less annoying with sonification added. There are several other similar situations when sonification could aid in “relaying” information about the driving scenario to the user without being overly intrusive or annoying (change of route, roadworks ahead, time to handover etc.) which in turn could increase comfort and the perceived usefulness of automation. This leads us to the following hypothesis:

Hypothesis 3: In comparison to silence or/and events-based sound design, sonification of motion patterns increases acceptance and reduces annoyance while having eyes-off-the-road.

*Application 3: Using sound to build appropriate mental models to improve usability, understanding and learning*
To be able to predict possible actions and their consequences, users create mental models of the situations which they partake in. If a systems’ behaviour corresponds to user expectations, encapsulated in a mental model, it heightens trust and provides a more positive user experience [21]. When a user approaches a new system, he or she builds a mental model based on previous experiences which might not be applicable in these new situations. However, with a proper user interaction design a user can be provided with a level of information which could help to build more appropriate mental models and foresee system's behaviour. Therefore, transparent interfaces adapted to the mental system of the user are a prerequisite for the user to be able to develop necessary situation- and system awareness in interactions with the automated system [22].

A use case that has already been identified as critical during lower levels of automation is handover of control from the AD system to the user. Supporting the user in this situation by creating awareness of the system’s state and providing the user with a correct mental model of the system is however also important for higher levels of automation as long as the technology allows for multiple levels of automation (i.e. it will obviously not be important in vehicles where only one level of AD is present, such as in robotaxi vehicles, e.g. [20]). In unsupervised AD, the transition to manual driving can be challenging to handle since the intended “driver” may be in very different states ranging from being asleep to fully aware of the traffic situation. According to Strabala et al. [23], to perform successful handover one needs to agree that handover will happen, establish timing of the handover and decide how the process will be performed.

Sonic interaction accompanying the handover process as well as other use cases could be a useful part of a supportive multimodal user interface and help the user in developing a correct system/automation mode awareness and mental model of the system. Using sonic interaction, the user can perceive the information given by the user interface even with eyes closed and allows the user to keep his/her eyes on the road/traffic during the time of the actual handover or on other things in case of a “AD ride along” scenario.
As mentioned in the background section, continuous sonic interaction should improve the users' mental models and general understanding of a system since humans have evolved to act and control their environment in a continuous fashion. We hypothesize that this is applicable also to the use cases within AD which require the user to perform certain actions, such as the handover situations discussed above. This leads to the following hypothesis:

Hypothesis 4: Proactive, continuous sonic interactive (sonification) allow the user to build a better understanding/mental model, increases awareness of the AD system state and in general increases usability in comparison to silence and/or events-based sound design

*Application / use case 4: Aesthetically pleasing, mood-inducing, enjoyable sonification*
Even though a particular sound design might be highly useful (e.g. it reduces motion sickness, increases trust, induces correct mental models etc.), it is likely that the sonification and the AD system as a whole needs to be aesthetically pleasing and induce a sense of joy-of-use [24] to make the user engage the AD system for an extended period of time, and for the user to prefer sonification over more traditional means of signalling (visual displays, traditional sound chimes etc.). Apart from the advantages identified earlier, continuous sonification could also be used to induce certain moods [25] in similar ways as is being done within cinema and computer game sound design. Sound can in this way be used to soothe the user and make them simply enjoy the ride. Moreover, a gradually built up sonic atmosphere can be used to gradually increase attention and awareness of the user when, for example, the autonomous drive is about to reach its operational design domain limits and the user is supposed to take over driving. Continuous sonification also has the possibility to make the automation user interface more responsive and adaptive to user behaviour/reactions which could make the whole experience more balanced and pleasant.
While the field of designing efficient but pleasing traditional, discrete sounds for in-car applications is quite well understood, research regarding how to design the above-described adaptive sonfication displays that people enjoy using is practically non-existent. Using guidelines and praxis from the art of sound design for movies or computer games could be a way to understand how appealing, aesthetically pleasing continuous sonic experiences intended for automotive information displays should be designed. This leads us to the final hypothesis:

Hypothesis 5: It is possible to create sonficiation/continuous sonic interaction that is useful and at the same time is aesthetically pleasing and induces desired mood and emotion, by combining the art of sound design for movies and computer games with the knowledge gained from scientific research on auditory displays and sonification.

## Methods

The project has been conducting research in two phases: the Design phase and the Main Evaluation phase which has used different methods for evaluation.

In the Design phase, the main design concepts have been established in an iterative fashion. The foundation for this work was built using the impact map methodology which allows for identifying different behaviours that users may have and their corresponding needs. The impact map was developed based on interviews with potential users both in Göteborg and Piteå and resulted in three main behaviours (for more detailed information on these, see section “Specific results” below). Sound designs that would meet the needs of the three main behaviours have then been developed in team workshop formats and through continuous iterations involving the project team members as well as potential users.

In the Main Evaluation phase, four controlled experiments were conducted with 20-40 participants each. The studies were conducted using recorded video material (Evaluation 0), VR with Head Mounted Display (HMD) -based setup (Evaluation 1), Real vehicle on test track (Evaluation 2) and VR with screen based setup (Evaluation 3). A within-subject design was used in all experiments. In addition, a final event was conducted on a test track using a real vehicle simulating an AD ride (WOz car) where a technical implementation based on the project findings were demonstrated. This demonstrator will be used to further evaluate the feasibility of transferring the project results into product development. In all studies, combinations of different subjective measures were used, such as trust scores, emotional measures, acceptance scales and motion sickness scales. All studies also included interview sessions after exposure to the test stimuli. In addition, behavioural measures such as task performance were used in some studies. For more information on the Main Evaluations, see “Specific Results” below.

It should be noted that for evaluations 2-3 and the final event, which were all performed mid-late 2020, specific precautions had to be taken due to the COVID-19 outbreak. For example, shields/partitions between experiment leaders and participants had to be installed in the test vehicle, a desktop screen solution had to be used instead of HMD and all equipment had to be disinfected between participants, which has complicated running the evaluations. In addition, COVID-19 restrictions also led to that we could not perform the final demo event with as many participants as we wanted. We think we have made the best of the situation and have produced the scientific investigations promised in the application. The final concept will also be further refined based on input from the demo event and evaluated after the project end.

