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Developing a strategic controller with haptic and audio feedback for autonomous driving

Master's thesis in Product development

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Abstract

Traffic accidents cause over 1.2 million deaths, and tens of millions of people are injured or disabled every year. Advanced driver assistant systems and other safety features have the possibility to reduce traffic accidents but do not account for human errors. Studies show that over 90% of all traffic accidents are caused by human errors. One way to reduce human errors is to introduce automation, and several major car manufacturers predict that autonomous vehicles will be available on the consumer marker as early as 2020. In theory automated cars could reduce deaths and injuries caused by traffic accidents, but there are several issues which need to be solved before it can be realized. One of these issues is how to keep the driver in the loop while the car is in autonomous mode.

A human-machine interface of a strategic controller for autonomous driving was developed. Multimodal feedback consisting of auditory and haptic signals was developed for the strategic controller using an iterative design process. A user study was carried out in order to evaluate the multimodal feedback and identify usability issues, and a simulator study was carried out in order to benchmark the concept's usability.

The strategic controller prototype developed in this thesis allows the driver to take part of the driving process and control of the car by inputting commands. The controller also provides the driver with multimodal feedback based on an analysis of mock-up sensor/image data from the vehicle. User input is either denied or accepted depending on the analysed data, and on demand feedback is also provided related to the general state of the autonomous system.

Multimodal feedback was found to be promising for communicating complex information in human-machine interactions. Although users had little to no experience of autonomous driving, they found the developed concept to be attractive and would use it for daily commuting. As it is difficult to mirror reality in simulators, test subjects may have had a more positive attitude towards the concept. However, the issue of keeping the user in the loop still persists. Feedback needs to be designed thoroughly and should not be limited to two modalities. Instead, information should be distributed through several modalities in order to reduce cognitive load and increase the user's situational awareness. The benchmark of the developed concept showed promising results, although the results may have suffered due to hardware limitations.

Keywords: Automotive, Audio feedback, Autonomous driving, C++, DirectX, Haptic feedback, Joystick, Multimodal feedback, Simulator, Wizard of Oz.

Preface

This report is the result of the master's thesis work carried out by Alexander Andjelkovic from Chalmers University of Technology, and Sonia Guijarro Carcelén from Lund University at Semcon in Gothenburg, Sweden. The work carried out by this thesis has been a part of the Automotive Integration of Multimodal Interaction Technologies (AIMMIT) project financed by VINNOVA. The goal of AIMMIT was to explore potential benefits of multimodal human-machine interfaces for current and future vehicle functionality.

Acknowledgements

First and foremost we wish to thank Peter Mohlin at Semcon, for his continuous support, technical expertise and encouragement. This thesis would not have been possible without him. We would also like to thank Jan Nilsson and all the other Semcon employees for their help and support throughout the project. Our sincere thanks also go to Azra Habibovic and Jonas Andersson from Viktoria Swedish ICT for all their support. Last but not least, we would like to thank our supervisors Associate Professor Jonas Fredriksson from Chalmers University of Technology, and Professor Anders Robertsson from Lund University for their valuable input.

Distribution of work

As the thesis has been carried out in a collaboration, we have worked side-by-side in many occasions throughout the thesis. Nevertheless, the workload was divided in order for us to focus and specialize in different areas. The literature study conducted in this thesis, and the design of the feedback signals was divided between the two of us according to Table 1.

Table 1: Distribution of work between the team members.

	Literature	**Feedback design**
Alexander	Automation and audio feedback	Audio
Sonia	Haptic and multimodal feedback	Haptics

Contents

1. Introduction

The purpose of this project has been to investigate how to keep the user in the loop during autonomous driving using multimodal feedback. This was done by developing a suggested solution proposed by AIMMIT; a joystick based strategic controller with audio and haptic feedback.

1.1 Background

The introduction of safety belts in the 1950's was a major contribution to vehicle safety, and ever since more safety features such as airbags and anti-lock braking systems have been introduced by the automotive industry. As technology develops even more advanced safety features are introduced in cars, and in the last couple of years advanced driver assistance systems (ADAS) have become available for the public. ADAS are systems meant to assist the driver during the driving process and as such increase vehicle and traffic safety. Common ADAS in the premium car segment are collision warnings, vision enhancements and lane departure warnings. ADAS are often based on but not limited to sensor technology, camera systems and vehicle connectivity.

However, traffic accidents still cause over 1.2 million deaths every year, and tens of millions of people are injured or disabled (WHO, 2015). Studies also show that over 90% of all traffic accidents can be estimated to be caused by human errors (NHTSA, 2008). ADAS and other safety features may very well contribute to a reduction in traffic accidents. However, such features requires the driver to actually make use of the system in place, and even when used one also has to account for the possibility of human errors. One way to reduce human error is to introduce automation, and several major car manufacturers predict that autonomous vehicles will be available on the consumer market as early as 2020 (AutoGuide, 2013; TechnoBuffalo, 2014; CNET, 2014). In theory automated cars could reduce deaths and injuries caused in traffic accidents (Lenior et al., 2006), but there are several issues which need to be solved before it can be realized.

One of these issues is how to keep the driver in the loop while the car is in autonomous mode. Even though an autonomous vehicle could have better driving skills than a normal driver, uncertainties exist, technology can fail requiring the driver to take over or there may also be a need for the driver to do complex multiple choice decisions. Commercial airlines have utilized automation called autopilots for decades, but several examples can be found where autopilot systems have failed and caused horrible accidents. One such example is Eastern Air Lines flight 401 which crashed close to Miami International Airport in 1972 causing 101 deaths. Investigators concluded that the crash was caused by the pilots having too much trust in the autopilot and not knowing how it actually works (NTSB, 1973). Another more recent example is the Air France flight 447 accident in 2010 which crashed in the Atlantic Ocean. The incident was said to be caused by the pilots having too much trust in the autopilot causing a decay of their piloting skills over time. Once the autopilot failed the pilots did not know how to handle the situation which in turn caused 228 fatalities (BEA, 2012). Even though an aircraft's complexity might be greater than the complexity of a car, the issue of keeping the user in the loop while in autonomous mode remains the same.

1.2 Purpose

In order to fulfil the desire to offer autonomous cars for the consumer market by 2020, research must be conducted prior to finalizing the first prototype cars. The purpose of this thesis was to investigate how the problem of keeping the driver in the loop when the car is in autonomous mode can be solved. One suggestion was to implement a joystick which acts as a strategic controller, which would allow the user to take part of the driving process and control of the car by inputting commands.

1.3 Goals

The goal of the thesis was to develop prototype hardware and software for the strategic controller. The controller was to provide multimodal feedback to the driver consisting of haptic and auditory feedback signals. The feedback was to be based on ”the car has analysed sensor data and has accepted your command” and ”the car has analysed sensor data and does not accept your command”. On demand feedback was also to be provided related to the general state of the autonomous system. The strategic controller prototype was used to evaluate the usability of having a joystick with multimodal feedback in an autonomous car. The results of this thesis project will serve as a benchmark for the concept developed in this thesis, and aims to create objective parameters which other concepts can be compared against.

1.4 Delimitations

As the focus of the thesis was to investigate how to keep the driver in the loop during autonomous driving, it did not look into how to solve the technological issues involved with autonomous driving. The thesis neither focused on political or societal issues associated with autonomous vehicles. In addition, this thesis has not investigated the handover between the autonomous system and the user for neither activation nor deactivation of the system.

2. Theory

Prior to development, a literature study was carried out. This chapter will present the theory which was gathered during the study and which was used as a starting point for development. The chapter starts with an introduction to automation and the human-machine relationship, and continues with theory regarding the design of auditory and haptic feedback. The chapter is finalized with a section regarding how effective multimodal feedback can be achieved.

2.1 Automation and the human-machine relationship

Automation has the ability to solve complex technical problems, but also introduces four new problems (Hoc, 2001):

1. **Loss of expertise.** When a certain task is allocated to the machine, humans do not maintain their skill, causing a gradual loss of expertise over time.

2. **Complacency.** Studies have shown that even experts which are aware of the limits of a machine can adopt to the machines' proposals even though they know that the solution is not optimal.

3. **Trust issues.** If the user does not feel comfortable with the machine performing the task, they may override the machine and take over control, making the automation redundant.

4. **Loss of adaptivity.** Humans have poor situational awareness and we tend to get "out of the loop" when we do not actively participate in a process. As such, this human flaw often makes manual take over difficult.

By designing a system with these four problems in mind, or more importantly by having the user in mind throughout the design process, the severity of the problems may be reduced. However, trust is something that builds up over time, and can only be achieved if the system is experienced as competent and usable (Hoffman et al., 2013). Therefore it is also necessary to consider the user's role in the system, as it will vary depending on the degree of automation used by the system. The degree of automation refers to how much responsibility has been transferred from the user to the machine. A low degree of automation will require the user to actively participate in the process, and a high degree of automation will reduce the user participation and make the user take the role of a supervisor. Consider an operator in a fully automated industrial production. The operator's main task is to make sure the robots are running and possibly supply materials for the robots. There is a high degree of automation and when compared against manual production, the user's role has shifted from being a craftsman to becoming a supervisor.

As such, automation should not disregard the user by any means. Applying a user-focused design process may also increase the usability of the system and provide other benefits such as (Maguire, 2001):Create a prototype for a joystick based strategic controller with audio and haptic feedback.

- **Increased productivity.** A usable system will allow the user to concentrate on the task rather than the tool.
- **Reduced errors.** By avoiding inconsistencies, ambiguities or other interface design faults user errors will be reduced.
- **Reduced training and support.** A well-designed and usable system is intuitive and requires less training and support.
- **Improved acceptance.** Most users would be more likely to trust a well-designed system.

Truly incorporating the user throughout development is not an easy task. The complexity of modern products also make product development difficult, as software and hardware development need to be synchronized. The standard of human-centred design for interactive systems (ISO 13407) presents a framework which can be utilized by both hardware and software components of interactive systems in order to enhance human-system interaction. The framework consists of recommended design principles and activities throughout the development process (as shown in Figure 2.1).

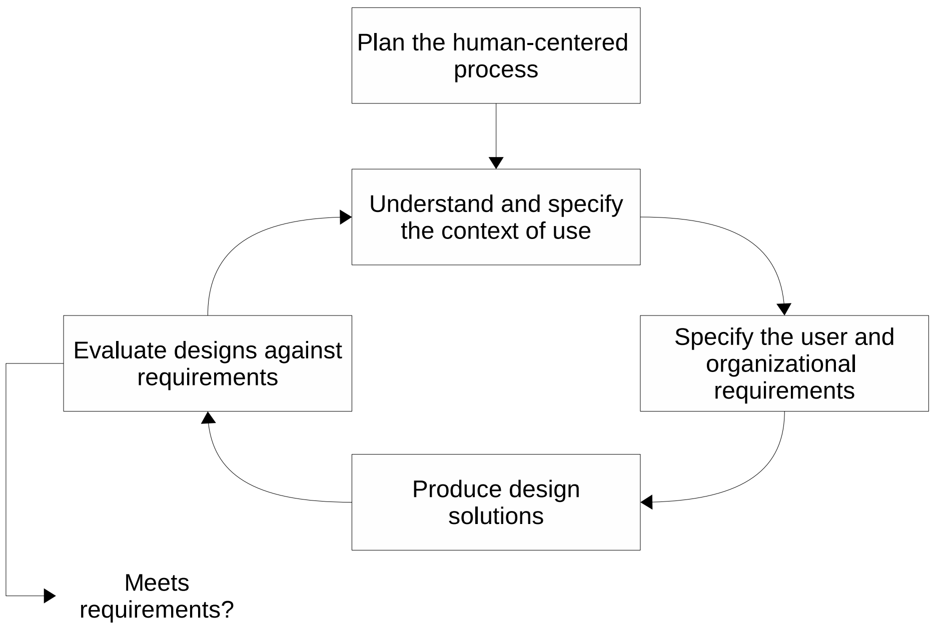


Figure 2.1: Human-centred design activities from ISO 13407 (Maguire, 2001).

2.2 Auditory interfaces

An auditory interface is a communicative connection between a technical product, which presents information, and a user. In order to present detectable and relevant information to the user the auditory interface needs to be accompanied with well-designed auditory feedback signals.

Sound is commonly used in human-machine interfaces in order to reinforce a message from another type of stimuli, such as a visual alert on a screen (Kortum, 2008). As such sound can be used to reduce the visual overload of the user, or be used to provide an additional source of information through the ears of the user.

This section will present the theoretical framework used during development of auditory feedback in this thesis project. First an overview of basic human anatomy will be presented which will create a natural bridge to psychoacoustics, the study of the perception of sound. The later parts of this section will present theory regarding how auditory feedback should be designed in order to communicate the desired information to the user.

2.2.1 The human auditory system

In order to create auditory feedback which the listener can understand, we need to understand how hearing works and what sound really is. Sounds can simply be described as vibrations of air; the propagation velocity of this vibration is the product of its frequency (Hz) and its wave length. The intensity of the vibration is given by the logarithmic notation decibel (dB). An illustrated description of how the human auditory system works is shown in Figure 2.2.

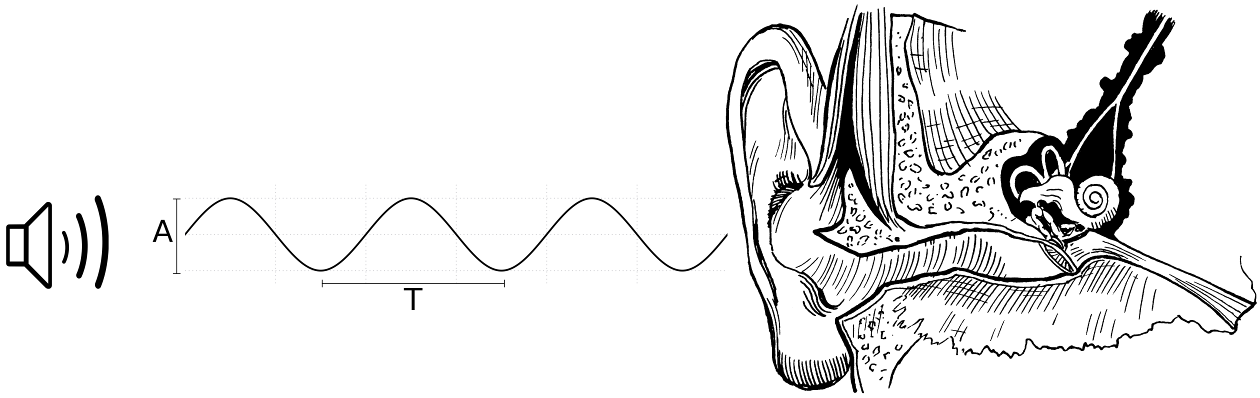


Figure 2.2: Sound waves with a certain amplitude (A) and period (T) enters the outer ear (pinna) which acts as a funnel, and redirects the sound waves through the auditory canal. The sound waves reach the middle ear where it causes the eardrum to vibrate. The vibrations of the eardrum trigger a mechanism consisting of three tiny bones (the hammer, the anvil, and the stirrup) which transfer the vibrations to the inner ear. A cavity in the inner ear called the cochlea which has the shape of a snail shell, converts the vibrations into nerve signals which the brain will interpret as sound.

The most intense sound a human can hear without damaging the ears is 120 dB (Brewster, 1994). In order to get a better understanding of this intensity it could be compared against a whisper which is around 30 dB, or noisy traffic which can be in the ranges of 100 dB (Theis, 1995). Sounds close or above 100 dB can be experienced as painful and long term exposure of sounds at or above 85 dB may cause hearing loss (NIDCD, 2015b). As such people can have accumulated hearing impairments from musical concerts or other high intensity listening. However, hearing sensitivity also varies according to the frequency of the sound. Children can perceive sound within a frequency range between approximately 20 Hz and 20000 Hz (Friauf, 2014). As we grow older most of us experience a gradual hearing loss, generally at the extremes and especially at the high frequencies (NIDCD, 2015a). Reports have shown that at the age of 30 an average person can hear frequencies no higher than 18 kHz. This upper limit gradually declines with age and at 50 years old the limit is 14 kHz, and by the age of 70 it is 10 kHz (Brewster, 1994). The ear is also more sensitive to some frequencies than others and takes an inverted U-shaped form, making most people sensitive to sounds in the 1000-4000 Hz range (Wilcox, 2011). The absolute threshold for a detectable sound for a person with normal hearing is 6.5 dB at 1000 Hz (Brewster, 1994).

2.2.2 Psychoacoustics

Psychoacoustics is the study of the perception of sound, and is vital when designing sounds for human-machine interfaces. Designing sounds without regard to psychoacoustics may lead to difficulties in being able to differentiate, hear and remember the sounds. The basic properties of sound are made up from three components (Brewster, 1994):

1. **Timbre**, which is the perceived ”quality” or ”color” of the sound. This attribute is what allows people to differentiate between different instruments even though they are played at the same note or chord.

2. **Loudness**, the volume of the sound which has a strong correlation with the amplitude of the sound waves,assuming steady spectral contents.

3. **Pitch**, which is the subjective attribute that allows the sound to be ordered on a frequency related scale such as musical scales.

Although these three properties are subjective, some objective properties can be identified due to their strong connection with the sound waves. One such example is the mel scale. By defining a tone of 1000 Hz at 40 dB with a perceived pitch of 1000 mels (Stevens et al., 1937) the authors were able to identify how the perceived pitch changes at different frequencies, as illustrated in Figure 2.3.

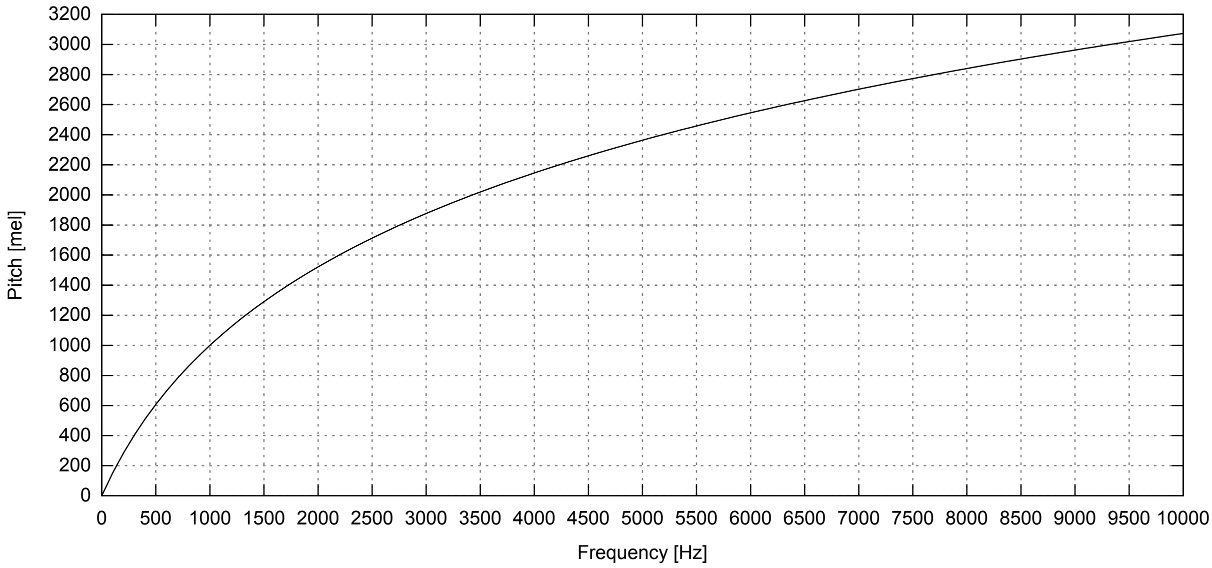


Figure 2.3: A mel scale plot, showing the relationship between frequency and pitch as defined by (Stevens et al., 1937).

As the relationship between frequency and pitch is logarithmic, it is not sufficient for a set of tones to have multiples of the same frequency apart if they are to be equally spaced in pitch. However, frequency is not the only factor that affects the perceived pitch of a tone; the sound's intensity and timbre are also major factors affecting pitch perception. Increasing the intensity of a tone at 2000 Hz or less will increase the perceived pitch, but if the frequency is 3000 Hz or above the perceived pitch will decrease. Sounds with a bright timbre also have a higher perceived pitch compared to a dark timbre (Brewster, 1994). As such we cannot expect sounds of different timbers at the same frequency to sound alike.

The perceived loudness of a sound is mainly related to the sound waves' amplitude, the intensity of the sound, but is also affected by its frequency. This can be an issue when designing auditory feedback, as the sounds used may vary in intensity and frequency. However, by conducting comparison studies where test subjects listened to pure tones at various frequencies, researchers have been able to develop ISO standardized equal-loudness contours, as shown in Figure 2.4. The contours are based on the loudness of a 1000 Hz tone at a given intensity and are measured in phons; 0 phon being the absolute hearing threshold and inaudible sound having negative phon levels. Using the equal-loudness contours one can see that in order for a 100 Hz tone to sound equally as loud as a 1000 Hz tone at 40 dB, it needs to have an intensity of 60 dB.

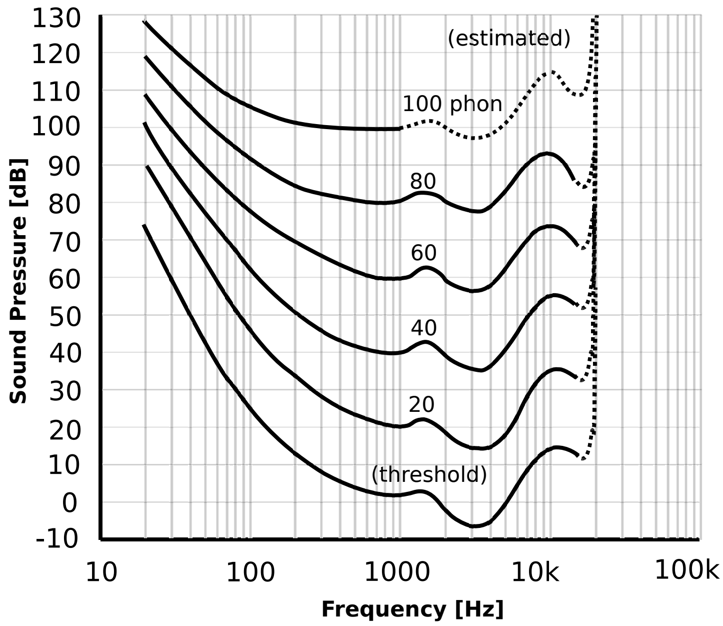


Figure 2.4: Equal-loudness contours from ISO 226:2003.

How a sound is heard is heavily affected by the presence of other sounds. This effect is referred to as *masking* and occurs when the masked sound and the masker have similar frequencies (Brewster, 1994). One example of masking is when two people try to have a conversation in a noisy environment; this often forces them to talk louder in order to hear each other. To avoid masking of auditory feedback one can either increase the auditory signal's intensity, or use frequencies which are different from the masker's. Patterson suggests that a sound must be 15 dB above the intensity of the masker in order to avoid loss of information (Patterson, 1990).

2.2.3 Auditory feedback

Auditory feedback is any sound that a system provides after a certain event has occurred. This sound can be considered to be a warning, an alarm, or any other type of sound such as a melody or a single tone. Warnings could be considered as a generic term for all sounds that attract attention, and as such auditory feedback will henceforth often referred to as auditory warnings or simply warnings. A person screaming in the city center will surely attract attention as we find the sound alarming, but the reason for the scream is perhaps unknown until we actually focus our attention on the screaming person and analyse the situation visually. This example might be considered extreme, but if we compare it to a generic fire or burglar alarm we have a similar situation; the situation needs to be analysed before we can make sense of the sound coming from the alarm. We have a common problem in these two examples; we need to learn the meaning of a specific sound in order to understand the warning. Over the last decade new warning systems have been designed to alert rather than alarm the listener (Edworthy, 1994). As such auditory warnings are being designed not only to attract attention, but also to inform the listener of the situation.

Designing auditory warnings in such a way can help the listener understand how urgent a warning is, or what type of hazard the warning indicates. Auditory warnings can be classified into verbal warnings; such as recorded voices or synthesized speech, and non-verbal warnings; such as abstract sounds (sirens, horns, buzzers, etc.), auditory icons or earcons (Edworthy, 2011). Abstract sounds include all type of mechanically made sounds, such as civil defense sirens and old doorbell buzzers. Both auditory icons and earcons need a more thorough explanation and will be presented in Section 2.2.3. For now let us define earcons as simple tones which utilize specific relationships to one another, and auditory icons as warnings which utilize environmental sounds in order to create intuitive feedback.

Differences between auditory feedback classes

There are pros and cons with each class of auditory warning, and choosing which type of class to use in a specific application needs careful consideration. However, it is also necessary to consider the product's brand identity which makes it unique to other brands. The chosen auditory warnings need to communicate the brand's core values and personality to the listener, and certain classes of auditory warnings may not be appropriate for this purpose. According to Edworthy, acceptability and feasibility are the most important criteria for auditory stimuli (Edworthy, 1994).

One of the major differences between different classes of auditory stimuli is the learnability of the sound itself. Studies have shown that abstract and tonal alarms such as earcons are difficult to learn, while auditory icons are easier (Leung et al., 1997). However, an auditory icon requires that there is some kind of link between the sound and situation. This link is often metaphorical, meaning that the auditory warning is mapped to represent the action or situation which is occurring (Edworthy, 2011). For example, emptying the recycle bin on a computer could use an auditory icon which sounds as if paper is being crumpled. If this type of mapping relationship is non-existent the auditory icon becomes just as difficult to learn as an abstract warning. Verbal warnings do not require any learning at all, provided that the listener understands the language used in the warning. However, a verbal warning requires the listener to hear the whole word or sentence communicated in the warning, and can therefore be difficult to understand if the listener does not hear the complete warning.

The effectiveness of different auditory warnings is also a factor which needs to be considered. The warning is meant to inform the listener of some particular event, but may certainly be ignored if the listener chooses to do so. If verbal warnings are used in environments where other voices are present, the effectiveness of such a warning would decrease dramatically (Edworthy, 1994). Presenting information in speech can also be slow, as the user needs to hear the whole message and process the information in order to understand it. Due to these reasons it may be more convenient to use abstract or tonal alarms as they could be more effective (Brewster, 1994). However, using abstract or tonal sounds can quickly become annoying for the listener, especially if the sounds do not represent something of high importance (Kortum, 2008). We also need to consider the human characteristic of habituation, which makes us filter out stimuli which we do not care about (Wilcox, 2011). Effective auditory warnings must therefore not only be detectable and easy to understand, but also informative so that we care about what they are trying to tell us.

Designing auditory feedback

Previous sections introduced and discussed four classes of auditory feedback: verbal (speech or synthesized voice), abstract sounds (sirens, horns, buzzers, etc.), auditory icons and earcons. Some pros and cons were briefly discussed but no best-use practice has been presented in literature. Instead auditory warnings need careful consideration and the chosen class or classes vary depending on the users of the system, the application and the context. This section will present the theory of how to design functional auditory feedback. Literature suggests that auditory feedback needs to be easily identified or have a short learning curve (Garzonis et al., 2009). The users should also be involved in the design process not only due to the users' aesthetic preferences, but also because the most functional sounds are not always the most preferable sound (Sikora et al., 1995) (Garzonis et al., 2009).

Auditory icons

In previous sections auditory icons were defined as intuitive warnings which utilize environmental sounds. The sounds are explicitly mapped with a specific situation so that they have a clear and distinct relationship. Auditory icons offer a way to naturally categorize information by taking advantage of the way people listen to the world in their everyday lives (Gaver, 1986). The idea is that the listener does not need to rely on how the sound is perceived and remember a mapping, but rather focus on the source of audio used in the warning. In order for auditory icons to be effective they need a clear and distinct mapping with the data they represent. This can be achieved by utilizing symbolic, nomic or metaphorical mappings, as shown in Table 2.1 (Gaver, 1986).

Table 2.1: Symbolic mappings tend to rely on social convention for their meaning. Metaphorical mappings use similarities between the data they represent and the representing system. Nomic mappings depend on the physics of the situation.

