An Investigation into the Role of Take-off Signals in Acoustic Vehicle Alerting Systems

Designing Acoustic Vehicle Alerting Systems for Electric Trucks in a Virtual Environment

Master's thesis in Interaction Design and Technology

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MASTER'S THESIS 2020

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Abstract

This research is concerned with designing Acoustic Vehicle Alerting Systems for electric trucks, and more specifically, Volvo Trucks. During this research, a virtual environment was created and the effects of a take-off sound on AVAS was examined. According to the results, adding a take-off sound improves the AVAS greatly and can contribute to an increased level of perceived safety and pleasantness. Moreover, a series of questions in an online questionnaire regarding the potential dangers of the statistically most fatal scenarios were asked of VRUs, in order to examine the knowledge gaps regarding these scenarios. The results of this questionnaire suggest that although the VRUs as a collective exhibit a good understanding of how dangerous each situation is, they failed to recognize the leading cause of fatal accidents involving HGVs and VRUs, namely taking off from a standstill. Moreover, the results of this research show a need for a better understanding of masking as a phenomenon and a need for the governing bodies to take this concept into consideration in order to reduce fatalities caused by the future electric vehicles.

To summarize, the research team of this thesis investigates:

1. the road users understanding of dangerous scenarios in traffic compared to the statistics generated by Volvo Truck & Swedish National Road Agency
2. how can a Virtual environment be an alternative & cost-effective solution to get a better understanding of the target group for a new feature/product and also be used to prototype new features/products in the automotive industry.
3. Gather user insight for a new feature in AVAS for electric trucks, a take-off sound.
4. Are regulations for Acoustic Vehicle Alerting System sufficient?

Keywords: Electric Trucks, Safety, Virtual Environment, Acoustic Vehicle Alerting System, Truck Take-off, Design Guidelines, Acoustic Vehicle Alerting System (AVAS) Regulations, Interaction Design, Unreal Engine, COVID-19

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Mahmoud Shirnazar & Sten Rõngelep
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List of Abbreviations and Terms

3D	Three Dimensional
AI	Artificial Intelligence
AVAS	Acoustic Vehicle Alerting System
CIT	Critical Incident Technique
CLOCS	Construction Logistics and Community Safety
CNG	Compressed natural gas
COVID-19	Coronavirus Disease 2019
DB	Decibels
DB(A)	A-weighted decibels
EBU	European Blind Union
EU	European Union
EV	Electric Vehicle
GDPR	General Data Protection Regulation
HGV	Heavy Goods Vehicle
HTML5	HyperText Markup Language 5
HVO	Hydrotreated Vegetable Oil
HZ	Hertz
ICE	Internal Combustion Engine
ISO	The International Organization for Standardization
KM/H	Kilometres per hour
LED	Light-emitting Diode
LO-FI	Low-Fidelity
NHTSA	The National Highway Traffic Safety Administration
NPC	Non-Player Character
NPRM	A notice of proposed rulemaking
RTD	Research Through Design
SID	Sonic Interaction Design
UE4	Unreal Engine 4
UI	User Interface
UK	United Kingdom
UN	United Nations
USA	United States of America
Volvo GTT/ Volvo Trucks	Volvo Group Trucks Technology
VR	Virtual Reality
VRU	Vulnerable Road Users
WBU	World Blind Union
WHO	World Health Organization

1

Introduction

Electric vehicles (EVs) are arguably the most promising vehicles of the future which will likely continue to disrupt the automotive industry in many ways such as vehicle design, or noise and air pollution. These vehicles are more environmentally friendly and far quieter than their combustion engine counterparts. However, the lack of engine noise in these vehicles can be detrimental to road safety and risk reduction in terms of fatal accidents. As such, the governing bodies such as the European Union and The National Highway Traffic Safety Administration have put in place a series of regulations that requires the automotive manufacturers who aim to produce hybrid and electric cars to implement an Acoustic Vehicle Alerting System (AVAS) to compensate for the lack of engine noise in EVs. At the time of writing this report, these regulations are set to become obligatory in 2021(United Nations, 2017). As such, in this report the master thesis workers focused on understanding the field and the knowledge gaps that can be crucial to AVAS's contribution to risk reduction in regard to fatal accidents.

During this project, a series of conceptual work including take-off sounds for the Acoustic Vehicle Alerting System were created and tested in a virtual environment. This environment was developed to replace a real-life test environment due to the COVID-19 pandemic. The virtual environment proved to be a very useful tool for communicating and evaluating conceptual works as it allowed for rapid prototyping of the concepts, as well as creating a realistic and complex simulation where the users can evaluate the AVAS as a pedestrian.