Moreover, due to the COVID-19 restrictions, we have not been able to perform as many joint design sessions as we wanted in the second year of the project. Although design work has been performed at respective sites, experienced with the help of VR mockups and discussed on online meetings, it is at some point vital to be actually seated in the car and ride along to get the full understanding of the user experience. During the final iterations we have experimented with combinations of different digital tools however to allow for a more rapid and fluent design feedback loop. We have for example used a setup where the sound designer from Pole Position Production located in Stockholm could stream sound to a car on a test track in Göteborg in which the Volvo team immediately could experience the sound in the right context and directly send feedback about desired changes to the sound designer. It has certainly not been an ideal situation for this type of joint work which requires the full appreciation of such a multimodal experience as riding in a car, but we believe that we have made the best of the situation.

# 5 Goals

An overall goal of the project has been to examine the potential of sound as a medium for communication during AD to support trust, comfort and safe user interaction in future cars and by doing so, improve the vehicle industry´s ability to guide technology development by suggesting appropriate user interaction- and experience paradigms. Thus, the work has focused primarily on raising the level of competence in the development area "User Experience / HMI" as specified in the FFI EMK roadmap. By generating new knowledge in sound design, multimodal interaction, adaptive HMI, evaluation methodologies as well as concrete design solutions for AD, the project has from start to finish had the goal to support the development of competitive highly automated vehicles.

The project has especially focused on bringing new knowledge to the following areas:

*Efficient human-machine interaction*

The project has aimed to increase the adaptability of the sonic interface by making use of sonification rather than, but not excluding, discrete sound events. By doing so, the sound interface will be able to adapt to external input such as driver/passenger behaviour or the surrounding environment, potentially creating a more efficient, proactive, seamless and natural sonic interaction. To further strengthen the emotional response and create a caring and trustful experience, the project has focused on using design approaches and methodologies from the gaming industry combined with the knowledge from sound design principles within the automotive industry.

*Driver and autonomous vehicle interaction*
The project has aimed to bring knowledge on how to secure the transition between driver and the autonomous system between automation level SAE 4 and lower automation levels. It should be mentioned that, although we did include transition use cases in one of our four main evaluations, our main focus and goal of the project has been the experience of the “in-AD” mode since we reasoned this would be the area would be the most innovative one and where our approach to in-car sound design would make greatest impact on the user experience.

*Driver input*
One of the project goals was to explore sonification as a method to represent a change in driving conditions such as drive modes or surrounding environment and making use of sensor data, to adapt the sound interface. A normal procedure would be to let the driver decide the level of sonification, both in terms of volume but also the amount of sensor data being sonified. During the course of the project, we have deemphasized the “driver” role since the main focus of the project is highly automated vehicles where the user is primarily a passenger. Since we have found this user role to be the most novel and innovative one, we have considered the various behaviours and needs of passengers by using the impact map methodology which is further described in the Specific Results-section.

# 6 Results and achievements

The main results/deliveries from the projects are as follows:

**Scientific publications**. In total, five scientific publications have been finished within the project (five were promised in the application): one M Sc Thesis, one peer-reviewed conference paper (awarded the “Best Use of Sound Award” by the conference), one published journal paper, one submitted journal paper and one book chapter. In addition, one journal paper is in preparation. The studies that have been conducted have in total involved around 140 test participants. See “Publications” for details.

**Functional prototype for sonic interaction.** Multiple prototypes have been implemented throughout the project both in VR and in real vehicles. The final prototype is based on a car which is driven from the backseat by a trained driver while the user is seated in the front seat to give the impression of a fully selfdriving car (a so-called WOz car). The prototype contains specific hardware and software for sound generation which was developed by the project. This prototype could only be demonstrated to internal stakeholders due to COVID-19 restrictions and builds on the results from the prior investigations and user studies conducted within the project.

**Design methods.** A set of design methods for sonic interaction in AD, based on the combined expertise from the vehicle industry, gaming industry and research have been developed and used in the project. We have also developed a framework that could guide further work in the area. This, as well as the methods along with examples of the sound design work process and the intended applications of the project’s work are presented on our website www.siicproject.com.

**Final seminar.** A seminar was held at SAFER on 2021-01-29 where project results were presented to relevant stakeholders (Swedish vehicle industry and academia) outside the project consortium. A recording of the final seminar is available on the project website..

**Project movie.** The project movie can be found on the SIIC project website www.siicproject.com. The project results will also be disseminated through Volvo Cars' PR channels.

For detailed information on the project results, see section 7.

### Contributions to EMK and FFI goals

The project has established a new sound interaction paradigm which potentially can make interaction between user and vehicle smoother, more natural, more effective and more trust-inducing. By making use of impact maps and predicted behaviours in building the foundation for the design work, we have shown a method for making the soundscape more adapted to the individual and his/her needs. This in turn can lead to greater acceptance of AD technologies and may therefore contribute to improving a wide-scale introduction of highly automated vehicles, which in turn will have a positive effect on both traffic safety and environmental footprint. Furthermore, the VR-based test methods that have been developed in the project indicate that the need of real-world tests during early vehicle development can be reduced which in turn can reduce the environmental effect of real world vehicle testing as well as contribute to making the tests more efficient and safer.

The project has also created a platform for collaboration between research, the gaming business and the automotive business. Knowledge regarding sound design from all partners have been brought in and shared through the project platform and helped build a common understanding of users' behaviours and needs and how the gaming sound approach can be utilized in the car context .The project has not only made use of the gaming industrys' experience in sound design but also adopted some of the methods for project planning, performing iterations and demonstrating concepts used by them. The involvement of Poles Position Production also fulfils the goal of promoting small business within Swedish industry.

One of the project's biggest achievements is perhaps the finding that our sonic interaction paradigm can reduce motion sickness and increase trust in AD cars. We see that this solution can potentially become a new customer function that is not only effective but - as our studies show - also is highly acceptable and desirable by users.

We believe that our results will strengthen the competitiveness of Swedish vehicle industry and can be applied to many of the innovative products and services that will emerge in the future. The results have been published on global research arenas and the project has been awarded for its unique way of using sound in cars. Furthermore the project is to our knowledge the first one taking a complete approach to sound design for intelligent cars and should therefore be seen as contributing to global leadership within this area, at least within the research domain.

# 7 Specific results

In this section, we describe some of the project work and the results from the design and main evaluation phases of the project in more detail. For even more details and information, please see the References section or our website www.siicproject.com.