Mapping	**Representation**	**Auditory icon**
Symbolic	Computer anti-virus software detects a threat	Sirens
Metaphorical	Falling down in a video game	Pitch
Nomic	A cut operation in an operating system	Scissors cutting

Stronger mapping relationships will make it easier for the user to understand what the sound represents, but also requires the user to recognize the sound itself (Mynatt and Edwards, 1992). In order to achieve effective auditory icons Mynatt purposes the following design methodology (Mynatt, 1994):

1. Choose short sounds which have a wide bandwidth, and where length, intensity, and sound quality are roughly equal.

2. Evaluate the identifiability of the auditory cues using free-form answers.

3. Evaluate the learnability of the auditory cues which are not readily identified.

4. Test possible conceptual mappings for the auditory cues using a repeated measures design where the independent variable is the concept which the cue will represent.

5. Evaluate possible sets of auditory icons for potential problems with masking, discriminability and conflicting mappings.

6. Conduct usability experiments with interfaces using the derived auditory icons.

Earcons

In previous sections we defined earcons as simple tones which utilize a specific relationship to one another. Unlike auditory icons, earcons are abstract and need to be learned. Due to their tonal characteristic designing earcons also utilize a more musical approach compared to auditory icons. Earcons are constructed using *motives* which are rhythmic sequences of pitches (Blattner et al., 1989). As motives are defined by rhythm and pitch these features are fixed parameters of motives. Timbre, register (the position of the motive in the musical scale) and dynamics (volume) are considered variable parameters of motives. Studies have concluded guidelines on how these parameters should be used in order to achieve useful earcons, as shown in Table 2.2.

Table 2.2: Brewster's guidelines for earcon design (McGookin and Brewster, 2003).

Attribute	**Guideline**
Timbre	Musical timbres that are subjectively easy to tell apart should be used for earcons.
Register	If absolute judgements are required then register should not be used. If relative judgements of register are to be made then there should be gross differences between the registers used.
Pitch	Introducing complex intra-earcon pitch structures can be effective when used with another attribute such as rhythm.
Rhythm	Putting different numbers of notes in each rhythm is an effective way of differentiating them. Changes to tempo are also useful in differencing earcons.

Due to their musical foundation, designing earcons may be difficult without previous musical experience. (Blattner et al., 1989) suggest involving an expert in sound relationships in the design team, and also present an in-depth methodology for earcon design written with novice users in mind. The structure of an earcon will consist of one or several motives. Earcons consisting of one motive are called *one-element earcons* and earcons consisting of several motives are called *compound earcons* (Blattner et al., 1989). Compound earcons can be achieved using different construction principles such as combining or transforming audio elements, but also through creation of *hierarchical earcons* also known as *family earcons*. In an earcon family earcons inherit all the properties from the previous level in the hierarchy, as shown in Figure 2.5 (Brewster, 1994).

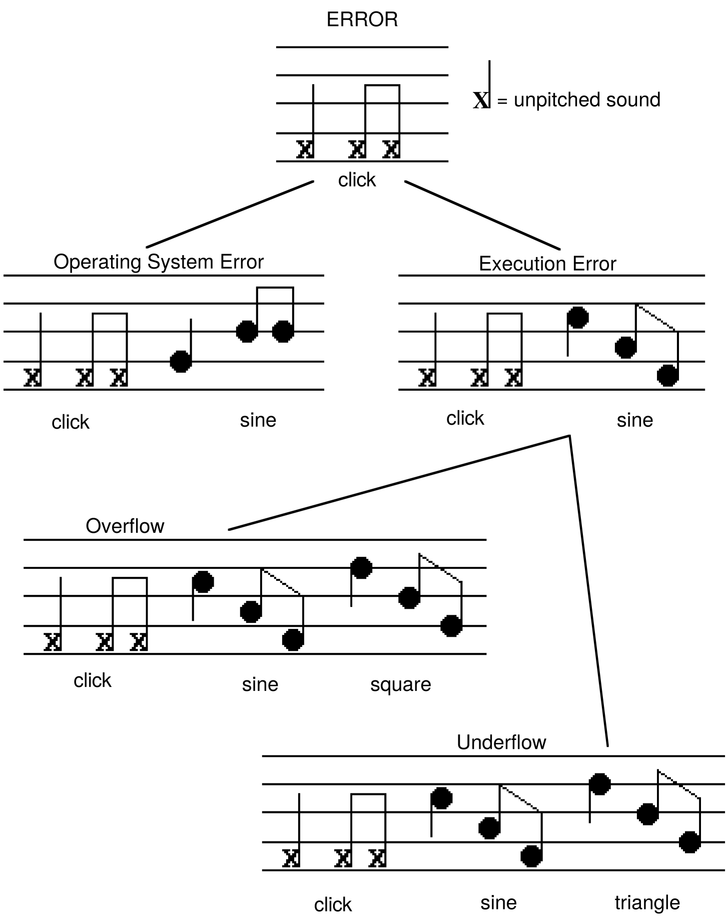


Figure 2.5: An earcon family for different errors in an operating system (Brewster, 1994).

Family earcons can be easier to learn due to their property inheritance; the listener only needs to learn one new piece of information at each level in the hierarchy (Blattner et al., 1989). They also shorten the learning period for additional warnings added in the future (Brewster, 1994).

Creating informative feedback

Taking the research made by Leung et al. into consideration, caution should be used when using abstract or tonal warnings due to their learnability issues (Leung et al., 1997). However, according to Edworthy these types of warnings can be coded into delivering clear information to the user without the need to learn what the warning means:

"... if the receiver needs to know precisely what the problem is, then a specific alarm is needed. If they simply need to know how quickly to respond, then urgency-coded alarms will suffice." (Edworthy, 2011).

Urgency coding can be advantageous when the user does not know the meaning of a specific warning. The coded urgency will allow the user to assess the seriousness of the warning and take action accordingly, as such urgency mapping increases the information contained in the warning. A technique for urgency mapping has been derived from psychophysics by applying Stevens' Power Law (Hellier and Edworthy, 1999):

$$S = kO^m \tag{2.1}$$

Stevens' Power Law describes the relationship between the magnitude of a stimulus and its perceived intensity. S is the value of the subjective parameter and O the value of the objective parameter. When S and O are plotted as xy-coordinates on a logarithmic scale, k is the value where S and O intercept, and m is slope of the straight line crossing at the interception point (Stevens, 1957). Hellier and Edworthy were able to conclude relationships between warning parameters and urgency through a series of studies, as shown in Table 2.3.

Table 2.3: Studies show that the percieved urgency can be altered by modifying warning parameters such as pitch, speed, repetition and inharmonicity. In order to double the urgency through repetition the number of repetitions would need to be multiplied by a scale of four (Hellier and Edworthy, 1999).

Parameter	**Increment to increase urgency**		
	50%	**100%**	**300%**
Pitch	x 2.8	x 6	x 17.4
Speed	x 1.3	x 1.6	x 2.2
Repetition	x 2.2	x 4	x 8.9
Inharmonicity	x 28.5	x 307	x 8773

Studies have shown that similar effects can be achieved with verbal warnings by altering the speed, pitch and loudness of a synthetic voice (Weedon et al., 2000) (Edworthy et al., 2003). However, the parameter relationships of Table 2.3 may not be valid for synthetic speech and should not be considered as general guidelines for design of verbal warnings.

Users may expect a certain level of urgency based on the function of the system. Literature suggests that failing to consider the context could diminish the effects of urgency mapping (Marshall et al., 2001). A major disadvantage of sound is annoyance (Kortum, 2008) and failing to consider the context of the warning the user might find the sound annoying and either ignore the warning or disable it completely. Studies suggest that there is a tradeoff between annoyance and urgency, and that speed may be most effective in increasing urgency while having little effect on the perceived annoyance (Marshall et al., 2001). However, as sound in general can be overheard by other users (such as passengers in a car) it may also be annoying to someone other than the main user (the driver). Urgency perception has also been investigated for other modalities such as haptics, but the results are limited and further research is needed. However, haptic signals proved to be well suited to present information with varying urgency levels (Baldwin et al., 2012).

2.3 Haptic feedback

The use of haptics is becoming important in our daily life. Haptics are utilized in different domains of communication such as medical, automotive, mobile phones, entertainment or education (Kim et al., 2013). Haptics is a way of communicating by using the sense of touch. However, haptics is not only applied for the information acquisition and object manipulation by humans, but also by machines or by a combination of both. In this way, haptics can be sub-divided in three areas (Srinivasan, 2006):

- **Human haptics**. It studies how humans sense and manipulate objects through touch. Inside this area, a deeper sub-division can be done, depending on how the interaction between the object and the human is carried out (Smith, 1997):
  - **Tactile feedback**. The interaction is carried out through the nerve endings in the skin to provide the feeling of heat, pressure and texture.
  - **Force feedback**. The interaction is carried out through the muscles and tendons so that the human get a sensation of a force being applied.
- **Machine haptics**. It is related with the design, construction and use of machines to replace or augment human touch. One of its applications is in haptic interfaces to virtual environments (VEs), i.e. computer-generated environments that interact with humans and allow them to perform some tasks, such as perceptual or motor tasks.
- **Computer haptics**. It is related with the algorithms and software used to reproduce the touch and feel of virtual objects to humans through a force reflecting device.

Haptic feedback is expected to be valuable when it is only possible to use the sense of touch or when the other senses risk being overloaded (MacLean, 2000). An example when haptic technology can be valuable is when using it as an alternative communication path for people with visual impairments (Kim et al., 2013). The increasing number of visually impaired or blind people is leading to a major concern in the use of haptic user-interfaces and how to design them in such a way that they can be used without any visual help. However, there are more applications where haptics can be useful, besides for visual impaired people. A spread application of haptic feedback is the use of force feedback to improve the steering abilities, particularly when steering wheelchairs or mobile robots (Crespo and Reinkensmeyer, 2008; Agrawal et al., 2012; Chen and Agrawal, 2013). Another spread application nowadays is in in-vehicle interfaces and it has been studied how the addition of haptics affects the driver's performance, as will be presented in Section 2.4.

2.3.1 Vibrations

Types of vibrations

When exposing the human body to vibrations, three categories can be found (Salvendy, 2012):

- **Whole-body vibrations**, when the whole body is over a vibrating surface.
- **Motion sickness**, as a cause of applying low frequencies (<1Hz), lead to interference of the movement of the person.
- **Hand-transmitted vibration**, caused when using tools that produces vibrations on the hand.

A common problem due to hand-transmitted vibrations is the Hand-Arm Vibration Syndrome (HAVS), also known as Vibration White Finger. Its name comes from the consequences it has: fingers get discoloured when the blood flow is reduced in response to some stress (vib,). This problem affects people who work with vibrating or percussive power tools or surfaces. The chances to develop HAVS depends on the intensity, frequency and duration of the vibration (vib,). To calculate if there is risk of HAVS, the weighted acceleration a_{hw} must be calculated according to:

$$a_{hw} = \sum a_i w_i \tag{2.2}$$

Where a_{i} is the the root-mean-square (r.m.s.) acceleration value of the vibration in each axe and w_{i} is the weighting factor, which is calculated according to Figure 2.6.

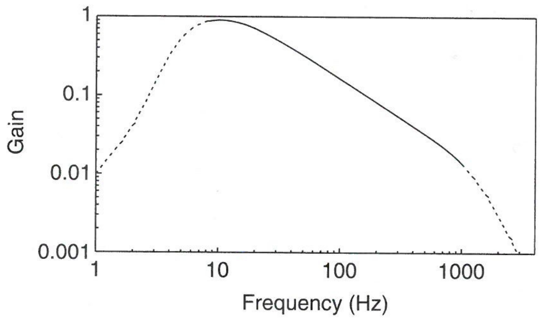


Figure 2.6: Weighting curve as defined in ISO 8041:2005. The weighting factor w_{i} depends on the frequency of the vibration. If two tools have the same acceleration and are used during the same period of time, there is more possibilities to develop HAVS if one of them vibrates at 10 Hz.

The obtained value, a_{hw}, can be used to calculate an eight hours energy equivalent, $A(8)$, which should be smaller than 2.5 m/s^2 for safe operations. From (Salvendy, 2012),

$$A(8) = a_{hw}(\frac{t}{T_{(8)}})^{\frac{1}{2}} \tag{2.3}$$

where t is the exposure duration to a weighted acceleration a_{hw} and $T(8)$ is the time period of eight hours given in seconds.

Creating haptic feedback

In Section 2.2.3 is explained how to design auditory feedback. How to create informative haptic feedback is however not a topic as well documented in the literature. A brief explanation on how to design haptic feedback is presented in this section.

Haptic feedback can be created by utilizing vibrations. Different signals are generated by modifying the magnitude, frequency and duration of them.

- **Magnitude**. The magnitude of a vibration is commonly quantified by its acceleration, even though its displacement or its velocity can also be used for that purpose. Magnitude is usually expressed in terms of the r.m.s. value, which for a sine wave is calculated as:

$$A_{rms} = \frac{A_{0p}}{\sqrt{2}} \tag{2.4}$$

where $A_{0\mathrm{p}}$ is the 0-to-peak value (see Figure 2.7).

- **Frequency**. It represents the number of cycles per second the wave performs, expressed in Hertz (Hz). This parameter has a great importance, as not all frequencies are felt equally for our body. Some studies have proven that the human hand has a higher sensitivity to frequencies within 200-400Hz (Russell, 2012). It is also important to take notice that frequency has a big importance in how vibrations are felt. The higher the frequency is, the more urgent the stimuli feels.

- **Duration**. The duration of the vibration is the time while the effect is applied and it influences how the effect is felt, as long effects are felt as more important and annoying than short effects.

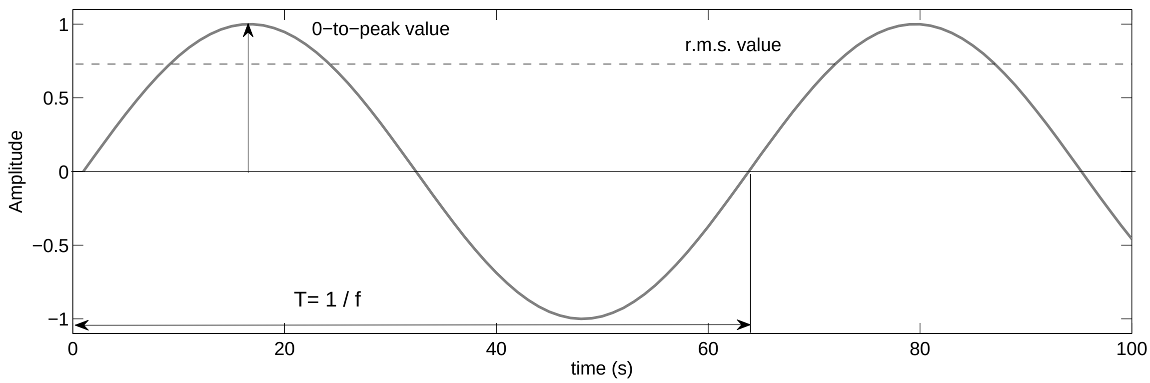


Figure 2.7: Characteristics of a wave

2.4 Multimodal feedback

Humans use their senses to acquire information provided by the environment. Regarding human-computer interaction, the exchange of information is done through channels, also known as modalities (Karray et al., 2008). Humans consciously and unconsciously process the information in a multimodal way (Nilsson, 2014). Multimodal interaction refers to a two-way communication that uses more than one modality in at least one of the directions, that is, the information is either sent or received using more than one modality (Vilimek et al., 2007). The brain does not give the same weight to the information coming from different sensory modalities (Hecht and Reiner, 2009). In multi-sensory events, there is a ”visual predominance”, being audio and haptic signals more likely to be unnoticed when combining with visual signals. However, when combining audio and haptic signals, no dominance of one sensory modality has been found (Hecht and Reiner, 2009).

When designing a multimodal system, it is relevant to analyse how the different modalities are combined (Vilimek et al., 2007). Six strategies can be used:

- **Equivalence.** Different modalities are used to achieve the same task, being used alternatively, not at the same time.

- **Specialization.** Some piece of information can only be transmitted using one specific modality.
- **Redundancy.** The same information is transmitted using several modalities at the same time.
- **Complementarity.** The complete information is distributed across several modalities, complementing each other.
- **Transfer.** The information which was created in one modality is used by another modality.
- **Concurrency.** Independent types of information are transmitted by different modalities at the same time.

Redundancy implies a fusion of signals, which needs a more complex design than other strategies of multimodality. If the fusion of signals is beneficial or not is not clear and depends on the application (Vilimek et al., 2007).

There are several theories on multimodal interaction (Nilsson, 2014). It will explained here the interaction model presented by MacLean (MacLean, 2000). The reason for presenting this interaction model is that it can be used with all sensory modalities, including haptics.

The model for multisensory interaction is shown in Figure 2.8. It is composed of four layers, being the user on the outside, the manipulated environment on the inside and layers of physical interface and interaction models between them (MacLean, 2000).

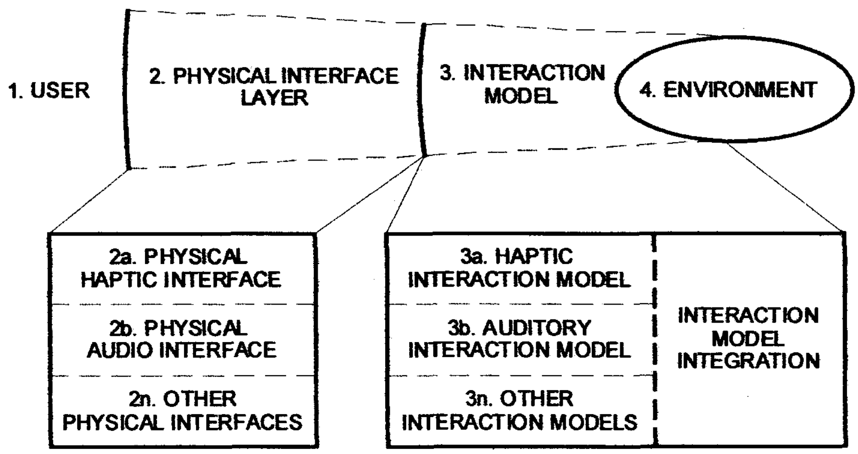


Figure 2.8: Multi-sensory interaction model

1. **User**. It is important to know who the user will be and take it into account when designing the interface.
2. **Physical Interface**. It consists of the physical devices that accept input and provide output to the user for all the sensory modalities.
3. **Interaction Model**. It defines the relation between user and environment. As can be seen in Figure 2.8, every modality has its own submodel where signals are produced before being integrated and transmitted to the environment. The presence of this layer between the physical hardware and the environment is one of the notable features of this model, as on previous models the emphasis dwelt on creating the physical layer instead.
4. **Environment**. It is whatever is intended to be observed or manipulated.

2.4.1 Multimodality in cars

Driving is mainly a visual task; however, the introduction of infotainment systems in the car, as well as safety and communication systems can interfere with the driving task causing a safety critical workload and distraction (Bengtsson et al., 2003). Thus there is a need to explore new modalities so that the driver is not overloaded and the interaction with infotainment systems is more efficient (Srinivasan, 2006). Combining a visual interface with haptic interface providing the same information allows the driver to keep eyes on the road (Grane and Bengtsson, 2011). The addition of haptics was also proven to reduce mental workload and error rate, as long as it is well designed (Bengtsson et al., 2003; Grane and Bengtsson, 2011). The system should be designed in such a way that the different sensory stimuli should be presented from approximately the same spatial location at approximately the same time, in order to have a better response to multisensory stimuli (Ho et al., 2007). The addition of haptic information within cars can provide considerable advantages. There are several reason why haptics is expected to become an important source of feedback within cars; some of them are (Burnett and Porter, 2001):

- Human hands and fingers can feel a wide variety of haptic features without using the visual system.
- As life expectancy increases, older people are becoming a bigger segment of car users. With the age, visual and auditory capabilities decrease markedly; whereas the discrimination with the sense of touch is less affected by the age.
- As physical contact is necessary for touch sensing, there is an emotional closeness to the interaction, which is not present in audio or visual interactions.

Even though haptics have these characteristics, several studies indicate that haptic feedback is more effective when it is combined with other modalities such as audio, while performing a driving task. It has been proven that driver's response time to unimodal auditory and unimodal vibrotactile warning signals were higher compared to the response time when multimodal audiotactile signals were applied (Ho et al., 2007). It has also been proven that the addition of haptics in automotive touchscreens does not provide significant improvements unless it is also combined with audio feedback (Pitts et al., 2009). It is due to the fact that haptic stimuli is perceived weaker when carrying out simultaneous performance of driving and touchscreen tasks as it imposes an attentional load. However, if audio stimuli is added, the haptic stimuli is felt stronger (Pitts et al., 2009). Similar results were found in other studies, where a fully corresponding visual-haptic interface was considered unnecessary, as the haptics were not felt as expected when performing a simultaneous task (Grane and Bengtsson, 2011).

3. Method

The methodology used in this thesis was heavily influenced by the human-centred design framework presented in Figure 2.1. The activities were slightly modified in order to better suit the needs of the project, although the same reasoning was applied in all work areas. Due to the project being research oriented, it had few requirements restricting the development. However, a pre-study was carried out in order to narrow the scope and provide guidance for the project team throughout development. The pre-study was used as an input in the development processes across all work areas, and consisted of two parts:

1. A literature review which created the theoretical framework on which the thesis was based on.
2. A usability context study describing by whom and how the strategic controller would be used.

A hardware and software prototype was created with audio and haptic feedback capabilities. The usability of the prototype controller was evaluated in iterations at different stages throughout development, and finalized through a validation study in a car simulator located at Volvo Cars Corporation in Gothenburg.

3.1 Prototype development

In order to reduce costs and save time, a decision was made to use hardware which was already available on the market. Force feedback joysticks are often used for hobbyist flight simulators available for personal computers. However, the market for force feedback joysticks has declined over the years, likely due to lacking consumer interest. The chosen joystick was a *Microsoft Sidewinder Force Feedback 2*, a joystick praised by enthusiasts for its robust design and modification possibilities. This joystick is not available in the market anymore, so a second-hand joystick was used instead. Due to its popularity within the hobby flight simulator community, the joystick capabilities are well documented. Hardware modifications were carried out in order to boost joystick performance and increase the concept's usability.

Software was developed for the joystick using the programming language *C++*, and *Microsoft DirectX* which is a collection of application programming interfaces (APIs) often used for video game development. DirectX offers the possibility to control video game controllers such as joysticks, and as such haptic feedback for the strategic controller could be created.

One of the key challenges to software development is the ability to react to scope changes as code can quickly become obsolete. The Agile development approach is designed to handle such changes, and the practicality of this approach can be described by a set of features (MacCormack, 2001):

- Work is broken down into short time (1-4 weeks) intervals called sprints.
- The team has short daily meetings (15-20 min), called scrums, which focus on solving problems that hinder progress.

- The output of each sprint is to be part of the final product. As such, working code is produced each sprint.
- Programming is carried out in pairs.
- Programmers are to write testing protocols before they begin to code.

The project team adapted this approach and the software development process utilized is illustrated in Figure 3.1.

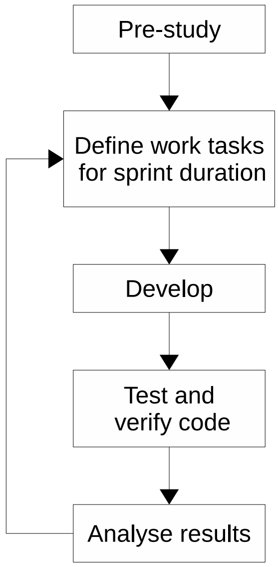


Figure 3.1: The software development process used in this thesis project.

As the development team only consisted of two people, frequent discussions were easily held while programming or over coffee breaks. Weekly meetings were held together with project supervisor Peter Mohlin at Semcon, where the results of each sprint were discussed and where tasks for the upcoming sprint were planned.

3.2 Multimodal feedback design

Several theories on how audio feedback should be designed are available in literature, but little theory has been presented on how to design effective haptic force feedback. This project also combined the two modalities in order to create multimodal feedback. Product developers often utilize visual sketches or prototypes in order to communicate their ideas with others (Ulrich and Eppinger, 2007). As such, ideas can be discussed and the thoughts of other people can result in design improvements or trigger new ideas to be born. Studies suggest that a similar sketch, analyse, and improve process should be utilized in sound design (Nykänen et al., 2015). These general product design principles and sound design theories both comply with the suggested framework of ISO 13407 (as shown in Figure 2.1), and there are clear benefits of an iterative design process which incorporates the user. The project team chose to adapt an iterative design process utilizing sketches for its multimodal feedback design, which resulted in a design process illustrated in Figure 3.2. The conducted pre-study would serve as a basis for sketching both audio and haptic feedback signals.

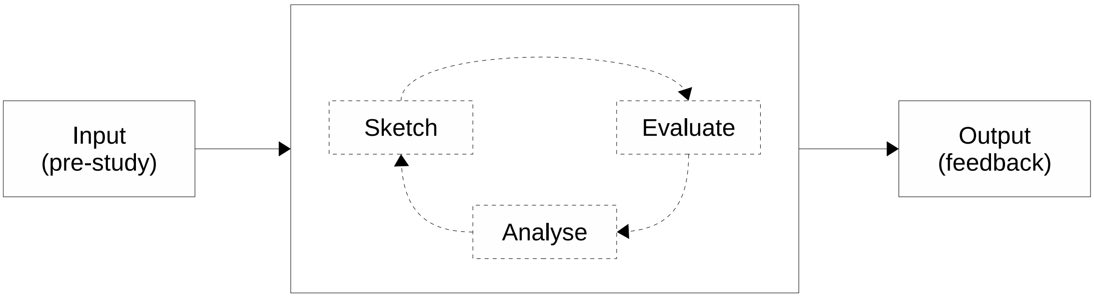


Figure 3.2: The multimodal feedback design process used in this thesis project. Sketches are evaluated and the results of the analysis are used to improve or create new sketches. The process is iterated until desired results have been achieved.

The haptic feedback was software based and created inside the prototype software written in C++ using DirectX. A component of DirectX called DirectInput allowed the team to gain access to the joystick. Feedback effects were created within the software and uploaded to the joystick when the software initialized, these effects could later be played by the software when certain feedback events were triggered. Several different types of effects are available such as constant forces, square/sine/triangle/sawtooth waves, spring forces, and friction forces. The gain and the duration of the effects can be modified in order to create the desired haptic signal along with the direction of the force itself.

Audio feedback was created in a studio located at Semcon in Gothenburg using MAGIX Samplitude Pro X, software synthesizers from Native Instruments Komplete 6, and a MIDI keyboard. Verbal feedback was created by utilizing text-to-speech synthesis. In order to assure that the perceived loudness of all audio feedback was equal, loudness measurements were made with Artalabs ARTA software. The gain of each audio file was adjusted accordingly until equal loudness across all audio feedback was achieved. All audio was exported to the Waveform Audio File Format (WAVE/WAV) in 16 bit stereo with a sample rate of 44100 Hz.

In order to explore as many solutions as possible, audio and haptic feedback sketches were designed and evaluated separately and later combined into multimodal feedback. The feedback sketches were evaluated in three stages, and the type of evaluation carried out was dependant on the maturity of the sketches. The three different evaluation methods are explained below:

1. **Self evaluation**. Early sketches were evaluated by the project team by voting, using a scale of 1 to 5. The sketches were rated according to their perceived urgency, annoyance and appropriateness. A rating of 1 would mean that the sketch was considered very bad, and a rating of 5 was considered to be a very good sketch. The final score of each sketch was obtained by taking the average value of the two project members scores.

2. **Expert evaluation**. Once the feedback sketches were mature enough, they were evaluated together with Peter Mohlin, senior audio technology engineer at Semcon. An expert opinion was given for each sketch, which gave the project members suggestions on how the sketches could be improved.

3. **User study**. The final sketches were evaluated by conducting a user study. Due to the large extent of the user study, it will be described separately in Section 3.3.1.

The evaluation process helped the team to systematically eliminate sketches until a final set of multimodal sketches were chosen as feedback for the strategic controller.

3.3 Usability studies

The usability of the strategic controller was evaluated through usability studies. The goal was to improve the concept by identifying usability issues, and to find out if people can use the concept successfully. The number of participants used in such evaluations often depend on the available budget, and the amount of time available for such studies. In order to decrease costs literature suggests that a lower amount of test participants can be used in order to detect severe usability issues (Virzi, 1992). The relation between the proportion of uncovered problems and the number of participants used in a usability study is given in Figure 3.3.