Furthermore, a knowledge gap was identified where the understanding of vulnerable road users (VRUs) did not match the statistics regarding fatal accidents. Particularly, the VRUs failed to recognize the number one most dangerous situation identified by the 2017 Volvo Safety Report (Kuckom, Örtlund, Ekfjorden & Wells, 2017), namely, truck moving forward at a constant speed, and ranked it as the fourth most dangerous scenario among a total of six scenarios.

The focus of this study is on adding a take-off sound to AVAS in order to reduce the risk for fatal accidents in urban areas. This is especially important as one of the main causes of fatalities in urban areas that have been marked by the Volvo Safety Report consists of heavy goods vehicles (HGVs) taking off from a standstill. Consequently, a series of take-off sounds were generated, implemented, and evaluated in terms of their noticeability, safety, pleasantness, and representativeness of the vehicle. According to the results of our study, a take-off sound is a clear improvement to AVAS and therefore it is recommended that a take-off sound is implemented when designing for future AVAS.

1.1 Report overview

This project consists of three iterations where the researchers I) investigate the subject matter, and especially the perception of dangerous situations by the VRUs, II) create a virtual environment for the testing of AVAS concepts and III) create and implement AVAS and take-off sounds as well as evaluate them.

Moreover, in the following pages a background consisting of necessary information regarding regulations, psychoacoustics, similar products and more are elaborated. Then, the research and design methods used for this process are explained, followed by a detailed description of the process. Furthermore, the results of the iterations are displayed and discussed, and a series of design- as well as research guidelines are offered, to help future researchers investigate the subject-matter.

1.2 Research Question

In this paper we aim to answer the following research questions.

What should be considered when designing AVAS for Volvo Trucks?

More specifically, we would like to investigate the following sub-questions and design to answer them:

I) What should be considered when designing a take-off sound for an electric truck?
II) How can a virtual environment be used in designing and evaluating AVAS?
III) How can the physical properties of a vehicle be communicated to the VRUs during take-off?
IV) Are the regulations set up by EU and NHTSA enough to make the future EVs detectable to an acceptable degree?

1.3 Limitations

As previously mentioned, this research coincided with the outbreak of COVID-19 in Europe. This consequently had important implications on this work and almost completely changed the trajectory of the research. Most importantly, the circumstances lead to an evaluation in a virtual environment replacing the real-life experiments which were to be in accordance to Volvo Trucks' guidelines and ISO standards.

1.4 Stakeholders

The direct stakeholders of this thesis were mapped in our ideation phase and later during the process new stakeholders were identified. Our main stakeholders are:

- Volvo Group Trucks Technology Division
- Road users
- Master thesis researchers, the authors of this thesis.

About Volvo Trucks

The Master thesis was carried out in collaboration with Volvo Trucks. Volvo Trucks is the second-largest heavy-duty truck provider in the world with over 50 000 employees. The core values of the company are quality, safety, and environmental care. Volvo Trucks global headquarters is in Lundby, Gothenburg, where we did our thesis. Their vehicles are sold and serviced in more than 130 countries and the trucks are assembled in 14 countries across the globe. About 95% of the company's production capacity is located in Sweden, Belgium, Brazil and the USA (Volvo Trucks, n.d. a.).

Volvo Trucks have 12 different truck models on the market with 5 different fuel types (Volvo Trucks, n.d. b.):

- Diesel
- CNG
- Biodiesel
- HVO
- Electric

Volvo Trucks proposed the general topic of this work, namely Acoustic Vehicle Alerting System. Initially, Volvo GTT did not have a specific research question and our mission was to provide the company with new insight into Acoustic Vehicle Alerting systems for Volvo electric trucks. As this type of system contributes to the general safety of Volvo trucks, it is important for Volvo GTT to better understand the dynamics between the AVAS and other road users, especially vulnerable road users (VRUs). Additionally, it is important for Volvo GTT to create a high quality AVAS that is not only safe, but also pleasant, and contributes minimally to noise pollution in the environment.

Road Users

Volvo electric trucks are currently mainly used in urban areas which brings us to our next stakeholders- namely road users in urban areas. These stakeholders consist of bicyclists, pedestrians, motorcyclists, car drivers and truck drivers whose safety may be compromised by a lack of engine noise in electric vehicles.

The Authors

The authors created an experiment with a take-off scenario for Volvo Electric trucks in a virtual environment, giving new insight to Volvo Trucks about Take-off sounds for AVAS and Virtual Environment as a tool for prototyping. Our goal is to write a strong thesis in order to obtain a master’s degree in Interaction Design & Technologies in Chalmers.

1.5 Other Stakeholders

As previously mentioned, a series of other stakeholders were identified by the researchers. These stakeholders primarily include

- Emergency services
- Municipalities
- Clients of Volvo Trucks and their employees who operate Volvo trucks

Emergency Services

Emergency services have daily calls to accidents. By making the communication of different road users clearer, the safety of VRUs and other road users will increase. Consequently, this would result in less accidents to attend to for the Emergency services.