### Impact map

Impact Mapping is a technique used to explore, discuss, and evaluate the impact of a digital product or service. In SIIC, the impact map was a result of an analysis of interviews with 20 potential users. In the interviews, the users were asked to recall a commute or a memorable trip. The emotional and sensorial aspects of these trips were identified in order to understand what shapes their experiences and how we may support the wanted parts and improve the ones which are troublesome.The analysis further allowed us to identify and prioritize the main behaviours people might demonstrate while using autonomous vehicles. Thanks to that, we could identify the main solutions we should strive for when it comes to both when selecting use cases to sonify as well as when designing the sounds. The behaviours labelled Mastering, Worker and Cautious were the top three behaviours that were identified by the interview analysis:

*Mastering*
This behaviour is about the feeling of being "the master of one´s domain" - not to be controlled by anyone, to control your own pace even though it might take longer to reach the goal.
Time efficiency is not the key here, but the sensation of always being in control.
During the mastering behaviour you want to know what is going on right now.

*Cautious*
This behaviour reflects a way of driving/riding that is not relaxed or joyful - the driving/riding is taking the attention. Driving/riding is not something wanted, but a hassle that needs to be taken care of for the means of transportation. The cautious one wants to know both what will happen and why it will happen, they also want an explanation for what just happened a moment ago.

*Worker*
The worker wants to be able to ignore the surrounding and the handling of the car and get on with their work. They want to spend time on productive work instead of wasting the time.

The complete impact map is shown in the Figure 1 below.

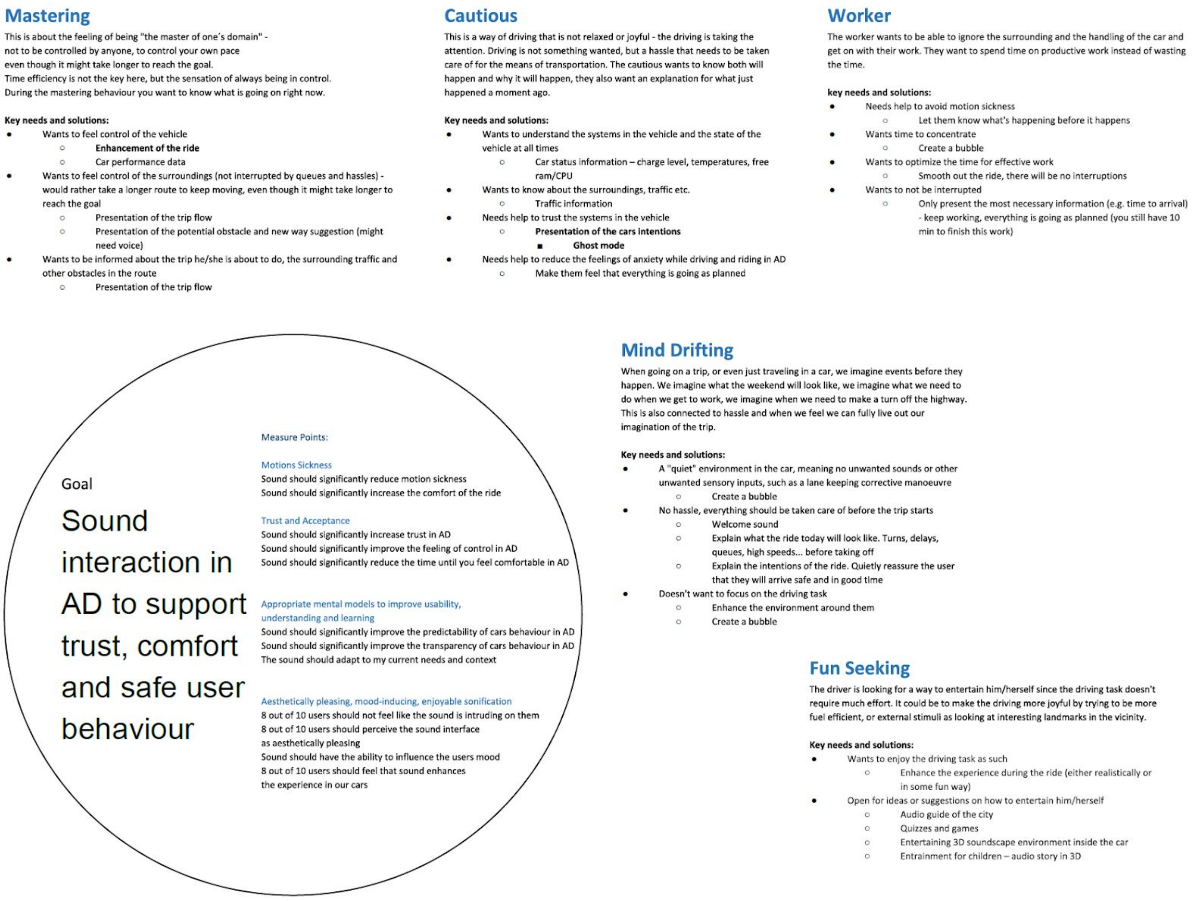


*Figure 1: The SIIC Impact map*

## Sound design framework

During the project, we have developed a sound design framework based on previous findings as well as project findings. The intention of the framework has been used to guide the project research and design, but we have also published the general ideas of the framework that could help other designers within the field. The framework categorizes the different sounds that could be used in a highly automated car into six different “layers”. We use the term layers instead of sound types since the sounds that we recommend using in self-driving cars are generally more continuous as opposed to today’s sound chimes in cars. Also, multiple sound layers may be active at the same time – hence the name layers.

Each layer has a different purpose when it comes to informing the passenger. They also relate differently time-wise to an event (for example, a specific planned manoeuvre or similar things happening in relation to the ride); some layers are supposed to be triggered well in advance to the event, others slightly in advance to the event, or even after the event has taken place (see Figure 2 below).