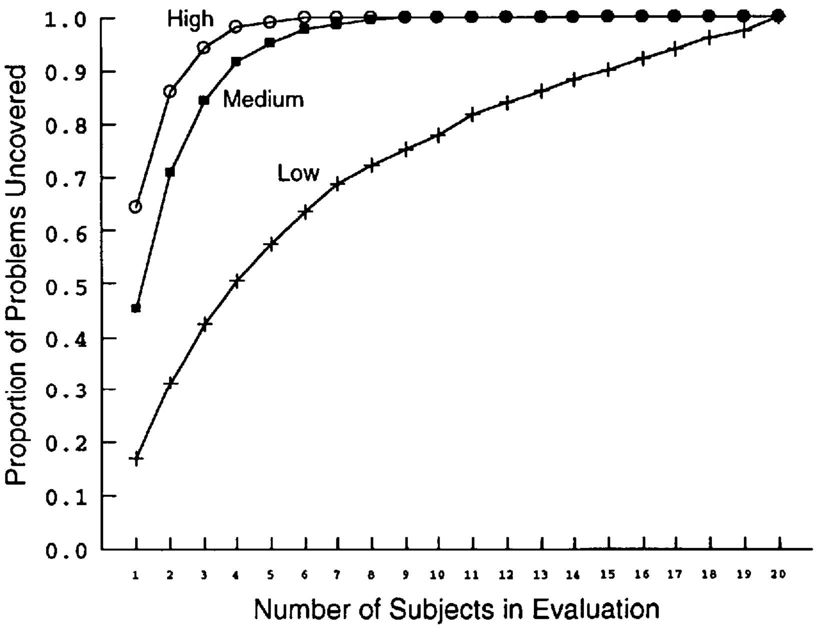


Figure 3.3: The proportion of usability problems uncovered shown as a function of the number of participants for problems of different severity (Virzi, 1992). Problems of high to medium severity are often discovered within the first few test participants, but in order to uncover issues with low severity a larger sample is required.

In order to successfully identify if people will be able to use the concept successfully, a close replication of the real world is necessary (Maguire, 2001). However, extreme realism is difficult to achieve in simulators and is not necessarily needed for research purposes. Literature suggests that face validity is enough, i.e. the initial look and feel of the simulator needs to be similar to the vehicle and task it simulates (Parkes, 2012).

The qualitative data gathered in the usability studies were analysed using an affinity diagram (also known as the KJ method after Jiro Kawakita) which is one of the seven management and planning tools presented by Professor Shoji Shiba in 1989 (Alänge, 2009). The analysis was carried out by creating simple notes explaining the issues which have been gathered and identified. The notes were then used to group issues which were related to each other. The grouped issues were given a header which both summarize the identified problems, and also increased the level of abstraction. A schematic illustration of the results from carrying out this method can be seen in Figure 3.4. The process was repeated until all notes have been used or until there was no possibility to group issues further. As such the affinity diagram was used to structure the large amounts of qualitative information which had been gathered during the user study.

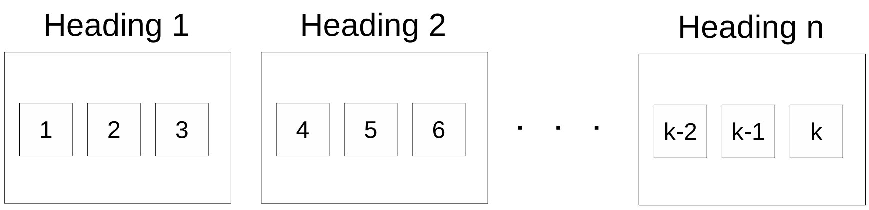


Figure 3.4: An affinity diagram can reduce the complexity of problems which can seem too large to grasp. Issues (denoted k) are grouped and given headings (denoted n) with a higher level of abstraction. The grouping is unique, so each issue can only be in one group. Two or more groups can be grouped in order to create an even higher level of abstraction if possible.

3.3.1 User study

A user study was carried out in the studio at Semcon in Gothenburg. The goal of the study was to evaluate multimodal feedback and identify usability issues in order to improve the concept. The study consisted of ten test participants and the illustration in Figure 3.5 shows a schematic overview of how the test participants were placed inside the studio. The volume settings were identical for all participants, and all participants were screened for hearing impairments prior to testing. The approximate duration of the study was two hours per participant, and all test participants were compensated for their participation. As the test was too long, test participants were allowed to take a break if desired.

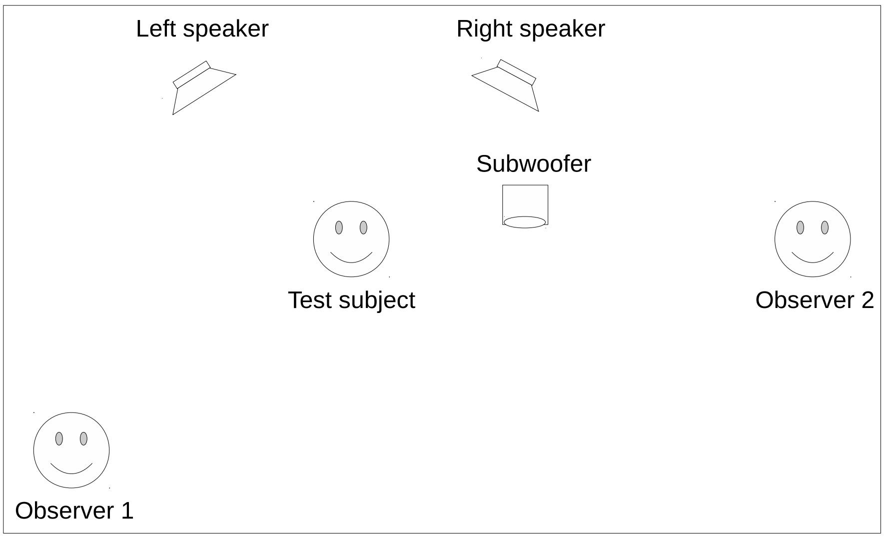


Figure 3.5: The test subject was placed in front of a desk in the studio at which the joystick had been secured with clamps. The joystick was connected to a PC controlled by Observer 1, at which the prototype software was run. The same hardware setup was used throughout the user study.

Prior to conducting the user study, test participants were asked to provide brief background information (see Appendix F.1). In order to give the participants a better understanding of how the concept was to be used a usability context was presented. A simple scenario was then followed in order to give the participant a better understanding of what type of situation he or she would be using the strategic controller. In each scene of the scenario, one or several commands were presented (as shown in Appendix F.2). The participant issued the commands with the joystick and rated the feedback according to a questionnaire. The questionnaire consisted of three self-assessment manikin (SAM) scales to measure the test participant's emotions (pleasure, arousal, and dominance), and sketch ratings for perceived urgency, annoyance and appropriateness. SAM allows for rapid assessment of the participant's emotional experience associated with a processed stimuli (Bradley and Lang, 1994). Users were also asked to give a brief comment on why they liked or disliked the sketch they were rating. This process was iterated until all sketches had been rated. The questionnaire used can be found in Appendix F.3.

The experiment was finalized by an interview (as shown in Appendix F.4) where the test participants also voted on their favourite and least favourite sketch. In addition, throughout the user study the test participants were observed by the project members and both expected and unexpected behaviours were noted. Each study began with one introduction scene, where essential functionality of the strategic controller was presented. This scene was considered necessary in order to understand the concept. The order of the remaining scenes was randomized and the sketch order for all scenes was also randomized.

The average values from the SAM, urgency, annoyance, and appropriateness scales were used to quantify a score for each sketch. The attributes used a 5 point scale ranging from low (1) to high (5), but the desired values for each attribute varied depending on the feedback event. The project team had already defined desired values for each attribute for each feedback event during the feedback design process. These desired values were categorized into high (H) or low (L), as such the ratings needed to be inverted for certain attributes i.e. in order to make a low rating more valuable than a high rating. The ratings were inverted according to:

$$\text{Rating}_{\text{Inverted}} = 5 - \text{Rating}_{\text{Average}} \tag{3.1}$$

The attributes were also compared against each other for each feedback event using a prioritization matrix. Two attributes were compared against each other; if one was considered more important than the other, it was awarded a score of 1. However, if it was considered less important it was awarded a score of 0, and in cases where they were equally as important a score of 0.5. The procedure was carried out until all attributes had been compared against each other. An example is given in Table 3.1.

Table 3.1: Attributes were compared against each other in order to quantify their importance for each feedback event.

Attribute	**A**	**B**	**C**	**D**	**E**	**F**	**Total**
A		1	1	1	1	1	5
B	0		1	1	1	1	4
C	0	0		1	1	1	3
D	0	0	0		1	1	2
E	0	0	0	0		1	1
F	0	0	0	0	0		0

The scores from this type of comparison were not appropriate to use in order to quantify the results from the questionnaire. For example, attribute F received a total score of 0 in the example above and this would spoil the user ratings for this attribute. In order to deal with this issue, the project team created a conversion table for the scores using a scale of 1-10, as shown in Table 3.2.

Once the attributes had been classified into the 1-10 scale, a weight was calculated according to:

$$w_{\text{attribute}} = \frac{\text{Scale}_{\text{attribute}}}{\sum \text{Scale}} \tag{3.2}$$

which also normalized the weight to 1 (i.e. the sum of all the weights equals to 1). A sketch score was calculated for each sketch by summing up the products of the average attribute ratings

Table 3.2: The total score got for each attribute is converted to a 1-10 scale using a conversion table.

Total	Scale
5	10
4.5	9
4	8
3.5	7
3	6
2.5	5
2	4
1.5	3
1	2
0-0.5	1

and their weights. The calculated result was also compared to the opinions and favouritism gathered from the interviews in order to select the most promising sketches.

3.3.2 Simulator study

A simulator study was carried out in a simulator located at Volvo Cars Corporation in Gothenburg. The goal of the study was to validate and benchmark the usability of the concept. The study involved five test participants and consisted of three parts; an introduction and a tutorial of the strategic controller, the experiment, and a questionnaire and interview session. The volume settings and hardware setup were identical for all participants, and the approximate duration of the study was half an hour per participant.

A low-range AutoSim simulator with static car seats was used for the experiment using a 180° screen. The simulator was also equipped with real parts for steering wheel, gear lever, important instruments and control lamps. An already developed simulator map was available for the project, but minor traffic modifications were made in order to create the desired scenario.

In order to simulate autonomous driving, a Wizard of Oz (WoZ) approach was utilized. With this approach the participant was meant to believe that the interaction was autonomous, but in reality the system was operated by a hidden person i.e. the WoZ. The illustration in Figure 3.6 shows a schematic overview of how the test participants were placed inside the simulator, and where the WoZ was located during the test.

The joystick was integrated and replaced the gear stick inside the simulator. A USB extension cable was used to connect the joystick to a PC running the strategic controller software, operated by the WoZ. Three GoPro® cameras were used to record the experiment. One was used to capture the test participants interaction with the HMI, possible interactions with the steering wheel, and part of the traffic environment. One camera was placed in the ceiling of the simulator and filmed the test participant's interactions with the HMI from above, and the third camera was used to capture the foot pedals and the test participant's feet.

The test participants were asked to fill out a background form (as shown in Appendix G.1), given brief information on why the study was conducted, and a tutorial of the strategic controller. Before starting the experiment, the participants were also given a habituation period inside the simulator. First the participants were asked to drive the simulator manually in order to familiarize themselves with the simulator environment. This was followed by an introduction of the AD concept using the strategic controller prototype. The car was driven autonomously and the test participant was asked to execute commands which were displayed on the simulator screen. Once the habituation period was over, the experiment started and a simulator scenario was followed. Special events were used in the scenario which could be experienced differently

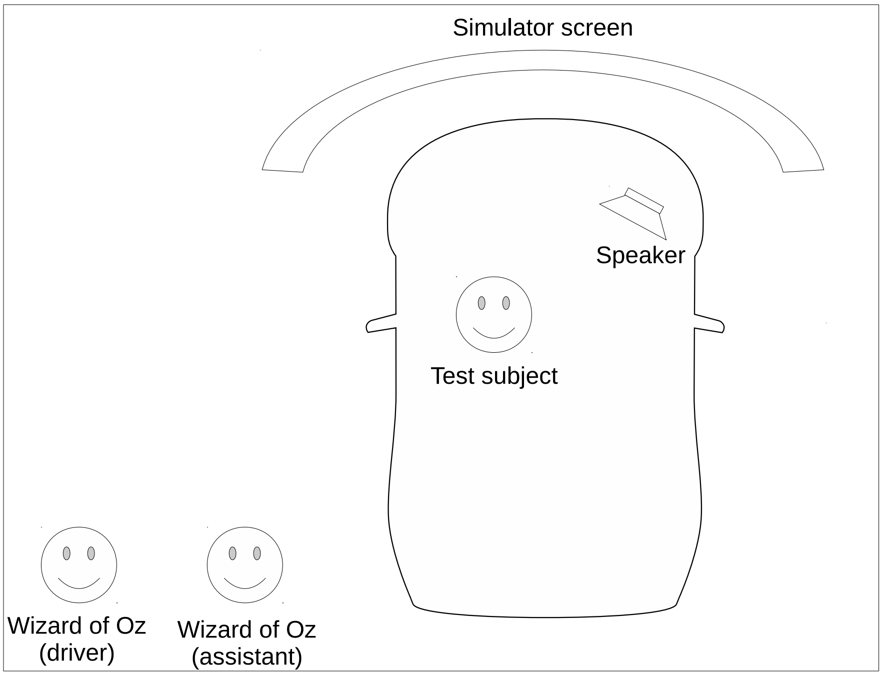


Figure 3.6: The test participants were placed inside the simulator. The WoZ consisted of two persons; one driving the car, and one assisting the driver by communicating the commands which the driver needed to perform. The assistant had the role of the strategic controller's system; constantly analysing the cars surroundings and handling the user's input. The assistant communicated with the driver through a simple HTML interface, which played the commands to be performed in the headphones of the driver.

depending on the user, all simulator events are further described in Appendix G.2.

In order to quantify usability, ISO 9241:11 suggests taking measurements for effectiveness, efficiency, and satisfaction. Where effectiveness is the user's degree of success, efficiency is the time it takes to complete tasks, and satisfaction is the user's acceptability (Maguire, 2001). However, it is difficult to define effectiveness and efficiency as they depend on the use context of the system. The way effectiveness and efficiency of a text editor for writing LaTeX is measured, may be very different to the way effectiveness and efficiency is measured for a HMI used for a vehicle infotainment system. As such it may be difficult to answer if one system or software is more usable than another, as the way they measure effectiveness and efficiency may be very different. In addition, the goal of the study was also to create a benchmark which future or similar concepts can compare against. As such, an easy to apply and standardized method for usability measurement was needed.

The User Experience Questionaire (UEQ) provides a standardized and reliable method for analysing usability and user experience. The questionnaire consists of 26 attributes which are designed to evaluate a product in three dimensions; attractiveness, design quality (stimulation, novelty), and use quality (efficiency, perspicuity, dependability) (Laugwitz et al., 2008). Test participants were asked to rate each attribute spontaneously using a 7 point scale, as shown in Appendix G.3. The mean values of the measured attributes were also set in relation to a benchmark data set. This data set contains data from 4818 persons from 163 studies concerning different products (business software, web pages, and social networks)[1]. As such, the results from the simulator study could be used to draw conclusions about the relative quality of the evaluated concept, in addition to being a benchmark for future concepts. However, UEQ does not create a usability score, and should therefore only be used as a comparison.

[1]UEQ analysis tools are available at http://www.ueq-online.org/ (last accessed 2015-05-26).

In order to get a deeper understanding of the usability of the concept, an interview was conducted with the test participant once the questionnaire had been completed. Test participants were asked about their autonomous car experience and their experience using the concept. A complete list of interview questions can be seen in Appendix G.4. The special events were used to trigger an emotional response from the user and were discussed in the interviews. Their response at the occurrence of an event was captured in the camera footage and used as communication media in the interview.

4. Results

The general vision of the strategic controller concept was made by Claes Edgren, research project manager for vehicle HMI at Volvo Car Group, and project leader of AIMMIT. Due the thesis project being research oriented, the strategic controller concept had no strict requirements. The only requirement was to make sure the joystick manipulodium had a solid and robust feeling, and as such the projected team was asked to avoid using any buttons or other sensors on the manipulodium. The project team began by realising Claes' vision of the joystick by implementing general ideas of how the strategic controller should work. The joystick was to be initialized by enabling autonomous drive (AD) mode, and commands were to be issued by creating specified patterns with the joystick. Claes' vision also included examples of such command patterns which were implemented and further developed by the project team. The project team has implemented concept usability improvements, designed multimodal feedback, created software and modified consumer grade hardware in order to achieve a prototype for the strategic controller. This chapter will disclose the results achieved throughout the development process of the strategic controller.

4.1 User analysis

The goal of automotive manufacturers is to offer automated vehicles on the consumer market by year 2020. New vehicle technology often gets introduced in the premium market segment before reaching the middle or budget segments. There will always be curious early adopters of such technology, but in order for a larger group of people to use such a system the technology needs to be accepted by the users. Theory suggests that trust is something which builds up over time, and requires a competent and usable system (Hoffman et al., 2013). The strategic controller utilizes multimodal feedback consisting of audio and haptic feedback signals, which will have a major effect on user experience. This feedback does not only need to be effective, but also needs to communicate the brand of the product in order to be accepted by the user (Edworthy, 1994).

In order to create appropriate feedback for the controller, a manufacturer of premium cars with plans of releasing an autonomous vehicle was used as a model for feedback development. Due to Volvo Cars close geographical location and affiliation with the AIMMIT project, Volvo was chosen to act as the model for which the strategic controller's feedback would be designed for. In order to create appropriate feedback for such a vehicle a brand analysis was conducted. First, a list of attributes which describe the values of the Volvo brand was created by analysing the company's website [1]:

- Volvo builds *safe cars which focus on the user.*
- Volvo puts people in the center, and *the cars aim to improve and simplify our lives.*
- Volvo does not limit design to aesthetics, and believes that *if a product is not functional it will never be beautiful.*

[1] Volvo Cars Swedish website: http://www.volvocars.com/se/ (last accessed 2015-02-05).

Through further analysis of the brand a list of attributes which communicate the brand identity was compiled, along with an imageboard which was used as creative guidance throughout the feedback design process (as shown in Appendix B). This data was compiled by analysing recent TV commercials made by the manufacturer [2], and combining them with the identified brand values. The goal was to conceive a creative foundation which could be used throughout the feedback design process.

As the project was research oriented the concept developed by the project team had no requirements, apart from the request to avoid buttons and sensor on the manipulodium. However, applying a user-centred design process is a difficult task when there is no clear picture of who the user is and what they want. No market research was performed due to the nature of the project, instead a short list describing the users of the system was compiled through discussions within the project team:

- The user will be of either gender and aged 16 or above.
- The user will have high functionality and usability demands when purchasing a car in the premium segment.
- There will be large variations in size and strength of the user and the average also varies between different countries.
- The user will have the sufficient vision required to obtain a driver's license.
- Depending on the laws of the country, deaf people may be allowed to drive cars (Sweden being one of them). As such, hearing ranges may vary from fully functional to none.
- Noise and vibrations from the car's engine and the road's surface may mask the feedback from the strategic controller. As such, the user's auditory and somatosensory sensitivity may be impaired while driving.

4.2 Usability context

There will most likely be a transition between non-autonomous vehicles and autonomous vehicles, as there are technological issues associated with automated driving. However, the strategic controller was developed with the assumption that such problems do not exist, i.e. they will be solved by other contributors to autonomous driving research.

The strategic controller was considered as a complementary feature for a non-autonomous car in the premium segment produced during the writing of the thesis. The steering wheel and pedals will still be used in such a vehicle, just in case manual takeover is required due to an emergency situation or in case of technological failure. The user could activate autonomous driving (AD) mode by setting the gear stick to AD, much like changing gears, transforming the gear stick into a joystick (as shown in Figure 4.1). AD mode would be disabled automatically when braking or taking control of the steering wheel, allowing the user to quickly regain manual control. In such scenarios, the gear stick would automatically disable AD mode in order to allow the user to drive normally. The handover between autonomous driving and manual driving was not further developed by the project team, as it was not included in the scope of the thesis.

[2]The three commercials analysed go under the names Made by Sweden; XC70 feat. Zlatan, Drive-E feat. Robyn, and Vintersaga.

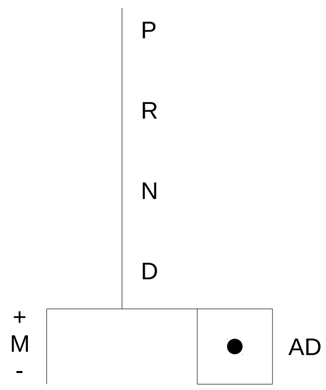


Figure 4.1: An example of how the strategic controller could be activated. AD mode is enabled by changing the gear stick to AD, which transforms the gear stick into a joystick and enables the strategic controller.

The mental model used for the strategic controller is that the user is a passenger in a taxi, the strategic controller is the chauffeur and the user dictates where he or she wants to go. Instead of communicating verbally with the chauffeur the user issues commands with the joystick. Typical commands the user would need or want to perform in this type of situation are:

- Overtake slow vehicles, such as trucks with speed restrictions.
- Turn right/left in order to change route.
- Stop the car.
- Change lane in order to position the car for an upcoming turn.
- Increase/decrease speed, without endangering the user or other road users.
- Move inside the lane or move right/left on roads without lanes (e.g. in rural areas).

Suggested joystick patterns for some of these commands were provided to the project team in early phases of development. Commands are executed with the strategic controller by performing a movement pattern with the joystick. If the system recognizes the pattern an associated command will be performed by the car. An example of how an overtake is issued is given in Figure 4.2. Detailed use cases of the commands and their associated pattern were further developed by the project team through brainstorming sessions, and can be found in Appendix A.1.

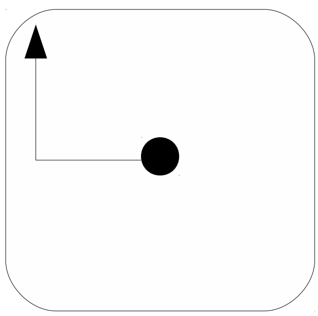


Figure 4.2: An example of how an overtake is issued with the strategic controller. The joystick is idle in the center position, and an overtake is issued by moving the joystick to the left and then upwards. The pattern is recognized by the system and appropriate action is taken. Joystick movements will also trigger feedback events such as notifications which clarify that the strategic controller is listening to the user. More details about such events are found in Appendix A.1.

If the user issues a command which is not safe to execute, the car will reject the command and give the appropriate feedback to communicate the rejection. Further explanation on how the strategic controller determines if the command is safe or unsafe will be given in Section 4.5. In the overtake example given in Figure 4.2, the joystick would lock in the upper left corner if the command was accepted by the car. When the command has been executed, the joystick will return to the center position and await further instructions from the user.

4.3 Hardware modifications

The chosen hardware came from the consumer market for PC gaming. The hardware was modified in order to adapt the joystick for the application of using it as prototype hardware for the strategic controller. The following changes were made to the hardware:

- Unnecessary buttons and associated circuits were removed to decrease the exterior complexity of the joystick.
- The joystick manipulodium was replaced with a crystal gear stick used in Volvo XC90 (see Figure 4.3) to create a robust and familiar user experience.
- Circuit modifications were made in order to double the power output of the joystick's two DC motors.

Figure 4.3: The strategic controller joystick with the replaced manipulodium.

The power (P) of the DC motor is given by:

$$P = UI \tag{4.1}$$

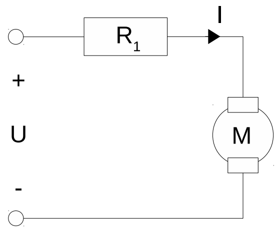
where U is the voltage and I the current which flows through the electrical component. Instead of replacing the complete power supply of the joystick, a more gentle approach was taken. According to Ohm's law the current (I) through a resistance (R) between two points is proportional to the potential difference (U) across the two points:

$$I = \frac{U}{R} \tag{4.2}$$

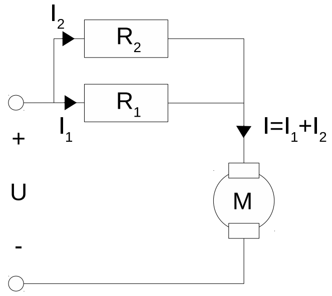
By combining Equation 4.1 and 4.2, Equation 4.3 is obtained, and it is clear that an increased power can be achieved by decreasing the resistance.

$$P = \frac{U^2}{R} \tag{4.3}$$

As such, an increased power was achieved by soldering additional resistors in parallel onto the circuit, increasing the current which flows to the motors. This can cause that the DC-motors get burned and should be taken into account for future prototypes. The results can be seen in the simplified circuit diagrams in Figure 4.4, illustrating the current (I) which passes through a resistance (R) before reaching one of the DC motor (M).



(a) Circuit before modification, the total resistance is $R_1 = 1\Omega$.



(b) Circuit after modification, $R_2 = 1\Omega$ has been added, $R_{total} = \dfrac{R_1 R_2}{R_1 + R_2} = 0.5\Omega$.

Figure 4.4: Simplified circuit diagrams showing the modifications made in order to increase the power output of the DC motors.

4.4 Feedback design

This section will explain the multimodal feedback which was designed during the development of the strategic controller. The user analysis and the usability context were used as input for the design process, together with guidelines and recommendations gathered during the literature study.

Haptic and audio feedback were design separately in the early phases of development, and later combined into multimodal feedback. The developed use cases (see Appendix A.1) were used to identify events where feedback was needed in order to keep the user in the loop. The following feedback events were identified:

1. **Initiating input.** When the user starts to initiate a command, feedback is given to alert the user that the strategic controller is ”listening” to the user’s input.

2. **Pattern recognized.** If the user input matches one of the defined patterns for the associated command, feedback is given so that the user understands that the pattern has been recognized.

3. **Command aborted/rejected**. If the command which the user has input is not safe or not possible to execute, feedback is given to alert that it is not possible.

4. **Command interrupted/cancelled**. If the user interrupts or cancels the input command, feedback is given in order to communicate the interruption/cancellation.

5. **Increase/decrease speed.** Although the car will start to drive faster/slower when the command is being executed, additional feedback will give the user a confirmation that the command is being accepted.

6. **Reaching maximum/minimum speed.** The car may need time before the desired speed has been reached. The additional feedback will give the user a faster response of when the maximum/minimum speed has been set.

7. **Moving inside the lane.** Although the car will start to move left/right when the command is being executed, additional feedback will give the user a confirmation that the command is being accepted.

8. **Increasing/decreasing the number of exits/turns.** When the user is incrementing/decrementing the desired number of turns/exits, feedback which communicates which turn/exit is being selected is necessary.

9. **Reaching the maximum/minimum number of exits/turns.** When the user is incrementing/decrementing the desired number of turns/exits, the user needs to be informed when the minimum/maximum number has been reached.

10. **Stopping.** In order for the user to understand that the car is stopping, and not just slowing down for other reasons (such as safety) distinguishable feedback is given when stopping.

11. **Command is being executed.** The user will need feedback which communicates that a command is currently being executed in order to stay in the loop.

However, multimodal feedback was not fully explored for all events. Decisions were made to only use one modality for certain events, and other events were not explored at all due to hardware restrictions. In general a redundancy approach (as presented in Section 2.4) was used for the multimodality, i.e. the same information was communicated using both modalities at the same time.

4.4.1 Haptic sketches

Haptic sketches were created for feedback events 2-10. However, the command confirmation (feedback event 2) was split into two seperate feedback sketches; one for commands ending in corners and one for commands ending at the edges of the joystick. This was done in order to compensate for the differences in haptic feeling one would experience in a corner compared to an edge of the joystick. Different type of waveforms were used for the sketches (sine, square, triangle and sawtooth) with varying parameters (magnitude, period, and duration). All results related to these sketches are located in Appendix C, but the feedback events are denoted using their development code names.

Twelve sketches were created for each event, and the details of each sketch can be found in Figure C.1. The sketches were evaluated by the project team using a score of 1 to 5, and the mean scores of each sketch can be seen in Figure C.2. Sketches which received an average score ≥ 3.5 were considered good and qualified for the next round of evaluation. In order to keep the number of sketches for all feedback events equal, some of the sketches which had recieved a rating of 3 were improved before continuing with the next round of evaluations. The criteria used to decide whether or not sketches rated with 3 were to be improved was to take only those in which both team members had given a similar rating (a sketch rated with 3 by both team members was improved but not one which was rated with 1 and 5). The final results of the self evaluation can be seen in Figure C.3.