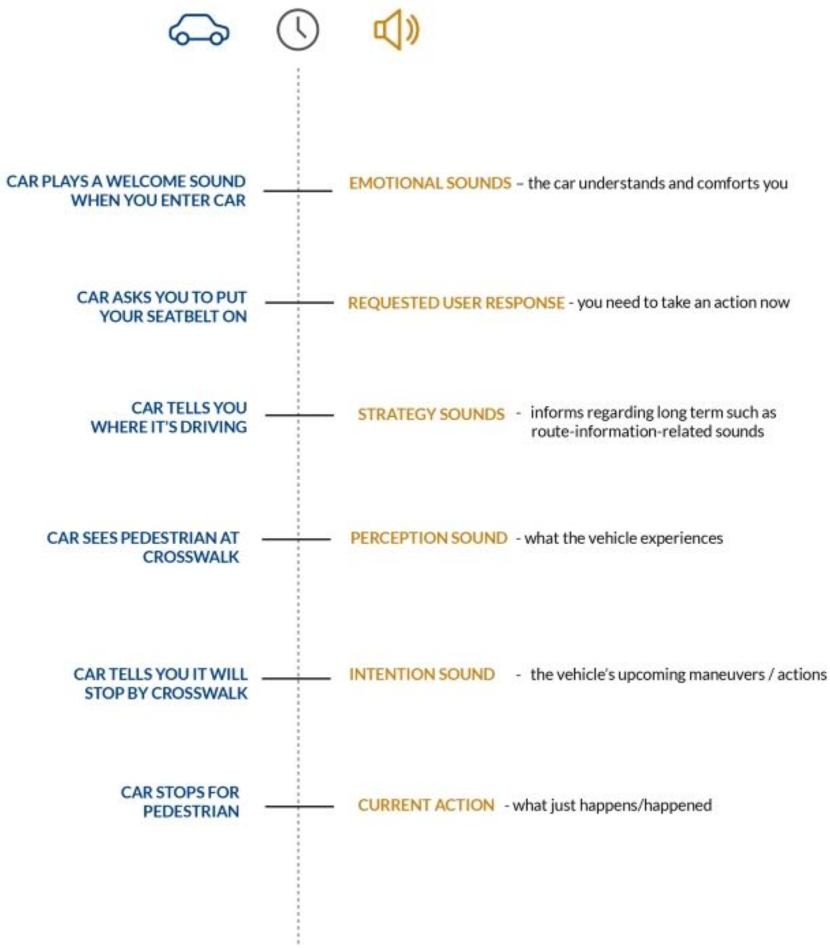


*Figure 2: Sound design framework layers along with examples.*

*The Emotional Layer*. In general we think it is important to design all sounds to evoke positive and calming emotional responses to support trust and overall positive user experiences. The emotional layer also represents that you could use sounds for no other reason than to create a good atmosphere in the car. An example could be presenting a calming, ambient welcoming sound when the passenger sits down in the car, to emphasise that the passenger is about to experience a reliable and high quality service, or a similar goodbye sound when the destination is reached and the ride is over.

*The Requested User Response Layer.* Although a self-driving car should be capable of handling all driving situations within its operational design domain, there are still some tasks that a passenger needs to perform. Examples of such tasks could be closing the door or putting on the seat belt. For these types of direct request, we suggest “requested user response” sounds to be used which resemble the sounds used in today’s car to request user action. In this category, we also include sounds which call for taking over driving when the vehicle reaches the end of its operational design domain

*The Strategic Layer informs* the passenger well in advance of an event (on the order of minutes to several seconds). It could for example be information about the planned route, how far away your destination is or that the upcoming route segment contains some particularly motion sickness inducing turns. As this type of information often can be rather complex, it is possible that it would be difficult to design a sound-only solution for this layer, so text (or speech) may be needed for the message to be conveyed properly.

*The Perception layer* tells the passenger what the car perceives that may be of specific interest to the passenger. Knowing that the car sees pedestrians or cyclists may promote passengers’ trust towards the car and may as well as give them a hint of what the car will do next, which could serve as a first preparation for upcoming maneuvers. In many cases, the Perception layer sounds will be followed by the Intention layer sounds (see next section) and can help passengers’ build a mental model of the automation system.

*The Intention layer* gives the passenger information regarding what the car will do within the next 1-2 seconds. Basically, it informs what the car’s next manoeuvre will be like - for example slowing down, speeding up, turning slightly left or hard right, or similar. Well-designed intention sounds, just like perception sounds, intuitively create an appropriate mental model of the AD car for the passenger and increase trust towards the system. Intention sounds seems to be especially important for reducing motion sickness by allowing the passenger to anticipate upcoming motions. Designed in the proper way using a sonficiation approach, we believe that intention sounds can even induce a perceptual-level anticipation, sometimes referred to as “percipation”.

*The Current Action Layer.* This layer provides explanations of what currently happens or just recently happened. The information presented through the Current action layer gives the passenger that comforting sense of being on top of all the strange things happening in daily traffic even if the automation system is in charge of driving. Since this layer may contain complex information, the usual toolbox for sound design could be too limited to create a compelling and understandable design. Sound chimes or speech in combination with information presented on a visual display may therefore be the best solution for this layer.

*Selection- and design of layers*
While it may appear as if an auditory display based on the SIIC framework would be sonically overwhelming, the framework should be considered as a toolbox and that all tools will likely not be needed for all users or use cases. Different types of user behaviours may call for both different layers to be used as well as different types of sound designs within each layer. Passengers exhibiting a typical cautious behaviour (see Impact map above) may want to have more support and a more comforting type of sound design than the regular self-driving commuter. A typical worker behaviour who needs to perform reading tasks but easily get carsick

may mainly want the intention layer sounds, but very subtly in the background not to disturb the work task. A Mastering behaviour may want to have more information and sounds designed to be more fun and engaging.

Regardless of how the personalisation and adaptation to different use cases and users is done, we suggest using different types of sounds for different layers so that the passenger can easily connect a sound to a specific type of information. A suggestion on how different sound types could be used for different layers is shown in Figure 3. In some cases, it may be good to use a traditional, well-established type of sound chime (such as traditional seatbelt sounds for a requested "put on your seatbelt"). In other cases, we advocate using a more continuous sound that is more easily linked to what's actually going on (for example, when the car is about to slow down, then you use a sound of a car slowing down).

| **Layer** | Sound design approach 1 "SIIC" | Sound design approach 2 "Classic" |
|---|---|---|
| **Strategic** | Musical/skeuomorphic sounds representing the destination + speech | Chime + text |
| **Perception** | Sound of e.g. footsteps | Chime + text, e.g. "pedestrian detected" |
| **Intention** | Sound of e.g. car slowing down | Chime + text, e.g. "slowing down" |
| **Current action** | Chime / skeuomorphic sounds representing the action + speech / text | Chime + speech / text |
| **Requested user response** | Chime / skeuomorphic sounds + speech / text | Chime + speech / text |
| **Emotion** | Adaptive musical sounds | None |

*Figure 3: Sound types/design approach proposed for the different layers within the SIIC project (left column) compared to how a classical approach to sound design would sound like (right column).*

*Spatial separation of layers.*
Another sound design feature that can help the passenger to connect the different layers to specific events is if the layers are spatialized, i.e. processed to be perceived as coming from different positions in space (both in terms of angle- and distance to the virtual source). The human spatial hearing ability allows for separating simultaneously sounding sources and for focusing our hearing on what we find interesting (sometimes referred to as the "cocktail party effect") which should improve separation of concurrent layers. In the framework, we suggest that Perception sounds, which represent something which could be at any position outside the car, should be spatialized to appear as coming from that position. Intention sounds, on the other hand, represent something that the car does and should therefore be perceived as coming from the car. Current action and Strategy sounds could relate to a variety of messages and their perceived location could either be at some fixed point or varied depending on message. Requested user response on the other hand always relate directly to the passenger and should therefore be perceived as coming from somewhere close to the passenger. Sounds specific to the Emotional layer, such as welcoming- and goodbye sounds, should be perceived as ambient

and soothing and diffuse in terms of direction. A visualisation of the proposed spatial dimension layout of the layers is shown in Figure 4.

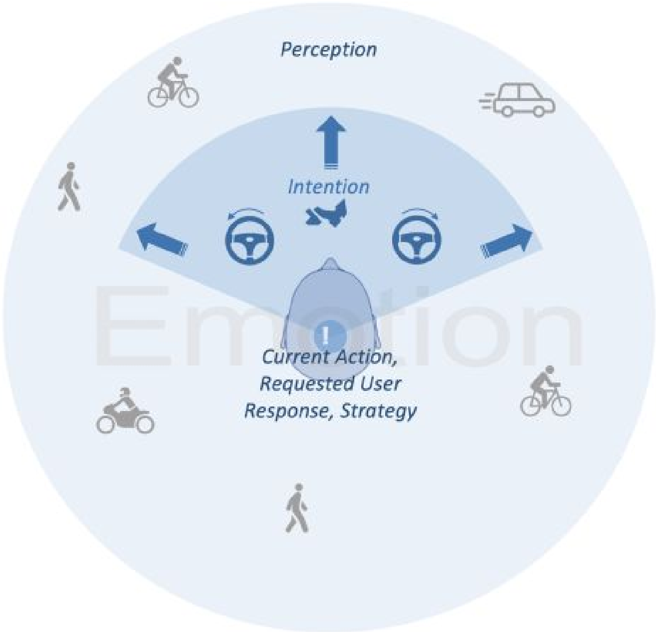


*Figure 4: A visualisation of the proposed spatial dimension layout of the layers*

## Main evaluation 0

Because of the SIIC project's visionary character, it was key to establish a foundation regarding future relevant information, user problems and user scenarios. The ideation within main evaluation 0 generated three conceptual sonic interfaces that accommodated the user problems motion sickness, low trust and informational overload. One of these concepts was developed into a functioning prototype implemented using video footage of relevant user scenarios. Carefully chosen metrics (Self Assessment Manikin-, Van der Laan's Acceptance- and Likert-scales) were assembled into an evaluation method. The method, together with the video prototype, was then implemented in study with 30 participants, providing analytical material to finally review the metrics of the evaluation method. The Self-Assessment Manikin and Van der Laan's Acceptance scale were thought to highly contribute to the evaluation of participants' experience of the interface. The Likert scales were less contributing, either deemed to be poorly implemented or simply not suiting the purpose. There was also a main indication showing that auditory displays would be capable of increasing a sense of trust towards the self-driving car and this capability seemed to be evaluable.

## Main evaluation 1

*Aim and hypotheses*

The main aim of the study was to investigate whether auditory displays can enhance users' trust in self-driving cars. The main hypotheses were:

**H1.** An AD Intention Auditory Display will increase passengers' trust in the automation as compared to when no auditory display is used.

**H2.** An AD Perception Auditory Display will increase passengers' trust in the automation as compared to when no auditory display is used.

*Methodology*

The experiment was performed in two different locations at RISE Research Institutes of Sweden, but using similar experimental setups. Twenty-eight subjects (10 females and 18 males) participated in the study. Sixteen subjects participated in Gothenburg and 12 in Piteå. Figure 5 shows the experimental setup in Piteå.

*Figure 5: Experimental setup in Piteå.*

In the experiment, subjects experienced traffic situations and audio signals in a virtual reality setup (HTC Vive Pro) and headphones (Sennheiser HD 600). A within-subjects design with a counterbalanced order of conditions was used. The study included two main conditions: “auditory display” and “baseline.” In the “auditory display” condition, the AD Auditory Display (containing intention sounds and perception sounds) was switched on, while in the “baseline” condition the AD Auditory Display was switched off.

The study consisted of two approximately five-minute user journeys, one for each condition of the test. In each journey, participants experienced three intention use cases (e.g. the car slowed down when approaching an intersection) and three perception use cases (e.g. the car saw a pedestrian at the side of the road).

During each driving session, after every use case, participants were asked if they trusted that car either saw something (perception use cases) or would do something (intention use cases). After the sessions the subjects answered questions/statements related to trust, acceptance, emotional response, audio signal interpretation, and overall experience with the autonomous car in VR. Trust was assessed by responses on a Likert scale to such statements as “I trusted that the car could drive safely.” Acceptance of the auditory display was assessed using both Likert scales and the acceptance scale proposed by Van der Laan et al. [26] (without the “sleep inducing” item).

*Results*
In general, it seemed as if the vast majority of the participants found the auditory display pleasant, useful and that it increased trust. Some specific results are presented below.

*Trust*

- Both intention sounds and perception sounds resulted in higher mean scores of trust (assessed during the rides) compared to baseline. Analysis of the effects on trust in individual use cases revealed that the differences between the conditions were statistically significant (paired t-tests, alpha=0.05) for all intention use cases, as well as one of the perception use cases.
- The statement “The sounds contributed to a feeling that I could trust the car to behave safely in traffic” (1=“not at all” to 7=“completely”), rated after each ride, received a high mean score of 6.0 (SD=1.1), and 25 of the 28 participants (89%) gave a score of 5 or higher to this statement. Similar results were found for the statements related to each type of sound (intention sounds and perception sounds).
- The rating for the statement “I experienced the car as intelligent” resulted in a mean score of 5.3 (SD=1.4) in the auditory display condition as compared to the baseline (M=4.6; SD=1.6). Analysis showed that the difference was significant (paired t-test, alpha=0.05).

*Acceptance*

- After riding in VR both with and without the auditory display, 27 of 28 subjects (96%) stated that they preferred riding in the vehicle with the auditory display..
- In accordance with the method of Van der Laan et al. [26], subjective ratings (assessed after auditory display condition) were summarized into the “usefulness” and “satisfaction” factors. Both scales ranged from -2 to +2. The auditory display received a high score in terms of both “usefulness” (M=1.0; SD=1.0) and “satisfaction” (M=0.7; SD=1.2), indicating a high acceptance of the auditory display.
- The statement “I can see myself doing daily rides in a self-driving car that communicates with sounds in this way” resulted in a relatively high score (M=5.4; SD=1.5). For this statement, 20 of 28 participants (71%) gave a score of 5 or higher.