4.4.2 Audio sketches

Audio sketches were created for feedback events 1-3, 5, 8, and 9. The majority of the audio sketches created were earcons, although some auditory icons were explored for the *initiating input* and *pattern recognized* events. The number of sketches differed between events as audio design is a creative process. However, over 20 sketches were created for each event using a variety of timbres, notes, and tempo. The sketches for *initiating input* and *pattern recognized* were designed in pairs in order to create synergy. All results related to these sketches are located in Appendix D, but the feedback events are denoted using their development code names.

The sketches were evaluated by the project team using a score of 1 to 5, and the average scores of each sketch can be seen in Figure D.1. Sketches which received an average score ≥ 3.5 were considered good and qualified for the next round of evaluation. As a large number of sketches for each event qualified for the next round, no improvements were carried out.

Verbal feedback was also created for commands which were expected to have a delay before execution, such as taking the next exit on a highway. These type of commands would be "queued" in the system, and not performed instantaneously such as increasing or decreasing speed. The verbal feedback would be played when the car starts to perform the command i.e. feedback event 11. The following verbal feedback was created using text-to-speech synthesis using the *Microsoft Zira (US English)* engine:

- Stopping.
- Overtaking.
- Taking the next exit on the left/right.
- Taking the 2nd exit on the left/right.
- Taking the 3rd exit on the left/right.
- Changing to left/right lane.

4.4.3 Multimodal sketches

Multimodal sketches were created by combining the audio and haptic sketches which had passed the first round of evaluations. Combinations were only made for events using more than one modality. All results related to these sketches are located in Appendix E, but the feedback events are denoted using their development code names.

The qualified sketches are presented in Appendix E.1, and all combinations were evaluated by the project team using a score of 1 to 5. Sketches which received an average score of 4 were considered good and qualified for the next round of evaluation. Exceptions were made for events which did not have as many high rated sketches, and the required mean score was lowered to ≥ 3.5. Certain events needed to be paired in order to work well together, one such example is the *increase/decrease speed* event and the *maximum/minimum speed error* event. These events required a second round of scoring as shown in Table E.2 and E.3. The multimodal feedback combinations created from this evaluation can be seen in Appendix E.3.

In order to evaluate the remaining sketches more efficiently, feedback sets were created which could be used with the prototype software (as shown in Figure E.4). These sets were evaluated with Peter Mohlin, a senior audio technology engineer at Semcon. Peter evaluated the remaining feedback sketches and provided the project team with his professional opinion. The results from this evaluation were used to improve the different sketches. The changes that the project team carried out were documented in Figure E.5, and the improved feedback sets are shown in Figure E.6.

As the next feedback evaluation would be carried out during a user study, the project team decided to reduce the feedback so that three feedback sets could be created. This would make the user study more efficient and reduce its duration. Reducing the duration of the user study was a major concern as evaluating feedback for a long period of time can be tiring. A tired test participant may loose motivation throughout the study, and therefore have a negative effect on the results.

The three most prominent *next exit* and *next exit error* haptic combinations were chosen and modified in order to increase joystick stability. Two new sound sketches were introduced for the events in order to increase timbre variants. The project team explored the best fit combinations of audio and haptic feedback, and decided which sketches to use through reasoning within the team. An additional *overtake* haptic sketch was created in order to increase variants. This resulted in three complete feedback sets presented in Figure E.7, which were evaluated in the user study.

4.5 Early design

The software created for the strategic controller was continously updated throughout development, as described in the development process of Section 3.1. However, this section will describe the early functionality of the prototype software created for the strategic controller. A flowchart of the program will be presented in Figure 4.5 followed by a step-by-step explanation.

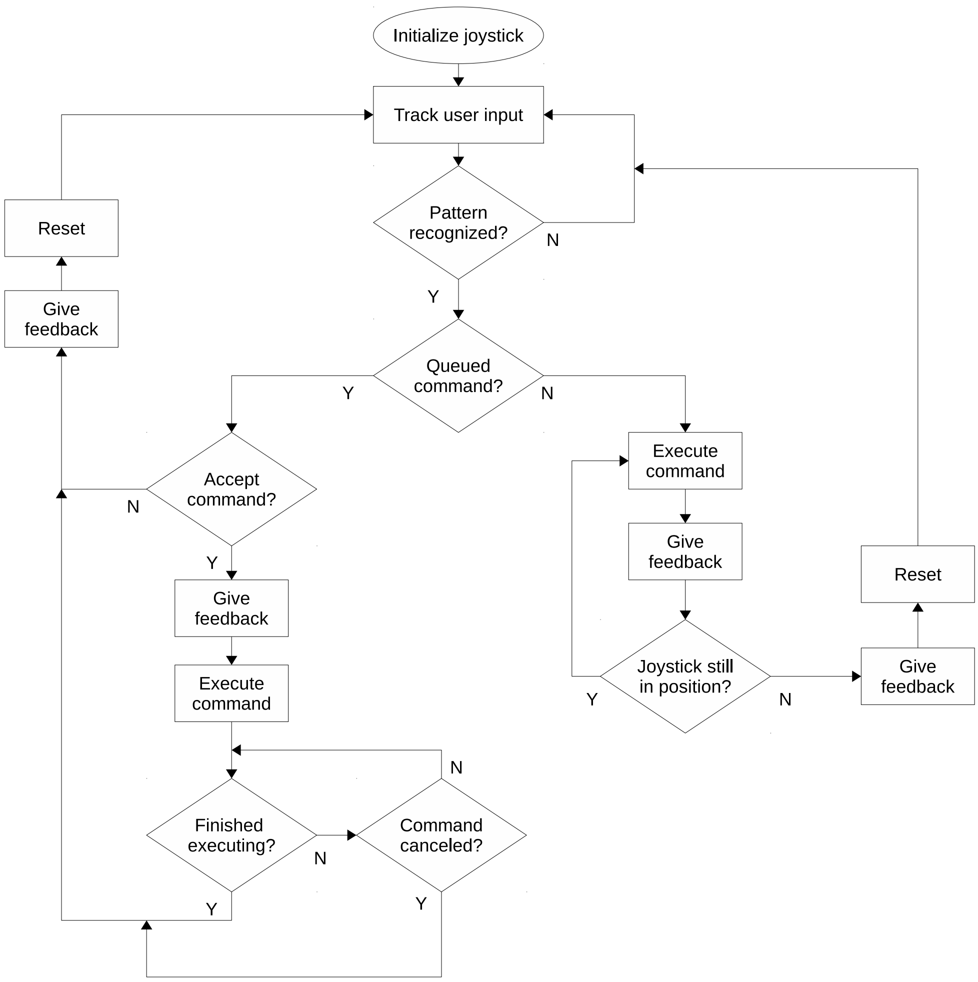


Figure 4.5: A flowchart describing the functionality of the first prototype software written for the strategic controller.

The software starts by initializing the prototype hardware. It then continues by tracking the position of the joystick and compares the movement to the defined patterns associated with each command.

If the pattern is recognized, and if the command is to be performed instantaneously, the command will be executed. This command will be performed continuously as long as the joystick remains in the same position as the pattern for the command ended. Feedback is given periodically to communicate that the command is being performed. However, if the joystick leaves the position, the joystick resets to the center.

On the other hand, if the issued command is an action which is to be placed in the ”queue” such as an overtake; the joystick is locked in the same position as the pattern for the command ended. The strategic controller will either accept or deny the command depending on if it is legal or possible to perform or not. If the issued command is not safe to execute, the user will be given feedback communicating the rejection and the joystick resets, allowing the input of a new command. If the issued command is safe to execute, the strategic controller will communicate the acceptance and perform the command.

An accepted command can be cancelled at any time. This is done by pulling the joystick back to its neutral position (i.e. the center). Feedback is given when the command is cancelled, and the controller resets allowing for new commands to be issued.

The way commands are issued can be seen as a ”queue” consisting of a single command. As such it is not possible to queue multiple commands, the user has to wait for the current command to finish in order to place another command in the ”queue”. Essentially the user can be considered as a backseat driver, giving the chauffeur (the autonomous system) one instruction at a time. Once the command has finished executing, the joystick is reset and the user may issue a new command.

However, major software changes were made after a usability study presented in Section 4.5.1. The performed changes will be presented in Section 4.6.

4.5.1 User study

The goal of the user study was to explore usability issues and evaluate the remaining multimodal feedback sketches. The study consisted of ten test participants and a short summary of their profiles is given below, but complete user profiles can be seen in Appendix F.5.

- The ten test participants all had engineering backgrounds, but their specializations varied.
- Ages ranged from 23 to 32 years old, the sample had an average age 26.7.
- Only one of the ten test participants was female.
- None of the test participant had hearing impairments.
- 60% of the participants had some kind of musical experience.
- 90% of the participants had some kind of experience with haptic feedback such as smartphones/tablets.
- 90% of the test participants had a drivers licence and their driving frequency varied from day-to-day commuting to driving a few times per year.

The duration of the user study was approximately two hours, and resulted in large quantities of data. In order to make sense of the information the project team analysed the data thoroughly. The procedure and the results of the analysis are presented in Section 4.5.1.

Analysis of data

The data from the user study was analysed in order to find the most promising feedback sketches, and identify usability issues.

Quantitative data

The quantitative data was used to find the most promising sketches. An extracted result for feedback event 1, which was denoted as *leaving inner area* will be used as an example throughout the section. Complete results for all sketches can be seen in Appendix F.7.

The scales used in the user study questionnaire ranged from 1 to 5. Depending on the sketch and the attribute a low score was sometimes desired over a high score and vice versa. An extract of the results is shown in Table 4.1 where the desired values for each attribute is located above each attributes column. In addition to rating sketch attributes, the users were asked to vote for a favourite and a least favourite of the three sketches presented for each feedback event. This voting was used to confirm the scores which the project team calculated, complete results of the voting can be seen in Appendix F.6. However, there were situations where users were unable to choose a favourite or least favourite and the total number of votes cast varied between sketches.

Table 4.1: Attributes were compared against each other in order to define priorities.

Leaving inner area	H	L	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	1	1	0	0	3
Arousal	0		0	0	0	0	0
Dominance	0	1		0.5	0	0	1.5
Urgency	0	1	0.5		0	0	1.5
Annoyance	1	1	1	1		1	5
Appropriateness	1	1	1	1	0		4

Once the attributes were compared against each other, they were converted to the 1-10 scale. Then their attribute weight was calculated according to Equation 3.2 which also normalized the weight to 1. An extracted result is given in Table 4.2 and Equation 4.4, where the weight for annoyance in feedback event 1 is calculated.

Table 4.2: The prioritized attributes were converted to a 1-10 scale and their weight was calculated. The calculated weight for annoyance is shown in Equation 4.4.

Scale	**Attribute**	**Weight**
10	Annoyance	0.323
9		
8	Appropriateness	0.259
7		
6	Pleasure	0.194
5		
4		
3	Dominance, Urgency	0.097
2		
1	Arousal	0.033

$$w_{annoyance} = \frac{10}{10+8+6+3+3+1} = 0.323 \tag{4.4}$$

An extract from the results showing the weighed score of feedback event 1 is shown in Table 4.3. The total score of each sketch was obtained by summing up the weighted attribute scores.

Sketch number 3 received the highest score in Table 4.3, and as such fulfils the desires of the project team better than the other sketches.

Table 4.3: A weighted value was calculated for each sketch using the weights for each attribute, and the average value from user ratings.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.194	3.5	0.679	2.7	0.5238	3.7	0.7178
Arousal	0.033	1.8	0.0594	2.5	0.0825	2	0.066
Dominance	0.097	3.5	0.3395	3.5	0.3395	4	0.388
Urgency	0.097	1.8	0.2716	2	0.194	2.3	0.2231
Annoyance	0.323	2.7	0.8721	2.1	0.6783	2.9	0.9367
Appropriateness	0.259	2.9	0.7511	2.5	0.6475	3.1	0.8029
Total score	-	-	2.97	-	2.47	-	3.13

The results obtained in this analysis were then compared with users' opinions of each sketch. The number of times users found a sketch as their favourite or least favourite was quantified and the total votes were calculated as the difference between them (see Table 4.4). The voting results were compared against the weighted score in order to confirm the most suitable sketch.

Table 4.4: The sketch considered as the best by the users was compared with the weighted value of each sketch. As sketch 3 received the highest rating in both cases it was considered the winning sketch for this feedback event.

	Sketch 1	**Sketch 2**	**Sketch 3**
Favourite	4	1	5
Least favourite	3	5	2
Total votes	1	-4	3
Weighted score	2.97	2.47	3.13

In cases where the weighted score was too similar for all three sketches, the user votes were used as the deciding factor. The same procedure was followed for all the commands, complete results can be seen in Appendix F.7 and all the winning sketches are presented in Table 4.5.

Table 4.5: The following winning sketches were obtained by analysing the user ratings and comparing them to user opinions.

Command	**Sketch selected**
Leaving inner area	3
Pattern recognized	3
Command aborted	3
Overtake	3
Next exit	3
Next exit error	3
Stop	3
Change lane	3
Increase/decrease speed	1
Max/min speed	1
Command interrupted	1
Move inside the lane	2

Qualitative data

A final set of sketches had been obtained through the analysis of the user study questionnaire. The qualitative data gathered from observations, interviews and user opinions was analysed using an affinity diagram in order to discover usability issues. The analysis aimed to answer the question:

What are the biggest problems of using a joystick as a strategic controller with audio and haptic feedback?

The complete analysis can be found in Appendix F.8. Three main issues were identified which needed to be solved in order to create a successful joystick-based strategic controller:

1. **Haptic feedback needs to be balanced.**

   If the haptic feedback does not adapt to the user, the user experience will differ from person to person. The issue does not only depend on users having different size and strength, but also because of how the user chooses to grip the joystick. Users who used a firm grip of the joystick while using it had a more pleasant experience of the feedback, as the team had designed the feedback for a firm grip. However, users who did not use a firm grip or who avoided to hold the joystick altogether had an unpleasant user experience. Either the feedback from the joystick was considered violent or they perceived it as something was wrong as the joystick vibrated for no apparent reason.

   Although the used grip has a major effect on the experience, the strength of the haptic feedback still matters. If the haptic feedback is too strong users get the feeling of not being in control of the controller, or that something is not working as it should. As such, too strong haptic feedback should be avoided. In addition, if the user needs to apply a big force to move the joystick they also get the feeling that they are doing something that they should not. This was apparent when users tried to interrupt or cancel a command, and the users needed to pull the joystick back to the center. Due to the strong haptic signals used to lock the joystick in place, several users found it too difficult to perform a cancellation. The strong haptic signals also caused the joystick to become unstable when certain forces were applied simultaneously or when applied with large gains.

2. **Inputting commands needs to be intuitive.**

   Users found the joystick to be similar to a gear stick and expected a similar behaviour. Although some of the patterns were similar to shifting gears with a manual gear box, users felt that some of the input patterns were not intuitive. This was mainly due to the reason of how taking the 2nd or 3rd turn/exit was performed, which consisted of a two part input process.

   There were also inconsistencies between the commands which are queued in the system, and commands which are instantaneous. Users expected commands to be performed in the same fashion, and the inconsistencies also made it difficult to remember the input patterns. The instantaneous commands were also experienced to be difficult to perform. Partially because of the small movements and delays, but also because it was not clear how much of a change one would perform when executing the command. Although the experience may have been different if the user study was carried out in a simulator, the users did not expect the need of moving inside the lane in the first place. Instead, this was expected to be handled by the autonomous car.

3. **Feedback needs to communicate the correct information at the correct time.**

   When feedback was not communicated at the right moment the user would get out of the loop. Issues with the joystick causes it not to reset properly when a pattern had not been recognized. It was already difficult for users to understand when the system was ready for a new command, but this made it even worse. In addition, users did not understand when it would be safe to step out of the car after stopping the vehicle.

Users also had difficulties distinguishing several feedback events. The feedback for *pattern recognized* was associated with *pattern accepted* and users found the feedback for an acceptance to be too similar to a rejection. In general audio feedback also had a bigger impact on the overall user experienced. The audio feedback often had a bigger effect on the users than the haptic feedback. However, some users also became annoyed by the audio feedback after a longer period of testing and expressed the desire to turn it off.

The identified problems were used to improve the prototype software and the multimodal feedback, the changes made by the project team will be presented in Section 4.6.

4.6 Final design

After analysing the data from the user study, improvements to the systems were carried out in order to reduce its complexity and in order to increase the consistency and usability of the concept.

The strategic controller was redesigned to automatically check if commands were safe to execute or not upon initialization. This safety check is also done continuously while the joystick is idle, or when returning to the center after an executed, aborted or interrupted command. The sensitivity of the joystick was also adjusted so that patterns no longer needed to be performed as strict as in earlier version of the prototype. Usability was further increased by reducing the complexity of the controller. Next exit/turn was limited to taking the upcoming exit/turn and the ability to queue 2nd or 3rd exit/turn was removed, as users experienced the command cumbersome and unintuitive.

The idea of instantaneous commands was completely scrapped as users found them difficult and unnatural to perform. Users did not expect the need of moving inside the lane to avoid obstacles such as potholes or to move inside the lane on rural roads. Instead, this was a functionality which the users expected the car to handle by itself. The project team decided to remove the command completely as users considered them redundant. Increase and decrease speed commands were changed and now allows the user to choose between two speed levels; according to the speed limit (maximum speed), or lower than the speed limit (minimum speed). Both levels will only allow the user to drive at legal speeds, the minimum speed will adapt to the surrounding environment. This would allow the user to drive slow enough in order to make navigation decisions in areas where the user has not been before (e.g. residential areas), and go back to maximum speed with little effort.

In order to increase the concept's intuitiveness and consistency, both increase and decrease speed and next exit/turn were changed to work in the same fashion as the other commands. The commands are ”queued” in the system, and once they have been performed the joystick returns to the center. This change also emphasized the team's original idea of splitting the execution of a command into several parts. All commands were now changed to follow a five step execution plan:

1. The user initiates a command by performing a pattern with the joystick.
2. The input is recognized by the system and different signals will be played depending on if the command is safe to execute or not. A safe command will lock the joystick in place, and an unsafe command will play the rejection feedback.
3. If the command is safe to execute, the command is placed in the ”queue” and the car will execute the command when the car is ready. While a command is placed in the queue, the command can be interrupted by the user as long as it has not been executed.

4. The command is executed and it is no longer possible to interrupt the command.
5. The joystick returns to center and awaits further instructions.

The winning feedback sketches previously presented in Table 4.5 were modified in order to comply with the identified issues, which resulted in several feedback events being redesigned.

Users found the sound used to communicate the initiation of a command to be annoying and did not find multimodal feedback to be necessary for this event. As such, the sound for this event was removed and the haptic feedback was slightly modified in order to give a more distinct feeling and compensate for the loss of sound. The feedback used for pattern recognition was also simplified. Vibrations were completely removed and only static haptic signals are used (i.e. locking the joystick in place). This was done to reduce annoyance and create a more uniform feedback, but also to create a bigger difference between acceptance and rejection. In addition, the direction of the haptic signal used for abort/reject was modified in order to give the same haptic feeling for all commands.

The interruption feedback was considered annoying and aggressive by 50% of the users, and as an interruption was something carried out by the user, vibrations were considered redundant by the test participants. In order to comply with the user opinions a new sketch was created without vibrations. Users also found it too hard to move the joystick back to the center, so they were not confident to perform the command. The force levels used for locking the joystick in place were reduced to make it easier to perform the cancellation.

The pulses applied while stopping the car were removed, as users could not understand the meaning of them and found them a bit annoying. Speech was added to let the user know when the car is completely stopped and it is safe to leave the car. In addition, speech was added for all commands which was to be played when the car is executing the command. A high quality text-to-speech synthesis engine by *Acapela Group (Sharon, US English)* was used to replace the previous speech which test participants found too robotic. The following verbal feedback was created:

- Cancelled.
- Changing to left/right lane.
- Driving at minimum/maximum speed.
- Overtaking.
- Stopping.
- Stopped.
- Turning left/right.

Users also had problems knowing when the system was ready to accept a new command. This was caused by the joystick not resetting properly after a command had been executed, but also due to a software bug which caused the joystick not to reset properly when a pattern was not recognized. Additional feedback was created in order to keep the user in the loop, and the feedback is played when the controller is ready for a new command. The same type of pulse which was used for the initiation of a command was used together with the old audio previously used for the same feedback event.

Several input patterns were changed or removed after the system improvements had been carried out, the new input patterns and their use cases are shown in Appendix A.2.

In order to thoroughly explain the prototype software created for the strategic controller, a flowchart of the program is presented in Figure 4.6 followed by a step-by-step explanation.

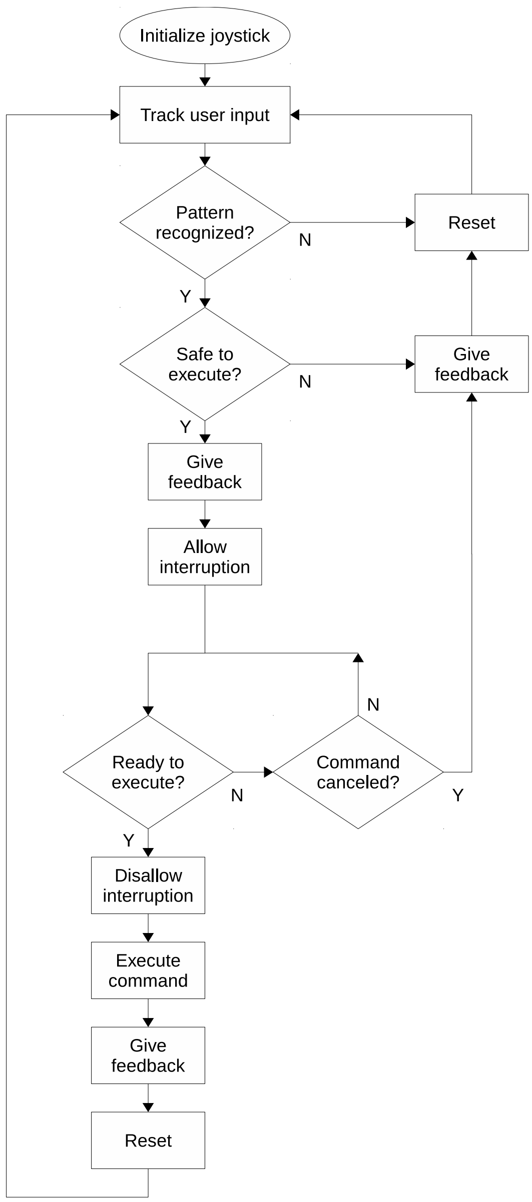


Figure 4.6: A flowchart describing the functionality of the final prototype software written for the strategic controller.

The software starts by initializing the prototype hardware. It then continues by tracking the position of the joystick and compares the movement to the defined patterns associated with each command. If the pattern is not recognized, the joystick returns to the center and awaits new input from the user.

On the other hand, if the pattern is recognized, the strategic controller will compare the command against a rule set which describes which commands that are safe to execute at the moment. This rule set is supposed to act as a mock-up for analysed sensor and image data which the car would be collecting while driving . The rule set continuously updates while driving and also considers traffic rules, regulations and hazards. If the issued command is not safe to execute, the user will be given feedback communicating the rejection and the joystick resets, allowing the input of a new command. If the issued command is safe to execute, the strategic controller will communicate the acceptance and lock the joystick in place.

An accepted command can be cancelled while waiting for the car to execute the command. This is done by pulling the joystick back to its neutral position (i.e. the center). Feedback is given when the command is cancelled, and the controller resets allowing for new commands to be issued. In the same way as in the first prototype (see Section 4.5) , the way commands are issued can be seen as a "queue" consisting of a single command. As such it is not possible to queue multiple commands, the user has to wait for the current command to finish in order to place another command in the "queue". Essentially the user can be considered a backseat driver, giving the chauffeur (the strategic controller) one instruction at the time.

Once the command is ready to be executed, interruptions are forbidden and the user needs to wait until the car has finished the command. As such, the user will not be able to move the joystick to the center and interrupt the command. The reason for this is to increase vehicle and traffic safety. When the execution is initialized, feedback is given in order to update the user on what the car is doing. Once the command has finished executing, the joystick is reset and the user may issue new commands.

4.6.1 Simulator study

The goal of the simulator study was to evaluate the usability of the concept and create a benchmark for similar and future concepts. The study consisted of five test participants, and a short summary of their profiles is given below. Complete user profiles can be seen in Appendix G.5.

- The youngest participants were aged between 18-30 and the oldest between 61-70 years old.
- 60% of the test participants were female.
- All participants had driving license, their driving frequency varied from day-to-day commuting to driving a few times per year.
- 60% of the participants had some previous experience with simulators.
- 60% of the users play computer games a few times per year.
- 80% of the participants had experience with driver assistance systems and found them useful.
- 80% of the participants would like to have a car that drives by itself but also have the opportunity to influence the decision it makes. The other 20% partially agree with this.
- 40% of the test participants completely trusts an autonomous vehicle. The other 60% only partially trust it.

The duration of the simulator study was approximately half an hour per participant, and resulted in large quantities of data. In order to make sense of the information the project team analysed the data thoroughly. The procedure and the results of the analysis is presented in Section 4.6.1.

Analysis of data

The data from the simulator study was analysed in order to evaluate user experience.

Quantitative data

The quantitative data was used to benchmark the concepts usability using UEQ. The attribute scores obtained from test participants, as shown in Appendix G.6, were transformed in order to make statistical calculations. The transformed data was used to calculate the concepts attractiveness, perspicuity, efficiency, dependability, stimulation and novelty. The average scales as rated by the test participants are presented in Table 4.6.

Table 4.6: The average scales as rated by the test participants on a scale range of -3 to +3.

Attractiveness	1.93
Perspicuity	1.85
Efficiency	1.55
Dependability	1.55
Stimulation	1.45
Novelty	0.70

In order to get a better understanding of the data, the results are visualized in Figure 4.7. Calculations of confidence intervals for items and scales are presented in Appendix G.6.

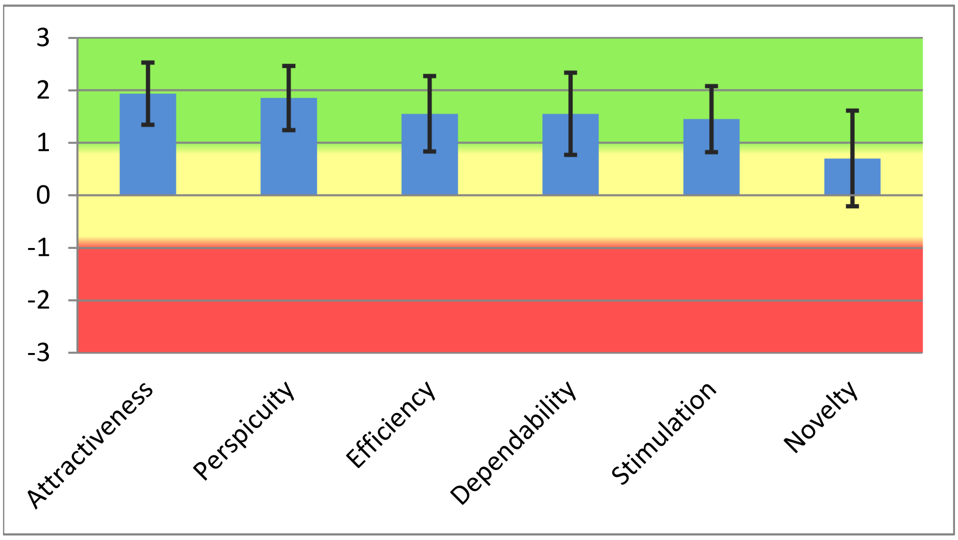


Figure 4.7: The average scales as rated by the test participants visualized with standard deviations.

However, as UEQ is not designed to create a score for user experience it may not be appropriate to draw conclusions from average scales alone. As such, the data was also used to create a comparison using the UEQ benchmark tool. This allowed conclusions about the relative quality of the evaluated concept to be made in comparison to other products. The results of the benchmark are presented in Table 4.7 and visualized in Figure 4.8.

Table 4.7: Results in comparison to the UEQ benchmark.

Scale	Mean	Comparisson to benchmark	Interpretation
Attractiveness	1.93	Excellent	In the range of the 10% best results
Perspicuity	1.85	Excellent	In the range of the 10% best results
Efficiency	1.55	Good	10% of results better, 75% of results worse
Dependability	1.55	Good	10% of results better, 75% of results worse
Stimulation	1.45	Above Average	10% of results better, 75% of results worse
Novelty	0.70	Above Average	25% of results better, 50% of results worse

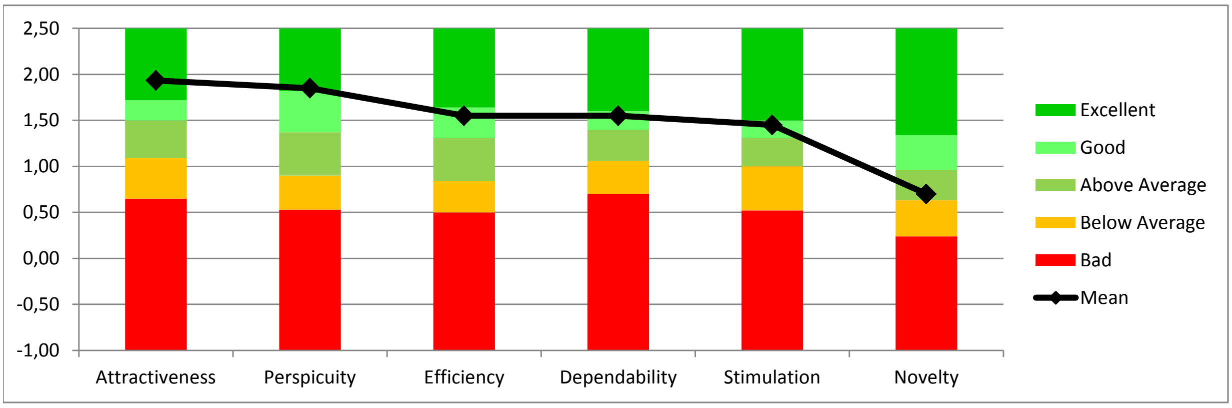


Figure 4.8: Scales visualized in comparison to the UEQ benchmark.

Qualitative data

The qualitative data was gathered from interviews where camera footage was used in order to explain events which occurred during the experiment. The analysis aimed to answer the question:

How do users experience autonomous driving using a strategic controller with audio and haptic feedback?

The complete analysis can be found in Appendix G.7. Five reasons describing the users' positive and negative experiences in the simulator study were identified:

- **Autonomous driving was found to be futuristic.** Some users found it hard to imagine how the concept would work in reality outside of the simulator environment. As such, users may need time to grasp autonomous driving.
- **Users are willing to use the system.** Users found that the strategic controller was cooperative, and found that the controller was supportive of their actions. They also appreciated the ability to influence the control of the vehicle.
- **Users get out of the loop.** As all commands are queued in the system, there were situations where certain commands were in queue for longer periods of time. One example is overtake, where oncoming traffic delayed the command. This caused users to become unsure if the input command was correct and made them wonder if something was wrong with the system. Users also expected that the car cancels commands which become redundant after being in queue for too long.
- **Using the joystick is easy and it works as expected.** Users did not find the joystick innovative, but felt a familiar feeling when using the joystick to instruct the car. On the other hand users found the commands to be well defined and easily learned the patterns for all commands. Users also felt that the available commands were sufficient and covered their basic and expected needs.
- **The strategic controller simplifies the driving process.** The general user opinion was that autonomous driving reduced the mental workload during the driving process. The car was able to make complex decisions and appreciated the ability to issue commands such as overtake and turn left/right, which otherwise requires the user to focus on the traffic. The strategic controller relieved the users from a somewhat monotonous driving process on the freeway in the simulator, and users expressed their interest in having the

same experience during for their daily commute to and from work. Driving autonomously was described as a relaxing process and users easily became bored inside the simulator.

5. Conclusions

Eleven feedback events were identified and over 250 combinations of multimodal feedback were created per command. The team systematically reduced the number of haptic and audio sketches, which resulted in three combinations per command prior to the user study. The user study the final evaluation for the feedback and a final set of combinations were obtained from it.

In general the multimodal feedback was appreciated by all of the test participants in the user study. All participants agreed that multimodality helped with understanding the information communicated by the feedback. However, it was noted that audio signals often had a bigger effect on the users compared to haptic signals in many occasions. This does not comply with theory which suggests that there is no predominance in the multi sensory relation of haptic and audio signals (Hecht and Reiner, 2009). The information gathered by the user study was utilized to identify usability issues of varied severities. System improvements were carried out in order to improve the usability of the concept, some feedback signals were changed and the prototype software was modified according to the usability issued found. The improved system was validated and benchmarked in a simulator study.

Test participants of the simulator study found the joystick to be easy to use, and that the strategic controller worked as they expected. Although autonomous driving was considered futuristic, users would be willing to use such a system in their daily commuting to and from work. The results from the simulator study was benchmarked using UEQ and promising results were obtained. The system was easy to understand and the test participants were attracted to the concept. Test participants also believe that they could trust and depend on the strategic controller which simplified their driving experience. However, the HMI was not considered to be innovative and some users found the system to be dull.

5.1 Discussion

Haptic and audio feedback sketches were designed and evaluated separately before being combined into multimodal feedback. This was done as the number of possible combinations were too big and evaluating all of them would have been very time consuming. However, discarding sketches early in development may also have resulted in that promising multimodal combinations were lost. In addition, the self evaluation method used to rate signals was purely based on the subjective thoughts of the project team. However, this evaluation method was used as we did not have any requirements to which sketches could be compared against. Involving users earlier in the process would be ideal, but also very time consuming due to the number of sketches that required evaluation. It also needs to be pointed out that none of the team members had previous experience in haptic or audio design. If we were more experienced we could have eliminated bad ideas earlier in the process without the need of evaluations, and possibly involve users earlier in the process with a smaller number of sketches. However, we do believe that the sketch, analyse and improve process used in this project certainly had a positive effect on multimodal feedback design. We believe it was suitable for both audio and haptic feedback design, and we also believe it may be applicable for other modalities as well.

An iterative design process was used for feedback design in this thesis. Although improvements were planned to be carried out after each evaluation, this was not always the case. Several sketches remained the same over the iterations as they were considered to be better than average. Although the project team had planned and developed the feedback thoroughly, users still had issues with understanding what the feedback was trying to tell them. The confusion was caused by two feedback events being too similar to distinguish or when consecutive multimodal feedback was played. Such issues would cause the users to get out of the loop, as the communication between the user and the vehicle was insufficient. Although such issues were identified and corrected after the user study, the team wanted to perform another iteration in order to improve the feedback further. However, due to the tight time schedule the team needed to prepare for the simulator study and the second iteration was cancelled. As a consequence of this it was later discovered in the simulator studies, that the acceptance and rejection feedback were still difficult to distinguish between. We believe the reason for this was that the auditory feedback used pitch changes to communicate acceptance and rejection. As audio was found more dominant than haptic signals, some users would have difficulties noticing the difference in pitch. We believe that this caused the confusion as the haptic feedback was easy to distinguish; the joystick either vibrated (rejection) or was simply locked in place (acceptance).

As the joystick causes hand-transmitted vibrations, the probabilities of developing HAVS should be taken into account. However, there are no values available to calculate the eight hours energy equivalent $A(8)$ for this application. According to theory, in over 50% of the cases HAVS did not develop until exposure of more than 8000 hours of vibrations. As such, the risk of developing HAVS can then be disregarded, as the vibrations applied are sporadic and of short duration. However, the range of frequencies used to create strong haptic signals for the joystick did not match the range which literature suggest, which are frequencies within the range 200-400 Hz. Instead, it was found that frequencies within the range of 3-25 Hz had a stronger feeling. The reason for this could be due to the way the forces are transmitted from the DC motors to the joystick.

Hardware modifications were performed on the joystick in order to adapt it for the use as a strategic controller. After the modifications the joystick's motors were approximately twice as strong, which caused the joystick to become unstable if big forces were applied. This problem could had been solved if the internal controller of the joystick would have been accessible and possible to recalibrate. Nevertheless, instability was also caused because there was a backlash in the mechanics on the x-axis. Due to time restrictions these issues were not further investigated and forces were tuned down in order to increase joystick stability. This workaround solved the stability issues, but it also made the haptic feedback suffer.

Originally the simulator study conducted for this thesis was planned to include ten test participants, but only five were included in the results. The simulator study was conducted simultaneously as other AIMMIT related studies. The study conducted for this thesis was incorporated into the other studies so that all parties could gather the desired data. The goal of AIMMIT's study was to explore different multimodal HMI concepts, by comparing the concept developed by this thesis against two other thesis concepts. As such the study was designed together with AIMMIT and the same simulator scenario and interview questions were used for both studies. However, half of the test participants started by evaluating the concept developed in this thesis, and the other half had used one of the other concepts prior to the experiment. The results obtained from the test participants which had already been familiarized with autonomous driving, and used another strategic controller concept was too difficult to compare to the other results. As it would be difficult to draw a conclusion from the studies if these results had been merged together, a decision was made to exclude them from the thesis. Although the results would have been better with a larger sample size, five test participants are still sufficient to create comprehensive conclusions, as mentioned in Section 3.3.

Theory suggests that for research purposes, simulators often only needs to be similar to the vehicle and the task it simulates. However, some of the test participants found the simulator environment to be poor. It is possible that the lack of face validity caused test participants to score the concept too positive or negative, and the end results may have been affected. Although the general view of the concept was positive and users would appreciate such car functionality in their daily lives, some users considered the HMI to be dull. We believe that this does not necessarily need to be something negative, but rather something which can be turned into a positive feature of the concept. As the joystick movements are similar to gear shifting it does not impose a major change in how we interact with the vehicle. As such, we believe that the concept may be easier for people for accept compared to a concept of higher novelty, especially for the older generation. However, there are still issues of users getting out of the loop which need to be solved before market introduction.

5.2 Future work

During the development of the feedback signals, the team realized that the haptic feeling will be different depending on how the user grips the joystick when inputting commands. This was also confirmed in the user study where some users experienced the forces too strong while for others the same forces were too weak. One way of solving this issue could be to use several haptic settings, so that the user can choose the one that suits him or her the best. However, it was also observed that users do not always grip the joystick in same manner. If the joystick is not gripped at all the user experience will suffer, as the joystick is vibrating for no apparent reason. In order to achieve a premium feeling the project team suggest to use sensors which adjust the haptic signals according to the users grip. This would add complexity to the system, both on the hardware and software, but would provide a more pleasant user experience.

Another big issue which was discovered during the user study is the fact that some users found the sounds annoying after a while and expressed their desire to mute the sounds after they learn how the system works. This is an option that needs to be considered for the future if ever fully implemented in a car. However, as one modality is disabled the feedback will suffer which may cause the user to get out of the loop.

Finally, some user were confused when a command was rejected because no reason for the rejection was given. Users requested to get this information either visually or through verbal feedback. One possible solution is to utilize a status window close to the speedometer gauge, such as the one being utilized for service prompts and other car related status messages. This could also be a good place to show which command the user has queued with the joystick. Verbal feedback could also be investigated, but we believe it will increase annoyance and several users already wanted to disable the sound.

No study regarding the input patterns of the strategic controller was performed during this thesis. As such it may be possible to improve the input patterns and increase the usability of the concept. However, the results obtained from both the user study and the simulator study seem to indicate that the pattern used are intuitive and easy to perform. The studies conducted in this thesis also identified several usability issues. Many of them were solved by improving the software and the feedback of the strategic controller. However, due to hardware restrictions the desired haptic feedback could not be designed. As such, the concept's full potential could not be achieved. Future prototypes should therefore consider investing in customized hardware in order to achieve an even better usability and feedback efficiency.

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A. Use cases and patterns

A.1 Initial use cases and patterns

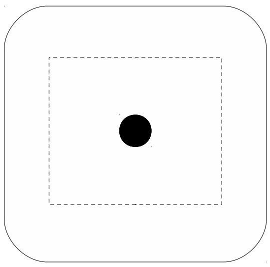


Figure A.1: **Inner area**. The joystick is idle in the center position. When idle, the performance level of the strategic controller is communicated through the joystick. If the technology facilitating the autonomous system is in order, firm haptic feedback will be applied to the joystick. However, if minor issues arise which affect the technology such as a sensor not being clean enough to give stable values, the joystick will feel loose which intends to communicate the issue. In such situations the user could manually disable AD mode if necessary, or be asked to take over control. This feedback is applied in the joysticks inner area. When the border of the inner area is passed, the sensation of overcoming a ”ridge” is communicated by the haptic feedback. This is to alert the user that a command is being initiated.

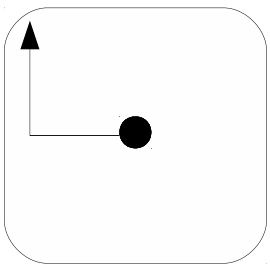


Figure A.2: **Overtake**. The joystick is idle in the center position. An overtake is issued by moving the joystick to the left and upwards to the upper left corner. The recognition of the command is communicated by locking the joystick in place and a confirmation pulse.

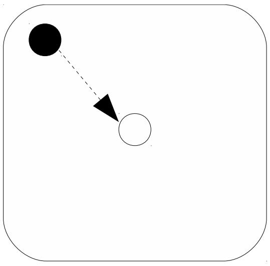


Figure A.3: **Cancel**. An accepted command will lock the joystick in place. In order to cancel a command the joystick is pulled to the center. Feedback is played in order to communicate the cancellation. The figure shows how to cancel an overtake.

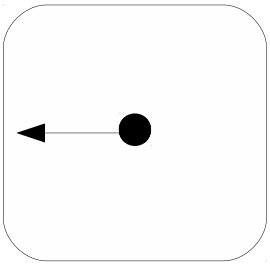


Figure A.4: **Change to left lane**. The joystick is idle in the center position. Changing to the left lane is carried out by moving the joystick to the left edge and holding it in place for 3 seconds. The delay is a safety feature; so that the user does not change lane by accident, it also allows other patterns to be performed at a slower pace. The recognition of the command is communicated by locking the joystick in place and a confirmation pulse.

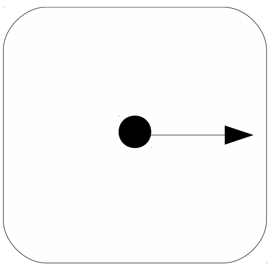


Figure A.5: **Change to right lane**. The joystick is idle in the center position. Changing to the right lane is carried out by moving the joystick to the right edge and holding it in place for 3 seconds. The delay is a safety feature; so that the user does not change lane by accident, it also allows other patterns to be performed at a slower pace. The recognition of the command is communicated by locking the joystick in place and a confirmation pulse.

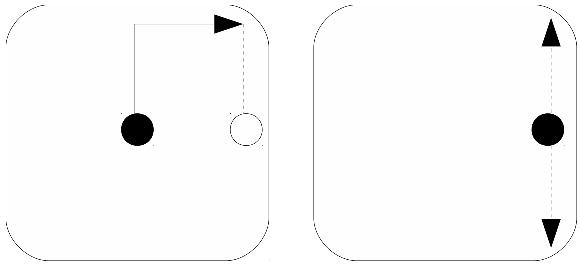


Figure A.6: **Take a turn ahead to the right**. The joystick is idle in the center position. To initiate a right hand turn the joystick is moved up and then to the right corner. The joystick will drop down to the middle position, where the user can increment or decrement the turn which the user desires to take. An increment is carried out by moving the joystick up, and a decrement is carried out by moving the joystick down. The joystick will automatically return to the middle position after an increment or decrement. If no increments or decrements are performed, the command defaults to the first turn on the right. The user can choose between the 1st to the 3rd turn ahead, e.g. moving the joystick upwards one time after initiating the command will select the 2nd turn on the right. The user has 5 seconds to increment or decrement the number of exits before the command defaults to the 1st turn. If an increment or decrement is issued, the timer will refresh, giving the user 5 additional seconds before the command is accepted. Feedback is used to communicate the incremental and decremental changes, and the joystick is locked in place once the command has been accepted.

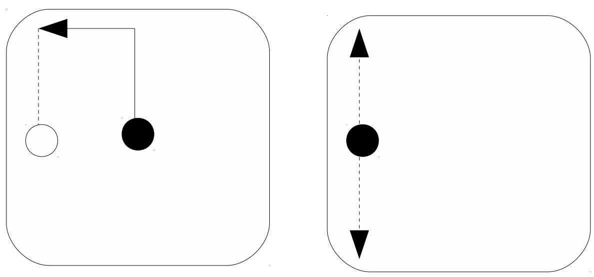


Figure A.7: **Take a turn ahead to the left**. The joystick is idle in the center position. To initiate a left hand turn the joystick is moved up and then to the left corner. The joystick will drop down to the middle position, where the user can increment or decrement the turn which the user desires to take. An increment is carried out by moving the joystick up, and a decrement is carried out by moving the joystick down. The joystick will automatically return to the middle position after an increment or decrement. If no increments or decrements are performed, the command defaults to the first turn on the left. The user can choose between the 1st to the 3rd turn ahead, e.g. moving the joystick upwards one time after initiating the command will select the 2nd turn on the left. The user has 5 seconds to increment or decrement the number of exits before the command defaults to the 1st turn. If an increment or decrement is issued, the timer will refresh, giving the user 5 additional seconds before the command is accepted. Feedback is used to communicate the incremental and decremental changes, and the joystick is locked in place once the command has been accepted.

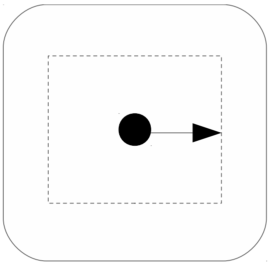


Figure A.8: **Move to the right inside the lane**. Instantaneous commands such as moving inside the lane are carried out without leaving the inner area. The joystick is moved to the right and held in position for 2 seconds. This will execute the command and continuously issue the command while the joystick is held in position. Feedback is played periodically as long as the command is being issued.

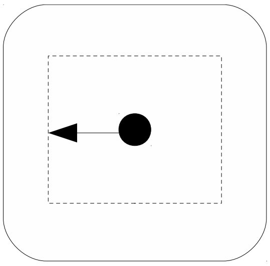


Figure A.9: **Move to the left inside the lane**. Instantaneous commands such as moving inside the lane are carried out without leaving the inner area. The joystick is moved to the left and held in position for 2 seconds. This will execute the command and continuously issue the command while the joystick is held in position. Feedback is played periodically as long as the command is being issued.

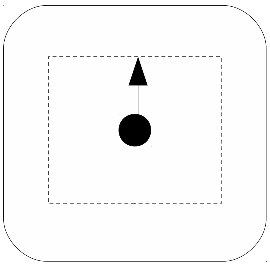


Figure A.10: **Increase speed**. Instantaneous commands such as increasing speed are carried out without leaving the inner area. The joystick is moved upwards and held in position for 2 seconds. This will execute the command and continuously issue the command while the joystick is held in position. Feedback is played periodically as long as the command is being issued.

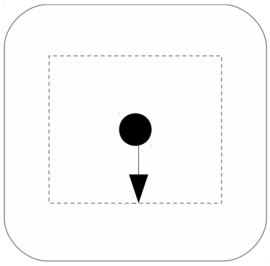


Figure A.11: **Decrease speed**. Instantaneous commands such as decreasing speed are carried out without leaving the inner area. The joystick is moved downwards and held in position for 2 seconds. This will execute the command and continuously issue the command while the joystick is held in position. Feedback is played periodically as long as the command is being issued.

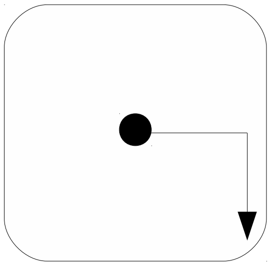


Figure A.12: **Stop**. The joystick is idle in the center position. To initiate a stop the joystick is moved to the right and then to the lower right corner. The joystick is locked in place if the command is accepted and periodical feedback will be played while the car is reducing speed and until the car has stopped.

A.2 Improved use cases and patterns

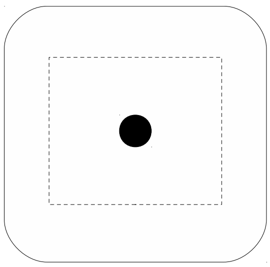


Figure A.13: **Inner area**. The general idea of the inner area was kept the same, however the haptic feedback and the sensation of the "ridge" was improved.

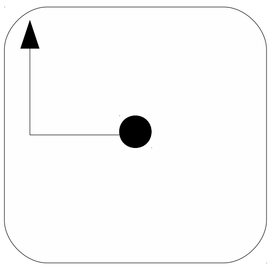


Figure A.14: **Overtake**. The pulse used for the confirmation was removed, but the joystick is still locked in place.

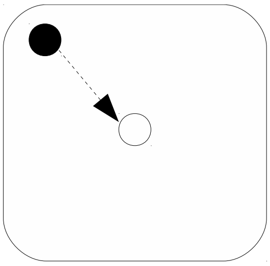


Figure A.15: **Cancel**. The haptic feedback was removed in accordance with user requests.

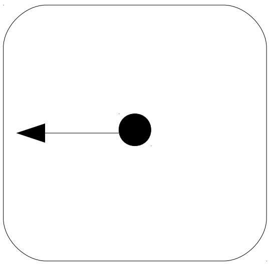


Figure A.16: **Change to left lane**. The pulse used for the confirmation was removed, but the joystick is still locked in place.

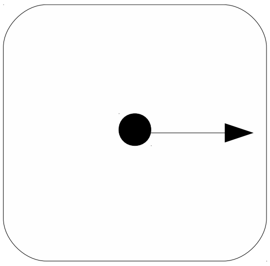


Figure A.17: **Change to right lane**. The pulse used for the confirmation was removed, but the joystick is still locked in place.

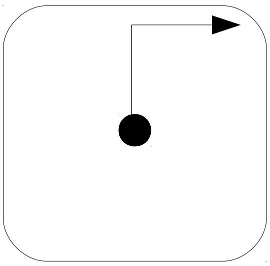


Figure A.18: **Take the next to the right**. No changes were made to the command's initial pattern. However, the use case was simplified and it is now only possible to take the first upcoming turn. As such, the previous middle position was removed and the pattern ends in the upper right corner. The joystick is locked in place when the command is accepted.

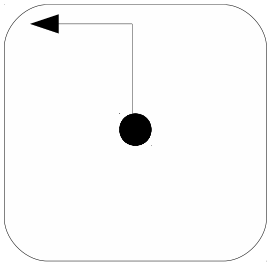


Figure A.19: **Take the next exit to the left**. No changes were made to the command's initial pattern. However, the use case was simplified and it is now only possible to take the first upcoming turn. As such, the previous middle position was removed and the pattern now ends in the upper left corner. The joystick is locked in place when the command is accepted.

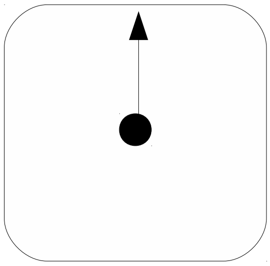


Figure A.20: **Increase speed**. The command was changed in order to work in a similar fashion as the other commands. The joystick is idle in the center position. To increase speed the joystick is moved to the upper edge and held in place for 3 seconds. The delay is a safety feature; so that the user does not increase speed by accident, it also allows other patterns to performed at a slower pace. Issuing the command will lock the joystick in place and make the car accelerate to maximum speed, i.e. to the allowed speed limit. The maximum speed is automatically adjusted in case of bad weather or other hazardous conditions.

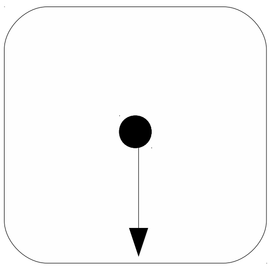


Figure A.21: **Decrease speed**. The command was changed in order to work in a similar fashion as the other commands. The joystick is idle in the center position. To decrease speed the joystick is moved to the downward edge and held in place for 3 seconds. The delay is a safety feature; so that the user does not decrease speed by accident, it also allows other patterns to performed at a slower pace. Issuing the command will lock the joystick in place and make the car decelerate to minimum speed according to the allowed speed limit and traffic conditions. The minimum speed is automatically adjusted in case hazardous conditions.

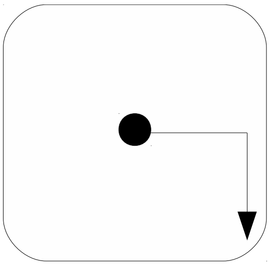


Figure A.22: **Stop**. No changes were made to the commands pattern. However, the previous periodical feedback was removed.

B. Brand analysis

Table B.1: A compiled list of attributes which describe Volvo Cars brand identity.

Scandinavia	Nature	Family	Safety	Ecological
Life	Love	Warmth	Protection	Functional
Present	Sweden			

Figure B.1: The imageboard used as creative guidance throughout the feedback design process.

C. Haptic sketches

This section will present the created haptic sketches and the evaluation results.

Table C.1: Characteristics of the initial haptic sketches. Three sketches of each type of wave were created for each command.

	Sine			Square			Triangle			Sawtooth		
Command interrupted	M=5000 P=17Hz D=0.5s	M=5000 P=10Hz D=0.4s	M=6000 P=12Hz D=0.6s	M=5000 P=17Hz D=0.5s	M=5000 P=10Hz D=0.4s	M=2000 P=5Hz D=1s	M=4000 P=17Hz D=0.5s	M=5000 P=10Hz D=0.6s	M=6000 P=3Hz D=0.9s	M=5000 P=17Hz D=0.5s	M=5000 P=20Hz D=0.6s	M=4500 P=5Hz D=0.6s
Command rejected	M=5000 P=18Hz D=0.44s	M=7000 P=10Hz D=0.4s	M=10000 P=12.5Hz D=0.32s	M=4000 P=18Hz D=0.44s	M=7000 P=10Hz D=0.4s	M=10000 P=11Hz D=0.27s	M=4000 P=18Hz D=0.44s	M=7000 P=10Hz D=0.5s	M=10000 P=11Hz D=0.27s	M=4000 P=18Hz D=0.44s	M=7000 P=10Hz D=0.5s	M=10000 P=11Hz D=0.36s
Increase/decrease speed	M=8000 P=17Hz D=0.001s	M=5000 P=5Hz D=0.1s	M=7000 P=5Hz D=0.2s	M=10000 P=17Hz D=0.001s	M=5000 P=5Hz D=0.1s	M=4000 P=10Hz D=0.1s	M=10000 P=17Hz D=0.002s	M=5000 P=5Hz D=0.1s	M=4000 P=10Hz D=0.1s	M=10000 P=17Hz D=0.002s	M=5000 P=5Hz D=0.3s	M=4000 P=10Hz D=0.1s
Max/min speed	M=1000 P=17Hz D=0.54s	M=2000 P=20Hz D=0.5s	M=3000 P=25Hz D=0.4s	M=1000 P=17Hz D=0.54s	M=2000 P=20Hz D=0.5s	M=3000 P=25Hz D=0.4s	M=1000 P=17Hz D=0.48s	M=2000 P=20Hz D=0.5s	M=3000 P=25Hz D=0.4s	M=5000 P=17Hz D=0.48s	M=2000 P=20Hz D=0.25s	M=3000 P=25Hz D=0.4s
Move inside the lane	M=8000 P=17Hz D=0.001s	M=5000 P=5Hz D=0.5s	M=8000 P=12Hz D=0.255s	M=6000 P=17Hz D=0.001s	M=3000 P=5Hz D=0.05s	M=2000 P=5Hz D=0.2s	M=8000 P=17Hz D=0.001s	M=3000 P=20Hz D=0.1s	M=2000 P=5Hz D=0.2s	M=10000 P=17Hz D=0.001s	M=7000 P=20Hz D=0.1s	M=5000 P=10Hz D=0.1s
Lock in a corner	M=10000 P=5Hz D=0.1s	M=10000 P=10Hz D=0.4s	M=10000 P=12Hz D=0.17s	M=10000 P=5Hz D=0.1s	M=10000 P=10Hz D=0.4s	M=10000 P=12Hz D=0.17s	M=10000 P=20Hz D=0.4s	M=10000 P=5Hz D=0.6s	M=10000 P=12Hz D=0.34s	M=10000 P=10Hz D=0.4s	M=10000 P=5Hz D=0.4s	M=10000 P=12Hz D=0.34s
Lock in the middle	M=10000 P=5Hz D=0.1s	M=10000 P=10Hz D=0.4s	M=10000 P=12Hz D=0.17s	M=10000 P=5Hz D=0.1s	M=3000 P=10Hz D=0.4s	M=3000 P=12Hz D=0.17s	M=10000 P=5Hz D=0.1s	M=3000 P=10Hz D=0.4s	M=3000 P=12Hz D=0.17s	M=8000 P=5Hz D=0.1s	M=5000 P=10Hz D=0.4s	M=5000 P=17Hz D=0.12s
Increase/decrease number of exit	M=7000 P=10Hz D=0.05s	M=7000 P=17Hz D=0.12s	M=7000 P=12Hz D=0.5s	M=7000 P=10Hz D=0.5s	M=7000 P=17Hz D=0.12s	M=7000 P=5Hz D=0.2s	M=9000 P=10Hz D=0.05s	M=7000 P=17Hz D=0.12s	M=7000 P=5Hz D=0.2s	M=10000 P=10Hz D=0.2s	M=8000 P=17Hz D=0.12s	M=7000 P=5Hz D=0.2s
Max/min exit	M=1000 P=20Hz D=0.75s	M=10000 P=17Hz D=0.5s	M=10000 P=10Hz D=0.4s	M=1000 P=20Hz D=0.75s	M=8000 P=12.5Hz D=0.17s	M=1000 P=11Hz D=0.72s	M=5000 P=20Hz D=0.1s	M=1000 P=12.5Hz D=0.17s	M=1000 P=11Hz D=0.72s	M=3000 P=20Hz D=0.15s	M=1000 P=12Hz D=0.17s	M=1000 P=11Hz D=0.72s
Stop	M=3000 P=17Hz D=0.5s	M=5000 P=5Hz D=0.5s	M=5000 P=12Hz D=0.5s	M=3000 P=17Hz D=0.5s	M=6000 P=5Hz D=0.1s	M=5000 P=12Hz D=0.5s	M=6000 P=17Hz D=0.5s	M=6000 P=5Hz D=0.1s	M=5000 P=12Hz D=0.5s	M=4000 P=17Hz D=0.48s	M=6000 P=5Hz D=0.1s	M=5000 P=12Hz D=0.5s

Table C.2: Sketches were evaluated by the team members. The sketches rated ≥ 3.5 were considered good (marked in grey). If any command had less than four sketches considered good, then some of the sketches rated 3 were improved (marked in blue).