## Main evaluation 2

*Aim and hypotheses*
The aim of the study was to investigate motion sickness mitigation by the use of subtle anticipatory auditory cues which are naturally associated with the car’s intended maneuvers (intention sounds). The main hypotheses were:

**H1.** Intention sounds (that show the car’s intended, upcoming maneuvers) can reduce motion sickness in AD.

**H2.** It is possible to design an effective auditory display (in terms of reducing motion sickness), that also has a high level of user acceptance.

*Methodology*
The experiment was performed on a surface located in Säve, Göteborg, formerly used as an airport runway. The path which the car driver was following was designed to contain different types of accelerations, decelerations, and turns (see Figure 6). One lap around the track was approximately 1,3 km long.

Twenty subjects (employees at Volvo Cars), 10 males and 10 females, participated in the study. Each participant took part in two sessions at the test track with an average of one week break between the two sessions. The study included two main conditions: “auditory display” and “baseline.” In the “auditory display” condition, the AD Auditory Display (containing intention sounds) was switched on, while in the “baseline” condition the AD Auditory Display was switched off.

The test was performed in a manually driven Volvo XC90 T8 plug-in hybrid car running in pure electric drive mode. The subjects sat in the front passenger seat. In the auditory display condition, intention sounds were played through a set of stereo loudspeakers mounted on the dashboard in front of the driver directly facing the participant, and through two loudspeakers in the headrest. Each session (auditory display or baseline) consisted of three laps around the track. During the test, the participant was supposed to focus on a reading task on a tablet. The task consisted of reading a number of short texts and answering questions.

The main test was followed by a discussion. The goal of the discussion was to encourage the participants to talk freely about their impressions and to better understand the subjective and qualitative effects of the intention sounds.

Motion sickness was assessed four times (denoted as Point 1-4 in the Results section below) during the rides using the Misery Scale (MISC; [27]), as well as before and after each ride using the Motion Sickness Assessment Questionnaire (MSAQ; [28]). Acceptance of the auditory display was primarily assessed after the ride using the acceptance scale proposed by Van der Laan et al. [26] (without the “sleep inducing” item). Reading task performance was logged during the rides.

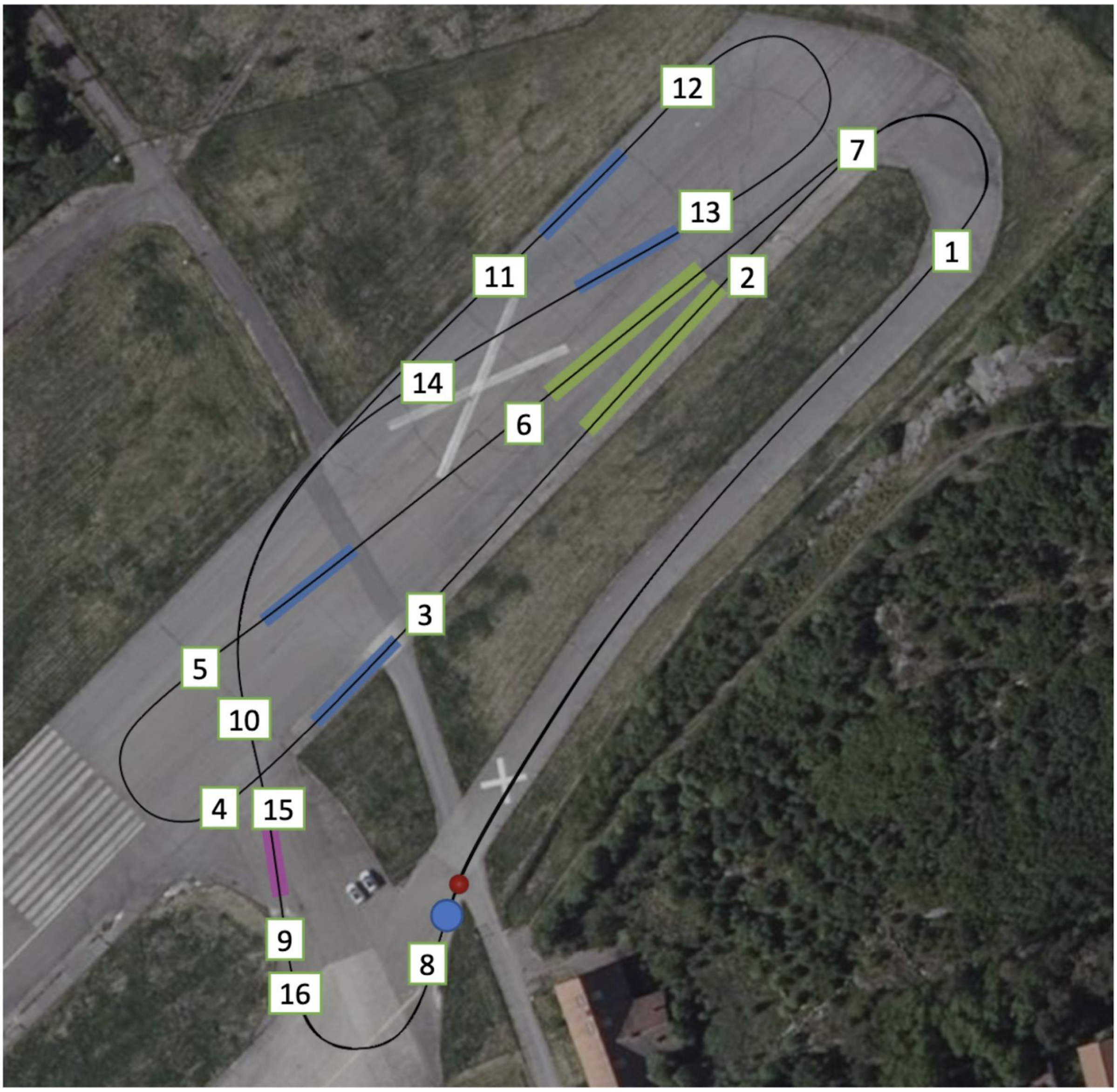


*Figure 6: Test track used in main evaluation 2. The red dot marks the starting position.*

*Results*
Overall, the results showed that the auditory cues had a reducing effect on motion sickness for a majority of the participants. Furthermore, the acceptance of the auditory display was high.