	Sine			Square			Triangle			Sawtooth		
Command interrupted	4	3	3,5	2,5	2	1,5	4	3	2,5	3,5	2,5	2,5
Command rejected	3,5	1,5	3	3	2	2,5	3	2,5	2	2,5	2	2,5
Increase/decrease speed	3,5	3,5	2,5	3	2	2,5	1,5	2	3	2	1,5	3
Max/min speed	3,5	2,5	4,5	1	2	3	3	2	2	1	2,5	3,5
Move inside the lane	4	2,5	1	3,5	2,5	1	2	2,5	3	2,5	1	1,5
Lock in a corner	4,5	1,5	2	3	2	2,5	1,5	2	1,5	2	2,5	1,5
Lock in the middle	2,5	1	1,5	2,5	2,5	3,5	3	1,5	3	3,5	2	4
Increase/decrease number of exit	2	1,5	1	3,5	3,5	3	3	3	2,5	3	4	2,5
Max/min exit	1	1	1	1,5	2	2,5	2	2	2	2,5	3,5	3
Stop	2	2,5	3,5	1,5	3,5	2,5	2	3	2	1	2,5	2

Table C.3: Characteristics of the haptic sketches after the self evaluation and the performed improvements.

	Sine			Square			Triangle			Sawtooth		
Command interrupted	M=5000 P=17Hz D=0.5s		M=6000 P=12Hz D=0.6s				M=4000 P=17Hz D=0.5s			M=5000 P=17Hz D=0.5s		
Command rejected	M=5000 P=18Hz D=0.44s		M=6000 P=12.5Hz D=0.32s	M=2000 P=18Hz D=0.33s			M=6000 P=15Hz D=0.52s					
Increase/decrease speed	M=8000 P=17Hz D=0.001s	M=5000 P=5Hz D=0.1s		M=10000 P=17Hz D=0.003s					M=3000 P=10Hz D=0.05s			
Max/min speed	M=1000 P=17Hz D=0.54s		M=3000 P=25Hz D=0.4s				M=1000 P=17Hz D=0.24s					M=3000 P=25Hz D=0.4s
Move inside the lane	M=8000 P=17Hz D=0.001s			M=6000 P=17Hz D=0.001s					M=5000 P=5Hz D=0.2s			
Lock in a corner	M=10000 P=5Hz D=0.1s			M=10000 P=3Hz D=0.2s								
Lock in the middle						M=3000 P=12Hz D=0.17s	M=9000 P=5Hz D=0.1s			M=8000 P=5Hz D=0.1s		M=5000 P=17Hz D=0.12s
Increase/decrease number of exit				M=7000 P=10Hz D=0.5s	M=7000 P=17Hz D=0.12s				M=5000 P=5Hz D=0.2s		M=8000 P=17Hz D=0.12s	
Max/min exit											M=1000 P=12Hz D=0.17s	M=1 P=11Hz D=0.18s
Stop			M=5000 P=12Hz D=0.5s		M=6000 P=5Hz D=0.1s			M=10000 P=5Hz D=0.1s				

D. Audio sketches

Leaving Area / Pattern Recognized			
Name	Alex rating	Sonia rating	Mean rating
808 Bongo (1)	2	2	2
808 Bongo (2)	2	4	3
808 Bongo (3)	3	3	3
Blip (1)	1	1	1
Blip (2)	1	1	1
Blip (3)	2	1	1,5
Closh (1)	1	1	1
Closh (2)	2	1	1,5
Closh (3)	2	1	1,5
Cyanide (1)	1	1	1
Cyanide (2)	1	1	1
Cyanide (3)	1	1	1
Filtered Claps (1)	3	2	2,5
Filtered Claps (2)	3	2	2,5
Filtered Claps (3)	3	1	2
Maracas (1)	1	1	1
Maracas (2)	1	1	1
Maracas (3)	2	1	1,5
Thin Analog Claps (1)	2	1	1,5
Thin Analog Claps (2)	2	1	1,5
Thin Analog Claps (3)	2	1	1,5
Castanets	5	4	4,5
Bongo	3	4	3,5
Conga	2	3	2,5
Shell	1	2	1,5
Cls	1	2	1,5
Block	1	3	2
Clack	1	4	2,5
Shaker	2	4	3
j1987 unlock/lock	3	4	3,5
ryding unlock/lock	5	4	4,5
mrauralization unlock/lock	4	3	3,5

(a) Leaving Inner Area/Pattern Recognized.

Increase / Decrease			
Name	Alex rating	Sonia rating	Mean rating
Rusty Wurlitz	5	4	4,5
Rusty Wurlitz (2 tone)	5	3	4
Shimmer Key	3	3	3
Shimmer Key (2 tone)	2	3	2,5
Soft E-piano	2	1	1,5
Soft E-piano (2 tone)	3	1	2
Wurlitzerich	2	1	1,5
Wurlitzerich (2 tone)	3	3	3
Electronic Harmonix	4	4	4
Epia	2	2	2
Proclaiming Metal	3	4	3,5
CCCP-70	4	3	3,5
CCCP-70 (2 tone)	4	2	3
Soft Rhodes	2	1	1,5
Soft Rhodes (long)	2	1	1,5
Soft Rhodes (long 2 tone)	3	1	2
Vibra a bit softer	3	4	3,5
Vibra a bit softer (long)	3	5	4
Vibra a bit softer (long 2 tone)	3	3	3
Digirimba	1	3	2
Digirimba (long)	1	2	1,5
Digirimba (long 2 tone)	1	1	1
Crispy Cream	2	1	1,5
Stereo Bells	3	2	2,5
Stringbells	3	2	2,5
VS-Bellpad	2	2	2
Xylobell	4	4	4
Horn (custom)	4	2	3
Violins (custom)	3	1	2

(b) Increase/Decrease Speed.

Abort			
Name	Alex rating	Sonia rating	Mean rating
Rusty Wurlitz	5	3	4
Shimmer Key	4	1	2,5
Soft E-piano	3	2	2,5
Wurlitzerich	3	1	2
Electronic Harmonix	4	5	4,5
Epia	3	4	3,5
Proclaiming Metal	3	3	3
CCCP-70	4	4	4
Soft Rhodes	2	3	2,5
Soft Rhodes (long)	4	2	3
Vibra a bit softer	3	2	2,5
Vibra a bit softer (long)	4	2	3
Digirimba	1	4	2,5
Digirimba (long)	2	4	3
Crispy Cream	2	3	2,5
Stereo Bells	3	1	2
Stringbells	3	1	2
VS-Bellpad	2	4	3
Xylobell	4	3	3,5
Horn (custom)	4	3	3,5
Violins (custom)	3	1	2
Bearbell	1	4	2,5
Shake it!	1	1	1
CCCP-70 D3A3	2	3	2,5
CCCP-70 D1	3	4	3,5
Rhodes C2 C2	3	4	3,5

(c) Aborted.

Next exit			
Name	Alex rating	Sonia rating	Mean rating
Rusty Wurlitz	5	4	4,5
Shimmer Key	2	2	2
Soft E-piano	3	1	2
Wurlitzerich	2	1	1,5
Electronic Harmonix	4	4	4
Epia	2	3	2,5
Proclaiming Metal	3	5	4
CCCP-70	4	2	3
Soft Rhodes	2	1	1,5
Soft Rhodes (long)	4	2	3
Vibra a bit softer	3	4	3,5
Vibra a bit softer (long)	4	5	4,5
Digirimba	1	4	2,5
Digirimba (long)	2	4	3
Crispy Cream	2	1	1,5
Stereo Bells	3	1	2
Stringbells	3	1	2
VS-Bellpad	2	3	2,5
Xylobell	4	4	4
Horn (custom)	4	1	2,5
Violins (custom)	3	1	2

(d) Next Exit.

Figure D.1: Self evaluation of the initial audio sketches.

E. Multimodal sketches

E.1 Audio and haptic sketches

In this section the haptic and audio sketches selected after the self evaluation are presented in a matrix form for each command. The commands using speech when accepted are marked in yellow.

	Audio (A)	Haptic (H)
Leaving inner area	Castanets Battery Percussive	Status dependent
	Bongo Battery Percussive	Status dependent
	j1987 Door unlock (auditory icon)	Status dependent
	ryding Door unlock (auditory icon)	Status dependent
	mrauralization Door unlock (auditory icon)	Status dependent

(a) Leaving Inner Area.

	Audio (A)	Haptic (H)
Pattern recognized	Castanets Battery Percussive	Command dependent
	Bongo Battery Percussive	Command dependent
	j1987 Door lock (auditory icon)	Command dependent
	ryding Door lock (auditory icon)	Command dependent
	mrauralization Door lock (auditory icon)	Command dependent

(b) Pattern Recognized.

	Audio (A)	Haptic (H)
Move inside lane	N/A	Sine M=8000 P=17Hz D=0.001s
	N/A	Square M=6000 P=17Hz D=0.001s
	N/A	Triangle M=5000 P=5Hz D=0.2s

(c) Move inside the lane.

	Audio (A)	Haptic (H)
Stop	N/A	Sine M=5000 P=12Hz D=0.5s
	N/A	Square M=6000 P=5Hz D=0.1s
	N/A	Triangle M=10000 P=5Hz D=0.1s

(d) Stop.

Figure E.1: Characteristics of the audio and haptic sketches for each command.

	Audio (A)	Haptic (H)
Next exit 1-3	Rusty Wurlitz FM8 C4, G4 G4, D5 D5 D5	Square M=7000 P=10Hz D=0.5s
	Electronic Harmonix FM8 C4, G4 G4, D5 D5 D5	Square M=7000 P=17Hz D=0.12s
	Proclaiming Metal FM8 C4, G4 G4, D5 D5 D5	Triangle M=5000 P=5Hz D=0.2s
	Vibra a bit softer FM8 C4, G4 G4, D5 D5 D5	Sawtooth M=8000 P=17Hz D=0.12s
	Vibra a bit softer (long) FM8 A3, E4 E4, B4 B4 B4	
	Xylobell FM8 C4, G4 G4, D5 D5 D5	

(a) Take the next exit.

	Audio (A)	Haptic (H)
Next exit error	N/A	Sawtooth M=1000 P=12Hz D=0.17s
	N/A	Sawtooth M=1 P=11Hz D=0.18s

(b) Exit number error.

	Audio (A)	Haptic (H)
Increase/decrease speed	Rusty Wurlitz FM8 G4 (inc), C4 (dec)	Sine M=8000 P=17Hz D=0.001s
	Rusty Wurlitz FM8 C4 G4 (inc), C4 F3 (dec)	Sine M=5000 P=5Hz D=0.1s
	Electronic Harmonix FM8 G4 (inc), C4 (dec)	Square M=10000 P=17Hz D=0.003s
	Proclaiming Metal FM8 G4 (inc), C4 (dec)	Triangle M=3000 P=10Hz D=0.05s
	CCCP-70 FM8 G4 (inc), C4 (dec)	
	Vibra a bit softer FM8 G4 (inc), C4 (dec)	
	Vibra a bit softer (long) FM8 E4 (inc), A3 (dec)	
	Xylobell FM8 G4 (inc), C4 (dec)	

(c) Increase/Decrease speed.

	Audio (A)	Haptic (H)
Inc/dec speed error	N/A	Sine M=1000 P=17Hz D=0.54s
	N/A	Sine M=3000 P=25Hz D=0.4s
	N/A	Triangle M=1000 P=17Hz D=0.24s
	N/A	Sawtooth M=3000 P=25Hz D=0.4s

(d) Maximum/Minimum speed.

Figure E.2: Characteristics of the audio and haptic sketches for each command.

	Audio (A)	Haptic (H)
Abort/reject	Rusty Wurlitz FM8 F3, C4, F3, C4	Sine M=5000 P=18Hz D=0.44s
	Electronic Harmonix FM8 F3, C4, F3, C4	Sine M=6000 P=12.5Hz D=0.32s
	Epia FM8 F3, C4, F3, C4	Square M=2000 P=18Hz D=0.33s
	CCCP-70 FM8 F3, C4, F3, C4	Triangle M=6000 P=15Hz D=0.52s
	Xylobell FM8 F3, C4, F3, C4	
	Horn (custom) FM8 F3, C4, F3, C4	
	CCCP-70 FM8 D1	
	Rhodes FM8 C2, C2	

(a) Command aborted.

	Audio (A)	Haptic (H)
Interrupt	N/A	Sine M=5000 P=17Hz D=0.5s
	N/A	Sine M=6000 P=12Hz D=0.6s
	N/A	Triangle M=4000 P=17Hz D=0.5s
	N/A	Sawtooth M=5000 P=17Hz D=0.5s

(b) Command cancelled.

	Audio (A)	Haptic (H)
Change lane	N/A	Square M=3000 P=12Hz D=0.17s
	N/A	Triangle M=9000 P=5Hz D=0.1s
	N/A	Sawtooth M=8000 P=5Hz D=0.1s
	N/A	Sawtooth M=5000 P=17Hz D=0.12s

(c) Change lane.

	Audio (A)	Haptic (H)
Overtake	N/A	Sine M=10000 P=5Hz D=0.1s
	N/A	Square M=10000 P=3Hz D=0.2s

(d) Overtake.

Figure E.3: Characteristics of the audio and haptic sketches for each command.

E.2 Creating multimodal sketches

Haptic (H) and audio (A) sketches were combined and rated in order to find good multimodal combinations. This section presents the results for all commands which used multimodality, i.e. *command aborted*, *increasing/decreasing speed*, *maximum/minimum speed*, *increasing/decreasing number of exit* and *maximum/minimum exit*. The highest rated sketches are marked in grey.

Table E.1: Multimodal combinations for command aborted were rated. Combinations with a score ≥ 3.5 were considered as good and were used at the next evaluation.

	H1	H2	H3	H4
A1	4	2.5	3	3
A2	3	3	3	3.5
A3	2.5	1.5	2	2
A4	3	2.5	2	3
A5	2	2.5	2.5	3
A6	3.5	2.5	2	3
A7	3	2	2	2.5
A8	3	2.5	2	2

Table E.2: Multimodal sketches for increasing/decreasing speed and maximum/minimum speed were created so that they matched together. Combinations for increasing/decreasing speed were rated (a) and the combinations whose score was ≥ 4.5 were used to create multimodal sketches combining them with the maximum/minimum speed feedback (b).

(a)

	H1	H2	H3	H4
A1	4.5	3.5	3.5	5
A2	5	4	4	5
A3	4.5	3	3.5	4
A4	4	2.5	3	4
A5	3	2	2.5	3
A6	3.5	2.5	2.5	3
A7	3.5	3.5	3	3.5
A8	2.5	2	2	2.5

(b)

	H1	H2	H3	H4
A1H1	2	4.5	3.5	5
A1H4	2.5	2.5	3	3.5
A2H4	1	2.5	2.5	4
A2H1	3	2.5	3.5	4
A3H1	2.5	3	3	4

Table E.3: Multimodal sketches for increasing/decreasing the number of exit and maximum/minimum exit were created so that they matched together. Combinations for changing the number of exit were rated (a) and the combinations whose score was ≥ 4 were used to create multimodal sketches combining them with the maximum/minimum exit feedback (b).

(a)

	H1	H2	H3	H4
A1	1	4.5	4	4.5
A2	1	4	3.5	4
A3	1	3.5	3	3.5
A4	1	3.5	3	3.5
A5	1	4	3.5	4
A6	1	2.5	2	2.5

(b)

	H1	H2
A1H2	4	4
A1H3	4	4
A1H4	4.5	3.5
A2H2	3.5	2
A2H4	3	3.5
A5H2	2	3
A5H4	2	3

E.3 Multimodal combinations

In this section it is shown the multimodal sketches for each command, according to the results from Appendix E.2. The commands using speech when accepted are marked in yellow.

	Audio (A)	Haptic (H)	Multimodal set
Leaving inner area	Castanets Battery Percussive	Status dependent	
	Bongo Battery Percussive	Status dependent	
	j1987 Door unlock (auditory icon)	Status dependent	
	ryding Door unlock (auditory icon)	Status dependent	
	mrauralization Door unlock (auditory icon)	Status dependent	

(a) Leaving Inner Area.

	Audio (A)	Haptic (H)	Multimodal set
Pattern recognized	Castanets Battery Percussive	Command dependent	
	Bongo Battery Percussive	Command dependent	
	j1987 Door lock (auditory icon)	Command dependent	
	ryding Door lock (auditory icon)	Command dependent	
	mrauralization Door lock (auditory icon)	Command dependent	

(b) Pattern Recognized.

	Audio (A)	Haptic (H)	Multimodal set
Move inside lane	N/A	Sine M=8000 P=17Hz D=0.001s	
	N/A	Square M=6000 P=17Hz D=0.001s	
	N/A	Triangle M=5000 P=5Hz D=0.2s	

(c) Move inside the lane.

	Audio (A)	Haptic (H)	Multimodal set
Stop	N/A	Sine M=5000 P=12Hz D=0.5s	
	N/A	Square M=6000 P=5Hz D=0.1s	
	N/A	Triangle M=10000 P=5Hz D=0.1s	

(d) Stop.

Figure E.4: The characteristics of the audio and haptic sketches for each command are shown, as well as the multimodal combinations which had received the highest scores.

	Audio (A)	Haptic (H)	Multimodal set
Next exit 1-3	Rusty Wurlitz FM8 C4, G4 G4, D5 D5 D5	Square M=7000 P=10Hz D=0.5s	A1H2
	Electronic Harmonix FM8 C4, G4 G4, D5 D5 D5	Square M=7000 P=17Hz D=0.12s	A1H3
	Proclaiming Metal FM8 C4, G4 G4, D5 D5 D5	Triangle M=5000 P=5Hz D=0.2s	A1H4
	Vibra a bit softer FM8 C4, G4 G4, D5 D5 D5	Sawtooth M=8000 P=17Hz D=0.12s	A2H2
	Vibra a bit softer (long) FM8 A3, E4 E4, B4 B4 B4		A2H4
	Xylobell FM8 C4, G4 G4, D5 D5 D5		A5H2
			A5H4

(a) Take the next exit.

	Audio (A)	Haptic (H)	Multimodal set
Next exit error	N/A	Sawtooth M=1000 P=12Hz D=0.17s	A1H2 + H1
	N/A	Sawtooth M=1 P=11Hz D=0.18s	A1H2 + H2
	N/A		A1H3 + H1
	N/A		A1H3 + H2
	N/A		A1H4 + H1

(b) Exit number error.

	Audio (A)	Haptic (H)	Multimodal set
Increase/decrease speed	Rusty Wurlitz FM8 G4 (inc), C4 (dec)	Sine M=8000 P=17Hz D=0.001s	A1H1
	Rusty Wurlitz FM8 C4 G4 (inc), C4 F3 (dec)	Sine M=5000 P=5Hz D=0.1s	A1H4
	Electronic Harmonix FM8 G4 (inc), C4 (dec)	Square M=10000 P=17Hz D=0.003s	A2H4
	Proclaiming Metal FM8 G4 (inc), C4 (dec)	Triangle M=3000 P=10Hz D=0.05s	A2H1
	CCCP-70 FM8 G4 (inc), C4 (dec)		A3H1
	Vibra a bit softer FM8 G4 (inc), C4 (dec)		
	Vibra a bit softer (long) FM8 E4 (inc), A3 (dec)		
	Xylobell FM8 G4 (inc), C4 (dec)		

(c) Increase/Decrease speed.

	Audio (A)	Haptic (H)	Multimodal set
Inc/dec speed error	N/A	Sine M=1000 P=17Hz D=0.54s	A1H1 + H2
	N/A	Sine M=3000 P=25Hz D=0.4s	A1H1 + H4
	N/A	Triangle M=1000 P=17Hz D=0.24s	A2H4 + H4
	N/A	Sawtooth M=3000 P=25Hz D=0.4s	A2H1 + H4
	N/A		A3H1 + H4

(d) Maximum/Minimum speed.

Figure E.5: The characteristics of the audio and haptic sketches for each command are shown, as well as the multimodal combinations which had received the highest scores.

	Audio (A)	Haptic (H)	Multimodal set
Abort/reject	Rusty Wurlitz FM8 F3, C4, F3, C4	Sine M=5000 P=18Hz D=0.44s	A1H1
	Electronic Harmonix FM8 F3, C4, F3, C4	Sine M=6000 P=12.5Hz D=0.32s	A2H4
	Epia FM8 F3, C4, F3, C4	Square M=2000 P=18Hz D=0.33s	A6H1
	CCCP-70 FM8 F3, C4, F3, C4	Triangle M=6000 P=15Hz D=0.52s	
	Xylobell FM8 F3, C4, F3, C4		
	Horn (custom) FM8 F3, C4, F3, C4		
	CCCP-70 FM8 D1		
	Rhodes FM8 C2, C2		

(a) Command aborted.

	Audio (A)	Haptic (H)	Multimodal set
Interrupt	N/A	Sine M=5000 P=17Hz D=0.5s	
	N/A	Sine M=6000 P=12Hz D=0.6s	
	N/A	Triangle M=4000 P=17Hz D=0.5s	
	N/A	Sawtooth M=5000 P=17Hz D=0.5s	

(b) Command cancelled.

	Audio (A)	Haptic (H)	Multimodal set
Change lane	N/A	Square M=3000 P=12Hz D=0.17s	
	N/A	Triangle M=9000 P=5Hz D=0.1s	
	N/A	Sawtooth M=8000 P=5Hz D=0.1s	
	N/A	Sawtooth M=5000 P=17Hz D=0.12s	

(c) Change lane.

	Audio (A)	Haptic (H)	Multimodal set
Overtake	N/A	Sine M=10000 P=5Hz D=0.1s	
	N/A	Square M=10000 P=3Hz D=0.2s	

(d) Overtake.

Figure E.6: The characteristics of the audio and haptic sketches for each command are shown, as well as the multimodal combinations which had received the highest scores.

E.4 Multimodal sets

This section will present the multimodal sets created prior to the expert evaluation, and the changes made until the sets were ready for the user study.

Table E.4: Multimodal sketches were combined to create sets which were evaluated by an expert.

	SET 1		SET 2		SET 3		SET 4		SET 5	
	Audio	Haptic	Audio	Haptic	Audio	Haptic	Audio	Haptic	Audio	Haptic
Leaving inner area	Castanets Battery Percussive	Status dependet	Bongo Battery Percussive	Status dependet	j1987 Door unlock (auditory icon)	Status dependet	ryding Door unlock (auditory icon)	Status dependet	mrauralization Door unlock (auditory icon)	Status dependet
Pattern recognized	Castanets Battery Percussive	Command dependet	Bongo Battery Percussive	Command dependet	j1987 Door unlock (auditory icon)	Command dependet	ryding Door unlock (auditory icon)	Command dependet	mrauralization Door unlock (auditory icon)	Command dependet
Abort/reject	Rusty Wurlitz FM8 F3, C4, F3, C4	Sine M=5000 P=18Hz D=0.44s	Electronic Harmonix FM8 F3, C4, F3, C4	Triangle M=6000 P=15Hz D=0.52s	Horn (custom) FM8 F3, C4, F3, C4	Sine M=5000 P=18Hz D=0.44s				
Overtake	N/A	Sine M=10000 P=5Hz D=0.1s	N/A	Square M=10000 P=3Hz D=0.2s						
Next exit	Rusty Wurlitz FM8 C4, G4 G4, D5 D5 D5	Square M=7000 P=17Hz D=0.12s	Rusty Wurlitz FM8 C4, G4 G4, D5 D5 D5	Square M=7000 P=17Hz D=0.12s	Rusty Wurlitz FM8 C4, G4 G4, D5 D5 D5	Triangle M=5000 P=5Hz D=0.2s	Rusty Wurlitz FM8 C4, G4 G4, D5 D5 D5	Triangle M=5000 P=5Hz D=0.2s	Rusty Wurlitz FM8 C4, G4 G4, D5 D5 D5	Sawtooth M=8000 P=17Hz D=0.12s
Next exit error	N/A	Sawtooth M=1000 P=12Hz D=0.17s	N/A	Sawtooth M=1 P=11Hz D=0.18s	N/A	Sawtooth M=1000 P=12Hz D=0.17s	N/A	Sawtooth M=1 P=11Hz D=0.18s	N/A	Sawtooth M=1000 P=12Hz D=0.17s
Stop	N/A	Sine M=5000 P=12Hz D=0.5s	N/A	Square M=6000 P=5Hz D=0.1s	N/A	Triangle M=10000 P=5Hz D=0.1s				
Change lane	N/A	Square M=3000 P=12Hz D=0.17s	N/A	Triangle M=9000 P=5Hz D=0.1s	N/A	Sawtooth M=8000 P=5Hz D=0.1s	N/A	Sawtooth M=5000 P=17Hz D=0.12s		
Increase/decrease speed	Rusty Wurlitz FM8 G4 (inc), C4 (dec)	Sine M=8000 P=17Hz D=0.001s	Rusty Wurlitz FM8 G4 (inc), C4 (dec)	Sine M=8000 P=17Hz D=0.001s	Rusty Wurlitz FM8 C4 G4 (inc), C4 F3 (dec)	Triangle M=3000 P=10Hz D=0.05s	Rusty Wurlitz FM8 C4 G4 (inc), C4 F3 (dec)	Sine M=8000 P=17Hz D=0.001s	Electronic Harmonix FM8 G4 (inc), C4 (dec)	Sine M=8000 P=17Hz D=0.001s
Increase/decrease speed error	N/A	Sine M=3000 P=25Hz D=0.4s	N/A	Sawtooth M=3000 P=25Hz D=0.4s	N/A	Sawtooth M=3000 P=25Hz D=0.4s	N/A	Sawtooth M=3000 P=25Hz D=0.4s	N/A	Sawtooth M=3000 P=25Hz D=0.4s
Move inside lane	N/A	Sine M=8000 P=17Hz D=0.001s	N/A	Square M=6000 P=17Hz D=0.001s	N/A	Triangle M=5000 P=5Hz D=0.2s				
Interrupt	N/A	Sine M=5000 P=17Hz D=0.5s	N/A	Sine M=6000 P=12Hz D=0.6s	N/A	Triangle M=4000 P=17Hz D=0.5s	N/A	Sawtooth M=5000 P=17Hz D=0.5s		

Table E.5: The feedback obtained from the expert evaluation was used to improve the sketches.

	SET 1		SET 2		SET 3		SET 4		SET 5	
	Audio	Haptic	Audio	Haptic	Audio	Haptic	Audio	Haptic	Audio	Haptic
Leaving inner area	Improved		Improved		Eliminated		Eliminated		Eliminated	
Pattern recognized	Improved		Improved		Eliminated		Eliminated		Eliminated	
Abort/reject	Used as foundation for new sketch		Used as foundation for new sketch		Used as foundation for new sketch					
Overtake										
Next exit	Improved, and used as foundation for new sketch	Magnitude was decreased, so the difference with the error can be felt.	Improved, and used as foundation for new sketch	Magnitude was decreased, so the difference with the error can be felt.	Imrproved, used as foundation for new sketches "Leaving inner area" & "Pattern recognized"		Improved, and used as foundation for new sketch		Improved, and used as foundation for new sketch	Magnitude was decreased, so the difference with the error can be felt.
Next exit error		Same frequency as next exit, but longer and stronger effect		Increase of the magnitude to feel it stronger than next exit		Increase of the magnitude to feel it stronger than next exit		Increase of the magnitude to feel it stronger than next exit		Increase of the magnitude to feel it stronger than next exit
Stop		Same as inc/dec speed to have the feeling of doing the same, different duration and magnitude so it can be felt well								
Change lane					Eliminated	Eliminated				
Increase/decrease speed	Improved, used as foundation for new sketch		Improved, used as foundation for new sketch	Eliminated as it is the same as set 1	Elimininated	Moved to set 2	Eliminated	Eliminated as it is the same as set 1	Improved	
Increase/decrease speed error		Same frequency as inc/dec speed, but longer effect						Eliminated as it is the same as set 3		Eliminated as it is the same as set 3
Move inside lane										
Interrupt		Decrease magnitude and duration as it was annoying			Eliminated	Eliminated				

Table E.6: Improved sets were obtained after the expert evaluation.

	SET 1		SET 2		SET 3		SET 4		SET 5	
	Audio	Haptic	Audio	Haptic	Audio	Haptic	Audio	Haptic	Audio	Haptic
Leaving inner area	Castanets (custom) Battery Percussive	Status dependet	Bongo (custom) Battery Percussive	Status dependet	Horn (custom) FM8 F3	Status dependet				
Pattern recognized	Castanets (custom) Battery Percussive	Command dependet	Bongo (custom) Battery Percussive	Command dependet	Horn (custom) FM8 F3, C4	Command dependet				
Abort/reject	Rusty Wurlitz FM8 G3, C3	Sine M=5000 P=18Hz D=0.44s	Electronic Harmonix FM8 G3, C3	Triangle M=6000 P=15Hz D=0.52s	Horn (custom) FM8 F3, B2	Sine M=5000 P=18Hz D=0.44s				
Overtake	N/A	Sine M=10000 P=5Hz D=0.1s	N/A	Square M=10000 P=3Hz D=0.2s						
Next exit	Rusty Wurlitz / Electronic / Horn FM8 C3, G3 G3, D4 D4 D4	Square M=3000 P=17Hz D=0.12s	Rusty Wurlitz / Electronic / Horn FM8 C3, G3 G3, D4 D4 D4	Square M=1000 P=17Hz D=0.12s	Rusty Wurlitz / Electronic / Horn FM8 C3, G3 G3, D4 D4 D4	Triangle M=5000 P=5Hz D=0.2s	Rusty Wurlitz / Electronic / Horn FM8 C3, G3 G3, D4 D4 D4	Triangle M=5000 P=5Hz D=0.2s	Rusty Wurlitz / Electronic / Horn FM8 C3, G3 G3, D4 D4 D4	Sawtooth M=1000 P=17Hz D=0.12s
Next exit error	N/A	Square M=7000 P=17Hz D=0.24s	N/A	Sawtooth M=2000 P=11Hz D=0.18s	N/A	Square M=10000 P=17Hz D=0.18s	N/A	Sawtooth M=5000 P=11Hz D=0.36s	N/A	Sawtooth M=10000 P=12Hz D=0.345s
Stop	N/A	Sine M=8000 P=17Hz D=0.06s	N/A	Square M=6000 P=5Hz D=0.1s	N/A	Triangle M=10000 P=5Hz D=0.1s				
Change lane	N/A	Square M=3000 P=12Hz D=0.17s	N/A	Triangle M=9000 P=5Hz D=0.1s			N/A	Sawtooth M=5000 P=17Hz D=0.12s		
Increase/decrease speed	Rusty Wurlitz FM8 E2, B2, F3, C4, G4, D5	Sine M=8000 P=17Hz D=0.001s	Rusty Wurlitz FM8 G3 (inc), C3 (dec)	Triangle M=3000 P=10Hz D=0.05s					Electronic Harmonix FM8 G3 (inc), C3 (dec)	Sine M=8000 P=17Hz D=0.001s
Increase/decrease speed error	N/A	Sine M=1000 P=17Hz D=0.18s	N/A	Sawtooth M=3000 P=25Hz D=0.4s	N/A	Sawtooth M=3000 P=25Hz D=0.4s				
Move inside lane	N/A	Sine M=8000 P=17Hz D=0.001s	N/A	Square M=6000 P=17Hz D=0.001s	N/A	Triangle M=5000 P=5Hz D=0.2s				
Interrupt	N/A	Sine M=3000 P=17Hz D=0.48s	N/A	Sine M=6000 P=12Hz D=0.6s			N/A	Sawtooth M=5000 P=17Hz D=0.5s		

Table E.7: Before performing the user studies, the number of sets were reduced to three.

	SET 1		SET 2		SET 3	
	Audio	**Haptic**	**Audio**	**Haptic**	**Audio**	**Haptic**
Leaving inner area	Castanets (custom) Battery Percussive	Status dependet	Bongo (custom) Battery Percussive	Status dependet	Horn (custom) FM8 F3	Status dependet
Pattern recognized	Castanets (custom) Battery Percussive	Command dependet	Bongo (custom) Battery Percussive	Command dependet	Horn (custom) FM8 F3, C4	Command dependet
Abort/reject	Rusty Wurlitz FM8 G3, C3	Sine M=5000 P=18Hz D=0.44s	Electronic Harmonix FM8 G3, C3	Triangle M=6000 P=15Hz D=0.52s	Horn (custom) FM8 F3, B2	Sine M=5000 P=18Hz D=0.44s
Overtake	N/A	Sine M=10000 P=5Hz D=0.1s	N/A	Square M=10000 P=3Hz D=0.2s	N/A	Sawtooth M=10000 P=3Hz D=0.2s
Next exit	Rusty Wurlitz FM8 C3, G3 G3, D4 D4 D4	Square M=1000 P=17Hz D=0.12s	Horn FM8 C3, G3 G3, D4 D4 D4	Square M=500 P=17Hz D=0.12s	Electronic FM8 C3, G3 G3, D4 D4 D4	Triangle M=5000 P=5Hz D=0.2s
Next exit error	N/A	Square M=1000 P=17Hz D=0.24s	N/A	Sawtooth M=1000 P=11Hz D=0.18s	N/A	Sawtooth M=1000 P=11Hz D=0.36s
Stop	N/A	Sine M=8000 P=17Hz D=0.06s	N/A	Square M=6000 P=5Hz D=0.1s	N/A	Triangle M=10000 P=5Hz D=0.1s
Change lane	N/A	Square M=3000 P=12Hz D=0.17s	N/A	Triangle M=9000 P=5Hz D=0.1s	N/A	Sawtooth M=5000 P=17Hz D=0.12s
Increase/decrease speed	Rusty Wurlitz FM8 E2, B2, F3, C4, G4, D5	Sine M=10000 P=17Hz D=0.001s	Rusty Wurlitz FM8 G3 (inc), C3 (dec)	Triangle M=10000 P=10Hz D=0.25s	Electronic Harmonix FM8 G3 (inc), C3 (dec)	Sine M=10000 P=17Hz D=0.001s
Increase/decrease speed error	N/A	Sine M=1000 P=17Hz D=0.18s	N/A	Sawtooth M=3000 P=25Hz D=0.4s	N/A	Sawtooth M=3000 P=25Hz D=0.4s
Move inside lane	N/A	Sine M=8000 P=17Hz D=0.001s	N/A	Square M=6000 P=17Hz D=0.001s	N/A	Triangle M=9000 P=5Hz D=0.2s
Interrupt	N/A	Sine M=3000 P=17Hz D=0.48s	N/A	Sine M=6000 P=12Hz D=0.6s	N/A	Sawtooth M=5000 P=17Hz D=0.5s

F. User study

F.1 Background form

Age: _________ years

Gender:

Female
Male

Occupation: _______________________________________

Highest level of education attained (choose one):

Less than high school
High school
Bachelor's degree
Master's degree
Doctorate degree

Do you have a hearing impairment?

No
Yes

Do you have any musical experience? If yes, what kind of experience?

No
Yes, _______________________________________

Do you have any experience with haptic feedback?

No
Yes, from smartphones, tablets or similar devices
Yes, from simulators
Other experience: ______________________________

Do you have a driver's license?

No
Yes

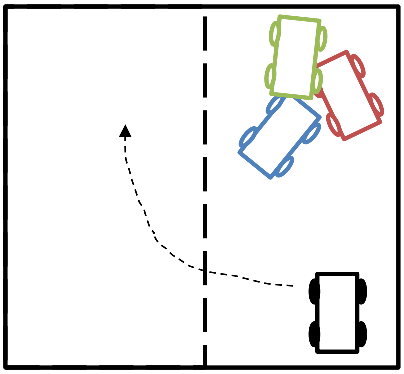
If yes, how often do you drive?

Every day
A few times per week
A few times per month
A few times per year

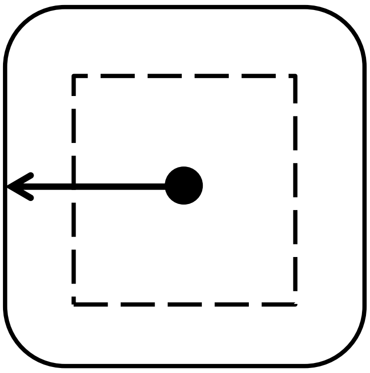
Figure F.1: The background form which users were asked to fill out prior to conducting the user study.

F.2 Scenario scene

You notice that there has been an accident on the right lane of the highway, so you decide to change to the left lane in order to drive past it.



Using your joystick execute a ***change lane (left)*** operation by moving the joystick to the far left, as shown in the picture below.



For your and other drivers' safety a small delay has been implemented, so do not worry if you cannot hear or feel an immediate response.

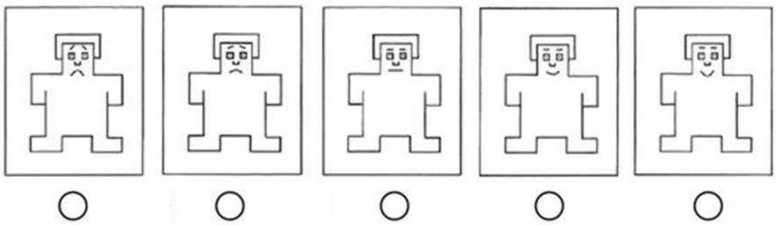
Feel free to play around with both left and right operations before answering the questionnaire on the next page.

Also notice how the feedback changes when the joystick moves from its central position and when a command has been recognized.

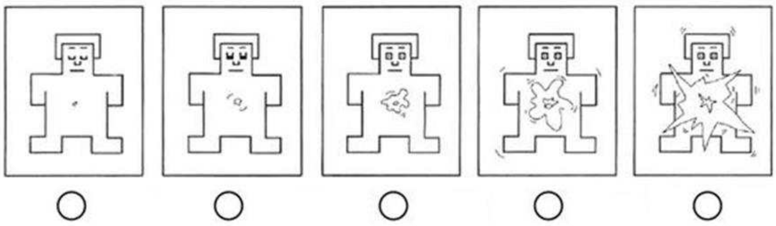
Figure F.2: One of the scenario scenes used in the user study in order to explain the use context of the strategic controller.

F.3 Questionnaire

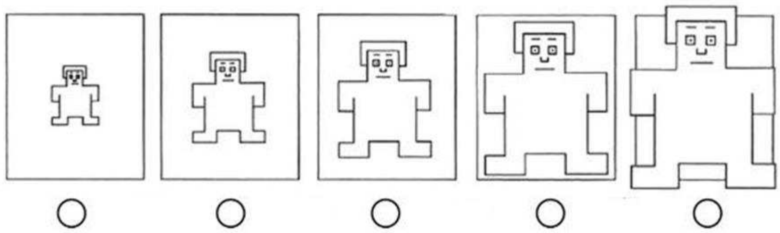
Pleasure (negative-positive)



Arousal (passive-active)



Dominance (dominated-dominant)



Do you find that the feedback communicates something urgent?

1 (not urgent)	2	3	4	5 (very urgent)

Do you find the feedback annoying?

1 (not annoying)	2	3	4	5 (very annoying)

Do you think the feedback is appropriate for a car in the premium segment?

1 (not appropriate)	2	3	4	5 (very appropriate)

Could you give a brief explanation of why you like or dislike the feedback?

Figure F.3: The questionnaire used in the user study.

F.4 Interview questions

- Which feedback sketch was your favourite? Why?
- Which feedback sketch was your least favourite? Why?

- Was it clear what the feedback was trying to tell you? Did it ever confuse you?
- Did you feel that there was feedback which was unnecessary? Why?
- Would you like to add any feedback which you felt was missing?
- Do you think multimodality helped you get a better understanding of the message the feedback was trying to tell you? Would you like to replace or add any other modality?

In addition, each user study was finalized by asking: *How would you feel "communicating" with a car in this way? Do you think there would be any situations where it would not be appropriate?*

F.5 Test subject profiles

Table F.1: Profiles of the test subjects.

User	Age	Gender	Occupation	Education level	Hearing impairment	Musical experience	Haptic feedback experience	Drivers license	Driving frequency
1	27	Male	Student (Interaction design)	M.Sc.	No	Electric guitar	Smartphones/tablets and haptic controllers	Yes	Yearly
2	25	Male	Student (Biomedical engineering)	M.Sc.	No	None	Smartphones/tablets	Yes	Monthly
3	27	Male	Simulation engineer	M.Sc.	No	Guitar	None	No	-
4	26	Male	Simulation engineer	M.Sc.	No	None	Smartphones/tablets and car simulators	Yes	Daily
5	25	Male	Student (Automotive engineering)	M.Sc.	No	None	Smartphones/tablets	Yes	Daily
6	23	Female	Student (Interaction design)	M.Sc.	No	Violin (orchestra)	Smartphones/tablets and simulators	Yes	Yearly
7	32	Male	Simulation engineer	M.Sc.	No	None	Smartphones/tablets	Yes	Yearly
8	23	Male	Student (Biomedical engineering)	M.Sc.	No	Trombone (orchestra)	Smartphones/tablets	Yes	Monthly
9	28	Male	Student (Interaction design)	M.Sc.	No	Music production and playing in a rock band	Smartphones/tablets and video games	Yes	Weekly
10	31	Male	Student (Mechanical engineering)	M.Sc.	No	Choir, piano, guitar, etc.	Smartphones/tablets and a little from simulators	Yes	Yearly

F.6 Favourite sketch votes

Table F.2: Leaving inner area.

	Sketch 1	**Sketch 2**	**Sketch 3**
Favourite	4	1	5
Least favourite	3	5	2
Total votes	1	-4	3

Table F.3: Pattern recognized.

	Sketch 1	**Sketch 2**	**Sketch 3**
Favourite	2	1	6
Least favourite	3	4	2
Total votes	-1	-3	4

Table F.4: Change lane.

	Sketch 1	Sketch 2	Sketch 3
Favourite	2	0	3
Least favourite	1	2	0
Total votes	1	-2	3

Table F.5: Overtake.

	Sketch 1	Sketch 2	Sketch 3
Favourite	1	0	8
Least favourite	5	5	0
Total votes	-4	-5	8

Table F.6: Abort/reject.

	Sketch 1	Sketch 2	Sketch 3
Favourite	1	2	6
Least favourite	7	2	0
Total votes	-6	0	6

Table F.7: Next exit.

	Sketch 1	Sketch 2	Sketch 3
Favourite	2	3	6
Least favourite	3	5	3
Total votes	-1	-2	3

Table F.8: Next exit error.

	Sketch 1	Sketch 2	Sketch 3
Favourite	2	3	5
Least favourite	3	5	3
Total votes	-1	-2	2

Table F.9: Stop.

	Sketch 1	Sketch 2	Sketch 3
Favourite	3	1	6
Least favourite	6	4	2
Total votes	-3	-3	4

Table F.10: Interrupt.

	Sketch 1	Sketch 2	Sketch 3
Favourite	7	1	2
Least favourite	2	6	2
Total votes	5	-5	0

Table F.11: Increase/decrease speed.

	Sketch 1	Sketch 2	Sketch 3
Favourite	6	2	3
Least favourite	3	8	3
Total votes	3	-6	0

Table F.12: Increase/decrease speed error.

	Sketch 1	Sketch 2	Sketch 3
Favourite	4	2	2
Least favourite	1	5	2
Total votes	3	-3	0

Table F.13: Move inside lane.

	Sketch 1	Sketch 2	Sketch 3
Favourite	3	4	3
Least favourite	3	1	5
Total votes	0	3	-2

F.7 Selection of the most suitable sketches

Leaving inner area

Table F.14: Attributes were compared against each other in order to define priorities.

Leaving inner area	H	L	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	1	1	0	0	3
Arousal	0		0	0	0	0	0
Dominance	0	1		0.5	0	0	1.5
Urgency	0	1	0.5		0	0	1.5
Annoyance	1	1	1	1		1	5
Appropriateness	1	1	1	1	0		4

Table F.15: Weights for each attribute were calculated.

Scale	Attribute	Weight
10	Annoyance	0.323
9		
8	Appropriateness	0.259
7		
6	Pleasure	0.194
5		
4		
3	Dominance, Urgency	0.097
2		
1	Arousal	0.033

Table F.16: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.194	3.5	0.679	2.7	0.5238	3.7	0.7178
Arousal	0.033	1.8	0.0594	2.5	0.0825	2	0.066
Dominance	0.097	3.5	0.3395	3.5	0.3395	4	0.388
Urgency	0.097	1.8	0.2716	2	0.194	2.3	0.2231
Annoyance	0.323	2.7	0.8721	2.1	0.6783	2.9	0.9367
Appropriateness	0.259	2.9	0.7511	2.5	0.6475	3.1	0.8029
Total score	-	-	2.97	-	2.47	-	3.13

Table F.17: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 3 was highest rated in both cases.

	Sketch 1	**Sketch 2**	**Sketch3**
Favourite	4	1	5
Least favourite	3	5	2
User score	1	-4	3
Weighted score	2.97	2.47	3.13

Pattern recognized

Table F.18: Attributes were compared against each other in order to define priorities.

Pattern recognized	H	L	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	1	1	0	0	3
Arousal	0		0	0	0	0	0
Dominance	0	1		0.5	0	0	1.5
Urgency	0	1	0.5		0	0	1.5
Annoyance	1	1	1	1		1	5
Appropriateness	1	1	1	1	0		4

Table F.19: Weights for each attribute were calculated.

Scale	**Attribute**	**Weight**
10	Annoyance	0.323
9		
8	Appropriateness	0.259
7		
6	Pleasure	0.194
5		
4		
3	Dominance, Urgency	0.097
2		
1	Arousal	0.033

Table F.20: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	User score	Weighted score	User score	Weighted score	User score	Weighted score
Pleasure	0.194	2.7	0.5238	2.4	0.4656	3.2	0.6208
Arousal	0.033	2.4	0.0792	2	0.066	1.5	0.0495
Dominance	0.097	3.4	0.3298	2.9	0.2813	3.2	0.3104
Urgency	0.097	2.3	0.2231	2.2	0.2134	2.1	0.2037
Annoyance	0.323	2.2	0.7106	2	0.646	2.5	0.8075
Appropriateness	0.259	2.3	0.5957	2.3	0.5957	3	0.777
Total score	-	-	2.4622	-	2.268	-	2.7689

Table F.21: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 3 was highest rated in both cases.

	Sketch 1	Sketch 2	Sketch 3
Favourite	2	1	6
Least favourite	3	4	2
User score	-1	-3	4
Weighted score	2.4622	2.268	2.7689

Command aborted

Table F.22: Attributes were compared against each other in order to define priorities.

Command aborted	H	H	H	H	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		0	1	0	0.5	0	1.5
Arousal	1		1	1	1	0	4
Dominance	0	0		0	1	0	1
Urgency	1	0	1		1	0	3
Annoyance	0.5	0	0	0		0	0.5
Appropriateness	1	1	1	1	1		4

Table F.23: Weights for each attribute were calculated.

Scale	Attribute	Weight
10	Appropriateness	0.334
9		
8	Arousal	0.267
7		
6	Urgency	0.2
5		
4		
3	Pleasure	0.1
2	Dominance	0.067
1	Annoyance	0.036

Table F.24: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	User score	Weighted score	User score	Weighted score	User score	Weighted score
Pleasure	0.1	2.5	0.25	3.3	0.33	3.2	0.32
Arousal	0.267	3.3	0.8811	3.1	0.8277	3.2	0.8544
Dominance	0.067	2.9	0.1943	2.8	0.1876	3	0.201
Urgency	0.2	2.9	0.57	3.1	0.62	2.2	0.44
Annoyance	0.034	2.8	0.0952	2.8	0.0952	2.6	0.0884
Appropriateness	0.334	2.8	0.9352	3.1	1.0354	3.2	1.0688
Total score	-	-	2.9358	-	3.0959	-	2.9726

Table F.25: The sketch considered as the best by the users was compared with the weighted value of each sketch. For users sketch 3 was consider better, however, the weighted value was slightly higher for sketch 2. As the difference between the weighted values is not considerable, sketch 3 was taken as the best.

	Sketch 1	Sketch 2	Sketch 3
Favourite	1	2	6
Least favourite	7	2	0
User score	-6	0	6
Weighted score	2.94	3.1	2.97

Overtake

Table F.26: Attributes were compared against each other in order to define priorities.

Overtake	H	L	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	1	1	0	0	3
Arousal	0		0	0	0	0	0
Dominance	0	1		1	0	0	2
Urgency	0	1	0		0	0	1
Annoyance	1	1	1	1		1	5
Appropriateness	1	1	1	1	0		5

Table F.27: Weights for each attribute were calculated.

Scale	Attribute	Weight
10	Annoyance	0.323
9		
8	Appropiateness	0.259
7		
6	Pleasure	0.194
5		
4	Dominance	0.13
3		
2	Urgency	0.065
1	Arousal	0.033

Table F.28: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.194	2.9	0.5626	2.4	0.4656	3.7	0.7178
Arousal	0.033	1.9	0.0627	2	0.066	2.1	0.0693
Dominance	0.13	2.9	0.377	3	0.39	3.5	0.455
Urgency	0.065	1.8	0.117	1.7	0.1105	2	0.13
Annoyance	0.323	2.1	0.6783	1.8	0.5814	2.8	0.9044
Appropriateness	0.259	2.6	0.6732	2.4	0.6216	3.4	0.8806
Total score	-	-	2.471	-	2.2351	-	3.1571

Table F.29: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 3 was highest rated in both cases.

	Sketch 1	Sketch 2	Sketch 3
Favourite	1	0	8
Least favourite	5	5	0
User score	-4	-5	8
Weighted score	2.47	2.24	3.16

Next exit

Table F.30: Attributes were compared against each other in order to define priorities.

Next exit	H	L	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	1	1	0	0	3
Arousal	0		0	0	0	0	0
Dominance	0	1		1	0	0	2
Urgency	0	1	0		0	0	1
Annoyance	1	1	1	1		1	5
Appropriateness	1	1	1	1	0		5

Table F.31: Weights for each attribute were calculated.

Scale	Attribute	Weight
10	Annoyance	0.323
9		
8	Appropiateness	0.259
7		
6	Pleasure	0.194
5		
4	Dominance	0.13
3		
2	Urgency	0.065
1	Arousal	0.033

Table F.32: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.194	3.5	0.679	3	0.582	3.7	0.7178
Arousal	0.033	1.6	0.0528	1.8	0.0594	1.7	0.0561
Dominance	0.13	3	0.39	3.3	0.429	3	0.39
Urgency	0.065	2.2	0.143	1.9	0.1235	2.1	0.1365
Annoyance	0.323	2.8	0.9044	2.7	0.8721	3.1	1.0013
Appropriateness	0.259	3.1	0.8029	2.9	0.7511	3.3	0.8547
Total score	-	-	2.9721	-	2.8171	-	3.1564

Table F.33: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 3 was highest rated in both cases.

	Sketch 1	**Sketch 2**	**Sketch 3**
Favourite	2	3	6
Least favourite	3	5	3
User score	-1	-2	3
Weighted score	2.97	2.82	2.74

Next exit error

Table F.34: Attributes were compared against each other in order to define priorities.

Next exit error	H	H	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		0	0	1	0	0	1
Arousal	1		0.5	0.5	0	0	2
Dominance	1	0.5		1	0.5	0	3
Urgency	0	0.5	0		0	0	0.5
Annoyance	1	1	0.5	1		0	3.5
Appropriateness	1	1	1	1	1		4

Table F.35: Weights for each attribute were calculated.

Scale	**Attribute**	**Weight**
10	Appropriateness	0.334
9		
8		
7	Annoyance	0.234
6	Dominance	0.2
5		
4	Arousal	0.134
3		
2	Pleasure	0.067
1	Urgency	0.033

Table F.36: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	User score	Weighted score	User score	Weighted score	User score	Weighted score
Pleasure	0.067	2.8	0.1876	2.7	0.1809	2.9	0.1943
Arousal	0.134	3.4	0.4556	3.3	0.4422	3	0.402
Dominance	0.2	2.5	0.5	2.3	0.46	2.8	0.56
Urgency	0.034	1.8	0.0612	1.8	0.0612	1.8	0.0612
Annoyance	0.234	2.4	0.5616	2.2	0.5148	2.5	0.585
Appropriateness	0.334	2.7	0.9018	3	1.002	2.8	0.9352
Total score	-	-	2.6678	-	2.6611	-	2.7377

Table F.37: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 3 was highest rated in both cases.

	Sketch 1	Sketch 2	Sketch 3
Favourite	2	3	5
Least favourite	3	5	3
User score	-1	-2	2
Weighted score	2.67	2.66	2.74

Increase/decrease speed

Table F.38: Attributes were compared against each other in order to define priorities.

Increase/decrease speed	H	L	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	1	1	0	0	3
Arousal	0		0	0	0	0	0
Dominance	0	1		1	0	0	2
Urgency	0	1	0		0	0	1
Annoyance	1	1	1	1		1	5
Appropriateness	1	1	1	1	0		5

Table F.39: Weights for each attribute were calculated.

Scale	Attribute	Weight
10	Annoyance	0.323
9		
8	Appropiateness	0.259
7		
6	Pleasure	0.194
5		
4	Dominance	0.13
3		
2	Urgency	0.065
1	Arousal	0.033

Table F.40: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.194	3.5	0.679	2.8	0.5432	3.3	0.6402
Arousal	0.033	1.4	0.0462	2	0.066	1.5	0.0495
Dominance	0.13	3.7	0.481	3	0.39	3.6	0.468
Urgency	0.065	2.3	0.1495	2.2	0.143	1.7	0.1105
Annoyance	0.323	2.8	0.9044	2.7	0.8721	2.8	0.9044
Appropriateness	0.259	3.3	0.8547	2.8	0.7252	3.2	0.8288
Total score	-	-	3.1148	-	2.7395	-	3.0014

Table F.41: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 1 was highest rated in both cases.

	Sketch 1	Sketch 2	Sketch 3
Favourite	6	2	3
Least favourite	3	8	3
User score	3	-6	0
Weighted score	3.11	2.74	3.54

Maximum/minimum speed

Table F.42: Attributes were compared against each other in order to define priorities.

Max/min speed	H	H	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		0	0.5	0	0	0	0.5
Arousal	1		0.5	0	0	0	1.5
Dominance	0.5	0.5		1	0	0	2
Urgency	1	1	0		0	0	2
Annoyance	1	1	1	1		0.5	4.5
Appropriateness	1	1	1	1	0.5		5

Table F.43: Weights for each attribute were calculated.