*Motion sickness*

- Analysis of the Misery Scale (MISC) assessments performed during the ride showed that the difference in perceived illness between conditions was significant (paired t-test, alpha=0.05) after riding two and three laps (measure points 3 and 4) around the track (see Figure 7).
- Analysis of the Motion Sickness Assessment Questionnaire (MSAQ), performed after the sessions, showed that 75% of the participants reported lower levels of overall motion sickness after the ride with auditory cues compared to the baseline.
- Statements about the sounds used 7-point rating scales ranging from 1 (completely disagree) to 7 (completely agree). The statement “The sounds made me feel less motion sick” resulted in a quite high mean score (M = 5.4; SD = 0.8).
- In the discussion part of the study, the majority of the participants reported in the auditory display helped them to feel less motion sick.

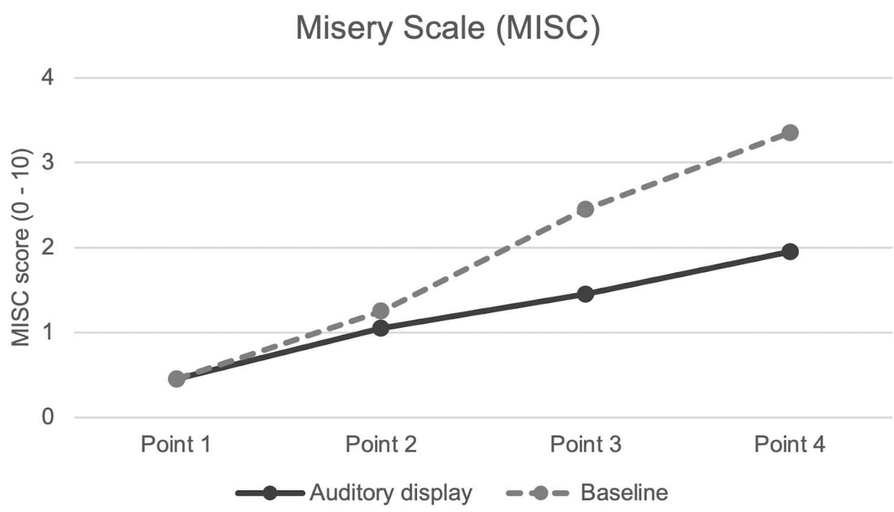


*Figure 7: Mean misery scale scores comparing the no sound (Baseline) condition to the sound condition (Auditory display).*

*Acceptance*

- Seventeen out of 20 subjects (85%) answered that they preferred riding in the vehicle with the auditory display on.
- During the discussion, 17 out of 20 participants answered that they would use this type of auditory display in autonomous vehicles.
- In the method by Van der Laan et al. [26], acceptance is described in terms of two factors: “usefulness” and “satisfaction.” Both scales range from -2 to +2. The auditory display resulted in a mean score of “usefulness” (M = 1.1; SD = 0.5). The mean “satisfaction” score was somewhat lower, but still on the positive side of the scale (M = 0.3; SD = 0.6).

## Main evaluation 3

*Aim and hypotheses*

The main aim of the study was to evaluate how aesthetic properties of sounds can influence emotional impact, and in turn trust and acceptance in AD. The focus was not understanding how specific sound characteristics affect emotional response or trust, but rather to understand if aesthetic expressions can be important to consider when intention sounds and perception sounds are implemented in an AD context. The main hypothesis was:

Perception/intention sound design that has characteristics that evokes positive, calming emotional responses is more trust-inducing than a sound design that evokes neutral or negative and arousing responses.

A set of specific hypotheses were formulated, including:

RQ1.1E Can aesthetic expressions, in addition to function, in a continuous sound design (using intention and perception layers) have an effect on emotional response?

RQ1.2E Will a continuous sound design (using intention and perception layers) that evokes more positive and calming emotional responses also have a more positive effect on trust?

RQ1.3E Will a continuous sound design (using intention and perception layers) that evokes more positive and calming emotional responses also have a more positive effect on acceptance?

RQ1.4E Will a continuous sound design (using intention and perception layers) that evokes more positive and calming emotional responses also have a more positive effect on (i.e. reduce) annoyance?

*Methodology*
The study was conducted at RISE in Piteå. Twenty subjects (9 females and 11 males) participated.

In the experiment, subjects experienced traffic situations and audio signals in a virtual reality setup. Due to COVID-19, the subjects experienced traffic scenes on a screen and all sounds were presented using two speakers. A within-subjects design with a counterbalanced order of conditions was used. The study included two main conditions: "positive concept" and "neutral concept." In the "positive concept" condition, the users experienced audio signals designed to express a calming and positive feeling, while in the "neutral concept" the audio signals were designed to express a neutral (neither positive or negative) feeling.

In order to create the negative and positive concepts, an iterative design process was conducted with sound designers and project members. The design was based on a set of design drivers believed (by project members) to have an impact on emotional reaction and trust. The design drivers included various aspects of the sounds related to spectral and temporal characteristics, as well as associations, including build quality, annoyance, age (e.g. whether the design feels old or modern), attack (e.g. sudden or slow) and timbre. A final online study with 30 subjects was conducted to examine the emotional reactions to the sounds. In the study, subjects rated sounds using the Self assessment Manikin (SAM) method [29] assessing perceived arousal and valence. The study showed that for all signals, the positive concept resulted in a more positive (higher mean score) emotional response compared to the neutral concept.

The study consisted of two approximately eight-minute long user journeys, one for each condition of the test. In each journey, participants experienced three intention use cases (e.g. the car slowed down when approaching an intersection) and three perception use cases (e.g. the car saw a pedestrian at the side of the road). In addition, the users experienced a hand-over situation (manual to autonomous driving).

After every use case, participants were asked if they trusted that car would do something (intention use cases), if the car saw something (perception use cases), or if the car would take over the driving. After the sessions the subjects asked a set of questions/statements related to trust, acceptance, emotional response, audio signal interpretation, and overall experience with the autonomous car in VR. Trust was assessed by responses on a Likert scale to such statements as "I trusted that the car could drive safely." Acceptance of the auditory display was assessed using both Likert scales and the acceptance scale proposed by Van der Laan et al. [26] (without the "sleep inducing" item).

*Results*
The results showed no clear effect on trust between the conditions. However, the discussions with subjects revealed that sound properties, in addition to the function of the sound (e.g. indicate an upcoming deceleration), can be important for trust. There was some difference in acceptance and emotional response between conditions, and the design concepts resulted in different associations among the participants. Overall, the results suggest that future research should be conducted to investigate the potential and importance of aesthetic properties of sound to affect UX in self-driving cars.