Scale	Attribute	Weight
10		
9	Annoyance, Appropriateness	0.3
8		
7		
6		
5		
4	Dominance, Urgency	0.134
3	Arousal	0.1
2		
1	Pleasure	0.034

Table F.44: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.034	3.4	0.1156	3	0.102	2.9	0.0986
Arousal	0.1	2.9	0.21	2.9	0.21	3	0.2
Dominance	0.134	3.7	0.4958	3.4	0.4556	3.1	0.4151
Urgency	0.134	2.7	0.3082	2.8	0.2948	2.4	0.3484
Annoyance	0.3	3.5	1.05	2.9	0.87	3	0.9
Appropriateness	0.3	1.3	1.11	2	0.9	1.8	0.96
Total score	-	-	3.2896	-	2.8324	-	2.9224

Table F.45: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 1 was highest rated in both cases.

	Sketch 1	**Sketch 2**	**Sketch 3**
Favourite	4	2	2
Least favourite	1	5	2
User score	3	-3	0
Weighted score	3.29	2.83	3.54

Stop

Table F.46: Attributes were compared against each other in order to define priorities.

Stop	H	L	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	1	1	0	0	3
Arousal	0		0	0	0	0	0
Dominance	0	1		1	0	0	2
Urgency	0	1	0		0	0	1
Annoyance	1	1	1	1		1	5
Appropriateness	1	1	1	1	0		5

Table F.47: Weights for each attribute were calculated.

Scale	**Attribute**	**Weight**
10	Annoyance	0.323
9		
8	Appropiateness	0.259
7		
6	Pleasure	0.194
5		
4	Dominance	0.13
3		
2	Urgency	0.065
1	Arousal	0.033

Table F.48: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		**Sketch 2**		**Sketch 3**	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.194	2.8	0.5432	3.3	0.6402	4	0.776
Arousal	0.033	1	0.033	2.2	0.0726	1.8	0.0594
Dominance	0.13	2.4	0.312	3.3	0.429	3.4	0.442
Urgency	0.065	1.2	0.078	2.2	0.143	2.3	0.1495
Annoyance	0.323	2.1	0.6783	2.8	0.9044	3.4	1.0982
Appropriateness	0.259	2.8	0.7252	2.8	0.7252	3.9	1.0101
Total score	-	-	2.3697	-	2.9144	-	3.5352

Table F.49: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 3 was highest rated in both cases.

	Sketch 1	**Sketch 2**	**Sketch 3**
Favourite	3	1	6
Least favourite	6	4	2
User score	-3	-3	4
Weighted score	2.37	2.91	2.84

Move inside the lane

Table F.50: Attributes were compared against each other in order to define priorities.

Move inside lane	H	H	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	0	1	0	0	2
Arousal	0		0.5	0.5	0	0	1
Dominance	1	0.5		1	0	0	2.5
Urgency	0	0.5	0		0	0	0.5
Annoyance	1	1	1	1		1	5
Appropriateness	1	1	1	1	0		4.5

Table F.51: Weights for each attribute were calculated.

Scale	Attribute	Weight
10	Annoyance	0.334
9		
8	Appropriateness	0.267
7		
6		
5	Dominace	0.167
4	Pleasure	0.134
3		
2	Arousal	
1	Urgency	0.034

Table F.52: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.134	2.7	0.3618	3.2	0.4288	2.9	0.3886
Arousal	0.067	2.4	0.1742	2.8	0.1474	2.5	0.1675
Dominance	0.167	3	0.501	3.5	0.5845	3.2	0.5344
Urgency	0.034	2.5	0.085	2.4	0.0816	3	0.102
Annoyance	0.334	3	1.002	2.8	0.9352	2.7	0.9018
Appropriateness	0.267	3.1	0.8277	3.2	0.8544	2.8	0.7476
Total score	-	-	2.9517	-	3.0319	-	2.8419

Table F.53: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 2 was highest rated in both cases.

	Sketch 1	Sketch 2	Sketch 3
Favourite	3	4	3
Least favourite	3	1	5
User score	0	3	-2
Weighted score	2.95	3.03	3.12

Change lane

Table F.54: Attributes were compared against each other in order to define priorities.

Change lane	H	L	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	1	1	0	0	3
Arousal	0		0	0	0	0	0
Dominance	0	1		1	0	0	2
Urgency	0	1	0		0	0	1
Annoyance	1	1	1	1		1	5
Appropriateness	1	1	1	1	0		5

Table F.55: Weights for each attribute were calculated.

Scale	Attribute	Weight
10	Annoyance	0.323
9		
8	Appropiateness	0.259
7		
6	Pleasure	0.194
5		
4	Dominance	0.13
3		
2	Urgency	0.065
1	Arousal	0.033

Table F.56: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		Sketch 2		Sketch 3	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.194	3.5	0.679	3.2	0.6208	3.7	0.7178
Arousal	0.033	2.7	0.0891	2.6	0.0858	2.3	0.0759
Dominance	0.13	3.4	0.442	3.3	0.429	3.1	0.403
Urgency	0.065	2.3	0.1495	2.2	0.143	2.4	0.156
Annoyance	0.323	2.7	0.8721	3	0.969	2.9	0.9367
Appropriateness	0.259	3.6	0.9324	3.1	0.8029	3.2	0.8288
Total score	-	-	3.1641	-	3.0505	-	3.1182

Table F.57: The sketch considered as the best by the users was compared with the weighted value of each sketch. For users sketch 3 was consider better, however, the weighted value was slightly higher for sketch 1. As the difference between the weighted values is not considerable, sketch 3 was taken as the best.

	Sketch 1	**Sketch 2**	**Sketch 3**
Favourite	2	0	3
Least favourite	1	2	0
User score	1	-2	3
Weighted score	3.16	3.05	2.45

Command cancelled

Table F.58: Attributes were compared against each other in order to define priorities.

Command cancelled	H	H	H	L	L	H	
	Pleasure	**Arousal**	**Dominance**	**Urgency**	**Annoyance**	**Appropriateness**	**Total**
Pleasure		1	0	1	0	0	2
Arousal	0		0	0	0	0	0
Dominance	1	1		1	0.5	0	3.5
Urgency	0	1	0		0	0	1
Annoyance	1	1	0.5	1		0.5	4
Appropriateness	1	1	1	1	0.5		4

Table F.59: Weights for each attribute were calculated.

Scale	**Attribute**	**Weight**
10		
9	Appropriateness	0.291
8	Annoyance	0.259
7	Dominance	0.226
6		
5		
4	Pleasure	0.13
3		
2	Urgency	0.065
1	Arousal	0.034

Table F.60: A sketch score was calculated for each sketch by summing up the products of the average attribute ratings and their weights.

		Sketch 1		**Sketch 2**		**Sketch 3**	
	Weight	**User score**	**Weighted score**	**User score**	**Weighted score**	**User score**	**Weighted score**
Pleasure	0.13	3	0.39	2.2	0.286	2.5	0.325
Arousal	0.033	3.8	0.0396	4	0.033	3.5	0.0495
Dominance	0.226	2.8	0.6328	2.2	0.4972	2.7	0.6102
Urgency	0.065	1.4	0.091	0.9	0.0585	1.7	0.1105
Annoyance	0.259	2.1	0.5439	1.6	0.4144	2.1	0.5439
Appropriateness	0.291	2.7	0.7857	2.2	0.6402	2.8	0.8148
Total score	-	-	2.483	-	1.9293	-	2.4539

Table F.61: The sketch considered as the best by the users was compared with the weighted value of each sketch. Sketch 1 was highest rated in both cases.

	Sketch 1	**Sketch 2**	**Sketch 3**
Favourite	7	1	2
Least favourite	2	6	2
User score	5	-5	0
Weighted score	2.48	1.93	3.07

F.8 Affinity diagram

The results of the analysis are summarized below using three levels of abstraction. The lowest level (denoted −) consists of issues discovered by the project team after reviewing the qualitative data. These issues were grouped in order to discover the root cause of the problems. Two levels of grouping were made in order to increase the abstraction, the first level (denoted ○) and the second and final level (denoted •). The final level was considered to be the root cause of the problems, resulting in the identification of three issues which needed to be solved in order to create a successful joystick based strategic controller.

- **Haptic feedback needs to be balanced.**
  - ○ Haptic feedback needs to be adapted to the user.
    - The users experience the haptic feedback differently depending on size and strength.
    - The users experience the haptic feedback differently depending on their grip of the joystick.
    - Too strong haptics gives the user the feeling of not being in control.
  - ○ Too strong haptic feedback should be avoided.
    - If the users need to apply a big force to move the joystick they get the feeling as if they are doing something they should not.
    - Strong vibrations make the user feel that something is not working as it should.
    - Users find it difficult to interrupt or cancel commands.
  - ○ Hardware limitations cause the joystick to become unstable when certain forces are applied simultaneously or when applied with big amplitudes.
- **Inputting commands need to be intuitive.**
  - ○ Commands need to be performed in the same fashion.
    - Users feel that there are inconsistencies between commands that are ”queued” and commands that are ”instant”.
    - The user is confused when changing speed as it is not clear how much it changes every time the command is performed.
    - Users find it difficult to perform manoeuvres with the joystick.
  - ○ It needs to be easy to input commands to the system.
    - Users feel that some input patterns are not intuitive.
    - Users feel that it is difficult to remember input patterns.
    - Users find it difficult to take the 2nd or 3rd turn/exit.
  - ○ Users find the joystick similar to a gear stick and expect similar behaviour.
- **Feedback needs to communicate the correct information at the correct time.**
  - ○ Feedback needs to be clear.
    - Users associate ”pattern recognized” with ”pattern accepted”.
    - Users find acceptance and rejection feedback too similar.
  - ○ Sounds have a big impact on overall user experience and need to be well designed.
    - Sounds have a bigger effect on users than haptic signals in many occasions.
    - Sounds can become annoying after a while.
  - ○ Users get out of the loop.
    - When the pattern is not recognized the joystick does not reset.
    - Users do not know when it is safe to step out of the car after stopping the vehicle.
    - Users do not know when the system is ready for a new command.

G. Simulator study

G.1 Background form

<table>
<tr><td>Age:
18-30 years
31-40 years
41-50 years
51-60 years
61-70 years
> 70 years</td><td>Gender:
Male
Female</td><td>Occupation:
Engineering
Economics
Administration
Student
Other: ………………………………
Cannot answer</td></tr>
<tr><td colspan="2">I have had a driving license for:
< 1 year
1-5 years
6-10 years
> 10 years
Cannot answer</td><td>I drive a car:
Daily
A few times per week
A few times per month
A few times per year
Never
Cannot answer</td></tr>
<tr><td colspan="2">I play computer/video games:
Daily
A few times per week
A few times per month
A few times per year
Never
Cannot answer</td><td rowspan="2">I have experience of the following driver assistance systems:
Automated cruise control (ACC)
Advanced emergency braking (AEB)
City safety assist
Forward collision warning (FCW)
Lane departure warning (LDW)
Lane keeping assist (LKA)
Blind spot detection (BSD or BLIS)
Driver Drowsiness Detection
Parking assist
Rear-view cameras
Front view cameras
Navigation (GPS)
Other: ………………………………………..
I do not have any experience of such systems</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">I think that driver assistance systems are useful:
Agree
Partially agree
Neutral
Partially disagree
Disagree
Cannot answer</td><td>I would rely on a system that allows the car to drive by itself:
Agree
Partially agree
Neutral
Partially disagree
Disagree
Cannot answer</td></tr>
<tr><td colspan="2">I would like to have a car that could drive by itself:
Agree
Partially agree
Neutral
Partially disagree
Disagree
Cannot answer</td><td>If the car can drive by itself, I would still want the opportunity to influence the decisions it makes:
Agree
Partially agree
Neutral
Partially disagree
Disagree
Cannot answer</td></tr>
</table>

Figure G.1: The background form which users were asked to fill in before the simulator experiment.

G.2 Simulator scenario

Figure G.2: A map of the scenario used in the simulator studies.

Event	Test subject instructions	Road type	Traffic conditions	Instructions to WoZ assist.	Instructions to WoZ driver
Introduction to simulator	Please drive the car as usual	Freeway	A mix of cars and trucks keeping a distance of 300-500 m between each other on the right lane driving 80 km/h. Speed limit is 90 km/h.		
	Stop the car	Freeway	No traffic		

Table G.1: Simulator introduction, test subjects were asked to drive manually in order to get familiar with the simulator environment.

Event	Test subject instructions	Road type	Traffic conditions	Instructions to WoZ assist.	Instructions to WoZ driver
Introduction to concept		Freeway			Car is in AD mode. Activate WoZ steering wheel.
	AD mode activated	Freeway	Cars with 200-500m spacing in right lane driving 70 km/h. Speed limit is 90 km/h.		
	Change to left lane	Freeway		Accept	Change to left lane
	Change to right lane			Accept	Change to right lane
	Take the next exit right	High road	No traffic	Accept	Take the next exit right
	Stop the car	High road		Accept	Stop the car at the exit

Table G.2: AD mode introduction, test subjects were asked to follow instructions in order to familiarize with the concept.

Event	Test subject instructions	Road type	Traffic conditions	Instructions to WoZ assist.	Instructions to WoZ driver
	Car is now in auto mode	High road			
		High road	Distant tractor driving 30km/h		
1.	Overtake vehicle	High road	Car is behind the tractor. Light traffic in left lane, one car 15/sec. No traffic in right lane.	Accept	Overtake
2.	Take the next exit to the right	Access ramp	No traffic	Accept	Take the next exit and enter freeway
	Cancel command	Access ramp	Command is being executed	Do nothing	Do nothing
3.	Change to left lane	Freeway	One truck passes, no other traffic	Accept	Change to left lane
4.	Change to right lane	Freeway	No traffic	Accept	Change to right lane
5.	Take the next exit to the right	Freeway	No traffic	Accept	Take the next exit to the right
6.	At the next crossing, turn **left**	Freeway	No traffic, road block ahead, only right turn is possible	Decline	Turn right
7.	Overtake	Freeway	Slow truck ahead driving 40 km/h. Oncoming traffic every 3 sec which delays the overtake for a while until traffic stops	Accept	Wait until traffic has passed. Overtake when possible.
8.	Overtake	High road	Car in front driving 50km/h.	Accept	Do nothing
	Cancel overtake	High road	Car in front accelerates to 70 km/h.	Do nothing	Do nothing. Increase speed when possible.
9.	At the next crossing, turn left	Urban	Speed limit is 50 km/h, there's no traffic. Car in front takes a turn and disappears.	Accept	Turn left
10.	Park the car	Urban	Two cars parked in front on the side of the road	Accept	Park the car at the side of the road

Table G.3: The scenario used for the experiment.

G.3 User Experience Questionnaire

	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	○	enjoyable	1
not understandable	○	○	○	○	○	○	○	understandable	2
creative	○	○	○	○	○	○	○	dull	3
easy to learn	○	○	○	○	○	○	○	difficult to learn	4
valuable	○	○	○	○	○	○	○	inferior	5
boring	○	○	○	○	○	○	○	exciting	6
not interesting	○	○	○	○	○	○	○	interesting	7
unpredictable	○	○	○	○	○	○	○	predictable	8
fast	○	○	○	○	○	○	○	slow	9
inventive	○	○	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	○	○	supportive	11
good	○	○	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	○	○	easy	13
unlikable	○	○	○	○	○	○	○	pleasing	14
usual	○	○	○	○	○	○	○	leading edge	15
unpleasant	○	○	○	○	○	○	○	pleasant	16
secure	○	○	○	○	○	○	○	not secure	17
motivating	○	○	○	○	○	○	○	demotivating	18
meets expectations	○	○	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	○	○	efficient	20
clear	○	○	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	○	○	practical	22
organized	○	○	○	○	○	○	○	cluttered	23
attractive	○	○	○	○	○	○	○	unattractive	24
friendly	○	○	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	○	innovative	26

Figure G.3: The User Experience Questionnaire, test subjects were asked to assess the product by ticking one circle per line.

G.4 Interview questions

- How did you experience driving in an autonomous car?
- How did you experience the user interface? What do you feel about inputting commands which impact the car's decision?
- Do you think the concept is appropriate? When would it be inappropriate?
- Did anything unordinary happen during your journey? How did you react? Did you experience this as something positive or something negative?
- What function was most useful for you?
- Did the system behave as you expected?
- Is the system reliable?

- What do you think about the reliability of the systems?
- Would you use such a system in your everyday life?
- How would you like to change the system in order to adapt it to your needs?

G.5 Test subject profiles

User	Age	Gender	Occupation	Driving license	Driving frequency	Simulator experience	Computer games playing frequency	Experience with driver assistance systems
1	51-60	Female	None	>10 years	Daily	None	Never	ACC, AEB, GPS, city safety assist
2	61-70	Man	Engineering	>10 years	A few times per week	Some previous experience	Never	ACC, FCW, BSD, GPS, rear-view cameras
3	18-30	Female	HR	6-10 years	Daily	Some recent experience	A few times per year	None
4	18-30	Female	Engineering	6-10 years	A few times per year	None	A few times per year	ACC, FCW, GPS, parking assist, rear- and front-view cameras
5	51-60	Man	Economics	>10 years	Daily	2-5 times	A few times per year	ACC, GPS

Figure G.4: User profiles of the participants in the simulator studies.

User	"I think driver assistance systems are useful."	"I could rely on a system that allows the car to drive by itself."	"I would like to have a car that could drive by itself."	"If the car can drive by itself, I would still want the opportunity to influence the decision it makes."
1	Agree	Agree	Agree	Agree
2	Agree	Agree	Agree	Agree
3	Agree	Partially agree	Agree	Partially agree
4	Neutral	Partially agree	Partially agree	Agree
5	Agree	Partially agree	Agree	Agree

Figure G.5: User profiles of the participants in the simulator studies.

G.6 UEQ results

Test subject scores

Table G.4: Test subject scores for items 1-13.

Item	1	2	3	4	5	6	7	8	9	10	11	12	13
Test person 1	5	6	5	7	7	7	6	5	5	7	5	1	7
Test person 2	6	6	3	2	2	5	5	6	2	2	6	2	7
Test person 3	7	7	2	2	1	7	6	6	3	2	6	1	6
Test person 4	6	5	2	1	3	5	5	6	5	2	6	3	7
Test person 5	5	6	4	2	3	6	6	5	3	3	5	3	5

Table G.5: Test subject scores for items 14-26.

Item	14	15	16	17	18	19	20	21	22	23	24	25	26
Test person 1	7	2	6	5	4	2	5	2	4	3	3	2	7
Test person 2	6	2	7	1	2	1	6	1	7	2	2	2	3
Test person 3	7	4	6	2	2	1	6	1	7	1	1	2	7
Test person 4	6	4	6	3	2	2	6	3	6	1	1	2	5
Test person 5	5	6	5	5	3	3	6	4	6	3	3	4	6

Transformed data

Table G.6: The transformed values per item for items 1-13. The +3 represents the most positive and the -3 the most negative value.

Items	1	2	3	4	5	6	7	8	9	10	11	12	13
Test person 1	1	2	-1	-3	-3	3	2	1	-1	-3	1	3	3
Test person 2	2	2	1	2	2	1	1	2	2	2	2	2	3
Test person 3	3	3	2	2	3	3	2	2	1	2	2	3	2
Test person 4	2	1	2	3	1	1	1	2	-1	2	2	1	3
Test person 5	1	2	0	2	1	2	2	1	1	1	1	1	1

Table G.7: The transformed values per item for items 14-26. The +3 represents the most positive and the -3 the most negative value.

Items	14	15	16	17	18	19	20	21	22	23	24	25	26
Test person 1	3	-2	2	-1	0	2	1	2	0	1	1	2	3
Test person 2	2	-2	3	3	2	3	2	3	3	2	2	2	-1
Test person 3	3	0	2	2	2	3	2	3	3	3	3	2	3
Test person 4	2	0	2	1	2	2	2	1	2	3	3	2	1
Test person 5	1	2	1	-1	1	1	2	0	2	1	1	0	2

Attribute to scale conversion

Table G.8: The results obtained from the five test subject questionnaires.

Item	Mean	Variance	Std. Dev.	Left	Right	Scale
1	1,8	0,7	0,8	annoying	enjoyable	Attractiveness
2	2,0	0,5	0,7	not understandable	understandable	Perspicuity
3	0,8	1,7	1,3	creative	dull	Novelty
4	1,2	5,7	2,4	easy to learn	difficult to learn	Perspicuity
5	0,8	5,2	2,3	valuable	inferior	Stimulation
6	2,0	1,0	1,0	boring	exciting	Stimulation
7	1,6	0,3	0,5	not interesting	interesting	Stimulation
8	1,6	0,3	0,5	unpredictable	predictable	Dependability
9	0,4	1,8	1,3	fast	slow	Efficiency
10	0,8	4,7	2,2	inventive	conventional	Novelty
11	1,6	0,3	0,5	obstructive	supportive	Dependability
12	2,0	1,0	1,0	good	bad	Attractiveness
13	2,4	0,8	0,9	complicated	easy	Perspicuity
14	2,2	0,7	0,8	unlikable	pleasing	Attractiveness
15	-0,4	2,8	1,7	usual	leading edge	Novelty
16	2,0	0,5	0,7	unpleasant	pleasant	Attractiveness
17	0,8	3,2	1,8	secure	not secure	Dependability
18	1,4	0,8	0,9	motivating	demotivating	Stimulation
19	2,2	0,7	0,8	meets expectations	does not meet expectations	Dependability
20	1,8	0,2	0,4	inefficient	efficient	Efficiency
21	1,8	1,7	1,3	clear	confusing	Perspicuity
22	2,0	1,5	1,2	impractical	practical	Efficiency
23	2,0	1,0	1,0	organized	cluttered	Efficiency
24	2,0	1,0	1,0	attractive	unattractive	Attractiveness
25	1,6	0,8	0,9	friendly	unfriendly	Attractiveness
26	1,6	2,8	1,7	conservative	innovative	Novelty

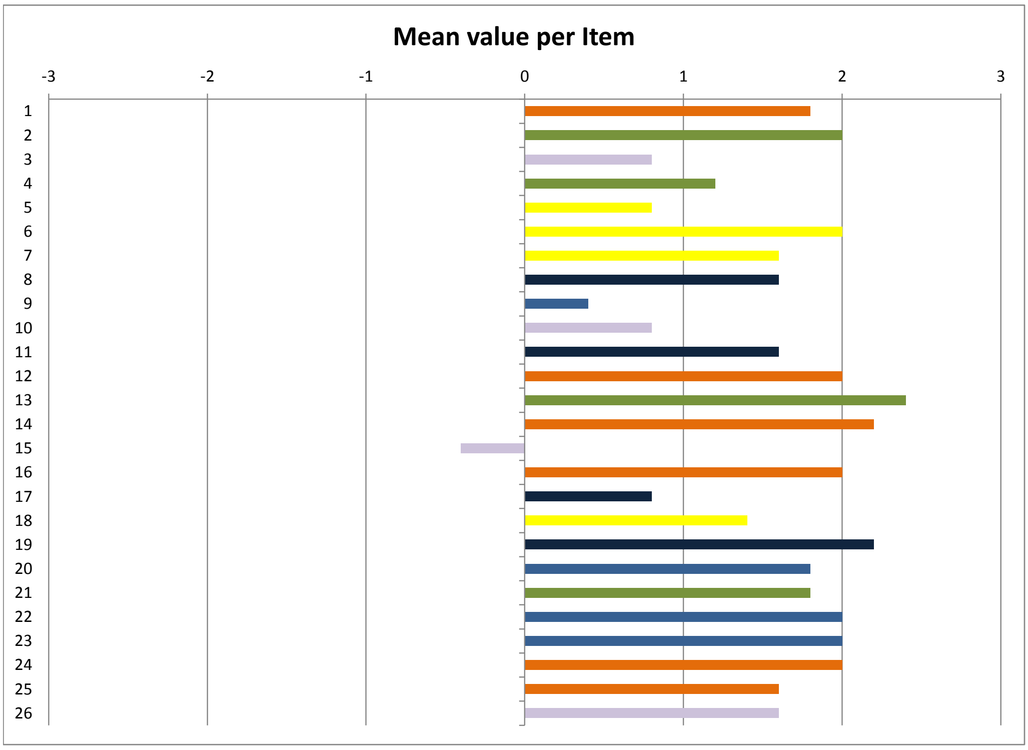


Figure G.6: Visualization of the mean values per item from the test subject questionnaire.

Confidence intervals for items and scales

Table G.9: Confidence interval (p=0.05) per item.

Item	Mean	Std. Dev.	N	Confidence	Confidence interval	
1	1,800	0,837	5	0,733	1,067	2,533
2	2,000	0,707	5	0,620	1,380	2,620
3	0,800	1,304	5	1,143	-0,343	1,943
4	1,200	2,387	5	2,093	-0,893	3,293
5	0,800	2,280	5	1,999	-1,199	2,799
6	2,000	1,000	5	0,877	1,123	2,877
7	1,600	0,548	5	0,480	1,120	2,080
8	1,600	0,548	5	0,480	1,120	2,080
9	0,400	1,342	5	1,176	-0,776	1,576
10	0,800	2,168	5	1,900	-1,100	2,700
11	1,600	0,548	5	0,480	1,120	2,080
12	2,000	1,000	5	0,877	1,123	2,877
13	2,400	0,894	5	0,784	1,616	3,184
14	2,200	0,837	5	0,733	1,467	2,933
15	-0,400	1,673	5	1,467	-1,867	1,067
16	2,000	0,707	5	0,620	1,380	2,620
17	0,800	1,789	5	1,568	-0,768	2,368
18	1,400	0,894	5	0,784	0,616	2,184
19	2,200	0,837	5	0,733	1,467	2,933
20	1,800	0,447	5	0,392	1,408	2,192
21	1,800	1,304	5	1,143	0,657	2,943
22	2,000	1,225	5	1,074	0,926	3,074
23	2,000	1,000	5	0,877	1,123	2,877
24	2,000	1,000	5	0,877	1,123	2,877
25	1,600	0,894	5	0,784	0,816	2,384
26	1,600	1,673	5	1,467	0,133	3,067

Table G.10: Confidence intervals (p=0.05) per scale.

Scale	Mean	Std. Dev.	N	Confidence	Confidence interval	
Attractiveness	1,933	0,673	5	0,590	1,344	2,523
Perspicuity	1,850	0,698	5	0,612	1,238	2,462
Efficiency	1,550	0,818	5	0,717	0,833	2,267
Dependability	1,550	0,891	5	0,781	0,769	2,331
Stimulation	1,450	0,716	5	0,627	0,823	2,077
Novelty	0,700	1,037	5	0,909	-0,209	1,609

G.7 Affinity diagram

The results of the analysis are summarized below using three levels of abstraction. The lowest level (denoted −) consists of issues discovered by the project team after reviewing the qualitative data. These issues were grouped in order to discover the real reason for why users had a pleasant or unpleasant experience. Two levels of grouping were made in order to increase the abstraction, the first level (denoted ◦) and the second and final level (denoted •).

- **Autonomous driving is found to be futuristic.**
  - It is hard to imagine how the concept works outside the simulator environment.
  - Users need time to grasp autonomous driving.
- **Users are willing to use the system.**
  - Users trust the system.
    - To be able to cancel a command gives the feeling of being in control.
    - Users feel safe and secure when using the controller.
    - Users feel they have the control of the car.
  - The controller cooperates with the user.
    - Users appreciate the ability to influence the control of the vehicle.
    - Users feel that the controller is supportive of their actions.
- **Users get out of the loop.**
  - It is difficult to understand when a command cannot be performed.
    - An explanation why a command is denied was missing.
    - The rejection was unclear, the user could not understand the reason of it.
    - The rejection and the acceptance feedback should be more different.
  - It is easy to get out of the loop with delayed commands.
    - If a command is delayed, the user is unsure if the input command was correct.
    - Users expect that the car cancels commands which become redundant after being in queue for too long.
- **Using the joystick is easy and it works as expected.**
  - Inputting command is intuitive.
    - Users do not find the joystick innovative.
    - Users feel familiar when using the joystick to instruct the car.
  - Users find commands to be well defined.
    - Users feel that the available commands are sufficient and cover their basic and expected needs.
    - It is easy to learn the patterns for all commands.
- **The strategic controller simplifies the driving process.**
  - Autonomous driving reduces the mental workload.
    - Users appreciate that the car is able to make complex decisions.
    - Overtake and turn left/right were the most useful commands.
  - It relieves the users from monotonous driving.
    - Users would prefer driving to work autonomously using a strategic controller.
    - Users found it suitable to use in road environments with low traffic density.
  - Autonomous driving allows the user to focus on other tasks.
    - Users quickly relax after a short period of driving.
    - Users easily become bored when driving autonomously.