*Trust*

- Both conditions resulted in high mean scores of trust (performed during the ride). The scores differed somewhat between use cases, but there were minor differences between conditions.
- Ratings performed after the rides revealed no considerable differences between conditions in terms of perceived trust.
- Statements such as e.g. “The sounds that gave me information about surrounding road users helped me to trust the car more” resulted in high mean scores for intention sounds and perception sounds in both design concepts. These findings support previous findings (Main Evaluation 1-2) that the sounds can have a positive effect on trust in self-driving cars.
- Results from the discussions with subjects revealed that various aesthetic properties of sound can potentially be important for trust.

*Emotional response and acceptance*

- Ratings of calmness, performed during the ride, resulted in high mean scores for both design concepts. However, no considerable difference between conditions were found.
- The SAM scale revealed no big differences in terms of arousal or valence between conditions. The positive concept resulted in somewhat higher scores valence and lower score of arousal, but the differences were not statistically significant (paired t-test, alpha=0.05).
- The intention sounds in the neutral concept resulted in a higher mean score of annoyance. The difference between conditions was statistically significant (paired t-test, alpha=0.05).
- Thirteen out of 20 subjects (65%) preferred the positive concept over the neutral concept indicating higher acceptance for the positive concept.
- Only three subjects (15%) stated that they would not have preferred to have an auditory display (neutral or positive concept) when riding a self-driving car while performing a work-related task.

# 7 Dissemination and publications

## Dissemination of knowledge and results

| How will the project results be disseminated? | | Comment |
|---|---|---|
| Increase knowledge within the area | X | Publications have been produced which both summarize the general idea behind the project as well as give detailed results on the studies and findings. In addition to the publications produced by the project, a website has been published which gives easy access to the project results and ideas, and may guide designers in their development of sonic interaction for intelligent cars. Thus we have both targeted the scientific community and the product developer side of the sound design community. |
| Transfer to other advanced engineering projects | X | Collaborations have been ongoing with the Echo 2 project regarding modelling of users' motion sickness. The results and methodology of the SIIC project has been used in this project. The collaboration with Echo 2 will continue after the SIIC project ends with the aim of providing a motion sickness model as input to the sound generation engine. This will allow for adapting the sound depending on harshness of upcoming maneuvers and hence give an even better user experience. |
| Transfer to product development projects | (X) | A Volvo-internal demo event will be held after the project with relevant stakeholders. It is too early to say whether or not the project results will be utilized in product development projects. The project results however offer a solid foundation for taking future decisions regarding possible productification of the project ideas. |
| Introduce in market | | To be decided, but high potential |
| Used in investigations/regulations/ political decisions | | The project has demonstrated the feasibility of using continuous sonification for presenting in car information and presented a framework for the design of such. This could be an input to regulatory discussions, although there is no concrete planned work at the moment. |

## Publications

Mattias Hedman: A practically developed approach to evaluate sonic interfaces of autonomous cars (M Sc Thesis, Luleå University, 2019)

Pontus Larsson, Johan Fagerlönn, Justyna Maculewicz, Max Lachmann: Auditory Displays for Automated Driving – Challenges and Opportunities (Proceedings of the The 25th International Conference on Auditory Display (ICAD 2019), 23–27 June 2019, Northumbria University)

Justyna Maculewicz and Katalin Osz: UX research and sonic interaction: Towards human-centric and intuitive sound interaction design in the context of Autonomous Driving in User Experience Design in the Era of Automated Driving, Springer (to be published)

Johan Fagerlönn, Pontus Larsson, Justyna Maculewicz: The sound of trust: sonification of car intentions and perception in a context of autonomous drive (Int. J. Human Factors and Ergonomics, Vol. 7, No. 4, 2020)

Justyna Maculewicz, Pontus Larsson, Johan Fagerlönn: Intuitive And Subtle Motion-Anticipatory Auditory Cues Reduce Motion Sickness In Self Driving Cars (submitted to Int. J. Human Factors and Ergonomics, 2021)

Pontus Larsson, Johan Fagerlönn, Justyna Maculewicz: Can making sounds more positive increase trust in autonomous cars? (in preparation, 2021)

# 8 Conclusions and further research

The SIIC project has been very successful in pursuing its research agenda and has had an effective collaboration throughout the project. Ideas from the computer game industry and automotive development and research have been merged and formed principles and concepts that have the potential of solving some of the user experience challenges related to highly automated cars. In turn, this may directly facilitate large-scale acceptance and adoption of automated vehicle products and services. One of the project's most important findings is that our auditory display principles can reduce motion sickness and increase trust in AD cars. We believe this display can be developed into an actual product function that is not only effective but also is highly acceptable and desirable by users. Also, the project is to our knowledge the first one taking a complete approach to sound design for intelligent cars and has established this new field of research on an international level.

The novelty of the project however also means that there are a number of possibilities for further research. Although we have involved a fairly large number of potential users in our experiments, future studies should investigate the effectiveness of the auditory display solution in a more realistic setting (such as a field test trial using a robot taxi vehicle) and during longer exposures. Such investigations should also include evaluating the user experience and acceptance of the sound when the user is performing other types of tasks than what have been used in the project - especially such tasks that involve audio content (music, audio books, films etc.).

In a more realistic setting, involving complex traffic scenarios there may be situations where the vehicle can not provide accurate enough information to the auditory display. Regarding trust, future research could therefore investigate what degree of auditory display information consistency and reliability is necessary not to counteract the trust induced by the same display. It would also be interesting to investigate how the driving situation and behaviour should interact with auditory saliency in such a way as to reduce unnecessary information whenever possible but still give a consistent impression to the user. An example of this from the motion sickness application would be not sonifying the upcoming maneuvers that are unlikely to induce motion sickness (based on road and scenario properties, vehicle dynamics and the user's motion sickness susceptibility).

A topic which we have partly covered in the project but not evaluated with a large number of users is considering the whole automated ride journey from start to finish. It would be interesting to apply our concepts and ideas also to use cases such as ordering a robotaxi trip, locating the vehicle, providing feedback for door unlocking/welcoming etc. This type of exploration could likely benefit from taking a universal design perspective in which e.g. visually impaired users' needs could inspire designs that are accessible to all.

In sum, we see a great potential in further developing the ideas and concepts presented here as well as implementing the project results in future products. The importance of the auditory modality is often downplayed but as the project has shown, sound designed and used in the right way can both be effective and highly appreciated by users.

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