Municipalities

As EVs emit less noise, the soundscape of municipalities changes. Consequently, the general picture of a city changes by reducing noise pollution, which can in turn affect the reputation of that city in regard to the quality of life.

Volvo Trucks' Clients

Clients of Volvo Trucks will have a high-quality safety Acoustic Vehicle Alerting System equipped on their new truck. With such a system implemented in the electric HGVs, the clients will likely have less accidents which consequently results in less time being spent off the roads, and a more efficient work routine for truck drivers.

Additionally, the clients will meet the safety requirements of different standards and get a high rating in the inspection. An example of these standards is a standard set up by the UK based organization Construction Logistics and Community Safety (CLOCS). This standard, and particularly the Requirement 3.2.4 regarding Vehicle Manoeuvring Warnings requires the logistic industry "to reduce the risk of close proximity collisions by audibly alerting vulnerable road users to vehicle hazards" (Construction Logistic and Community Safety, 2015, p 5).

2

Background

The emergence of electric vehicles can be seen as the emergence of a disruptive technology. A disruptive technology consists of an innovation that creates a new market, usually resulting in changes in the market leadership and the emergence of new companies as dominant actors (Øverby & Audestad, 2018, p 6). A famous example of disruptive technology is the emergence of digital cameras which transformed the respective market drastically. This led to the collapse of established and traditional photography companies such as Kodak as a main manufacturer of photography cameras, as they failed to embrace the new technology.

Established and newly founded car and truck manufacturers such as Volvo and Tesla, are embracing the production of EVs in order to have a share of the current and future market. Clearly, the emergence of the new technology and market requires development of new features, exploration of possibilities and addressing of the new challenges that consequently arise.

2.1 Similar Products and Related Work

Although the regulations regarding acoustic vehicle alerting systems are not obligatory at the time of writing this report, a series of automotive manufacturers have implemented some type of AVAS on their electric vehicles. Automotive manufacturers who have already implemented this system and meet the requirements of the regulations include Mercedes-Benz, Audi, and Jaguar.

Additionally, an AVAS has been implemented and tested in the electric buses in the Tottenham area, London. The AVAS implemented in this case consists of a set of speakers inside the front of the bus which emit a sound for when the vehicle is not in operation - more specifically a F#maj7, and as the vehicle starts to move, a single tone of C# together with a rhythmic pulsating sound are added over the F#maj7, (Sustainable Bus, 2019).

Moreover, some well-known manufacturers of automotive parts, such as HELLA who is known for manufacturing lighting and electronics for vehicles have started developing AVAS (HELLA, 2019) and as such, it is expected that yet more similar products will be produced and released in the coming years.

Furthermore, a similar system has since long been an optional feature for different types of vehicle, namely the vehicle reversing alarms which are alerting systems warning the VRUs of the intentions of trucks and sometimes lighter vehicles while reversing.

2.2 Previous research on AVAS

Several studies have already been done on AVAS and designing sounds for electric and hybrid vehicles. The approach taken in these articles varies greatly depending on the perspective of the author(s) and their branch of profession, As such, several knowledge gaps have been exposed and investigated where for example blind people, the elderly and pedestrians have been identified as vulnerable road users (Hwang, 2016, Rötz & Kelkar, 2019). Moreover, it is established that although AVAS should be able to alert other road users of the intentions and behaviours of a quiet vehicle (car), the sound generated should not be annoying nor out of place for the vehicle and the environment it is operating within (Rötz & Kelkar, 2019; Hwang, 2016).

For instance, a (2014) article by Kihlman, Kropp and Lang deep dives into the health related issues of noise pollution and states that in reality, the lack of engine sound is a non-problem and warns that AVAS can become a problem in quiet areas. Interestingly, Kihlman and colleagues (2014) investigate the noise emission from heavy trucks and its correlation with vehicle speed versus engine speed. The findings of this investigation show that the noise emission is better correlated with engine speed, rather than with the vehicle speed (Kihlman, Kropp & Lang, 2014).

Some studies, on the other hand, focus on designing for AVAS and investigate the requirements and contexts within which the design of AVAS should be framed. For example, Rötz and Kelkar (2019) have identified that broadband sounds are perceived as very pleasant whereas tonal components are needed for safety reasons. Coupled with this, an investigation of the technical aspects, namely, using loudspeaker versus transducers [shakers] and speaker position have found that the sound generated by a loudspeaker was better identified in comparison to that of a transducer (Rötz & Kelkar, 2019). Coupled with this, the study shows that the position of the loudspeaker that best addresses the legal requirements is on the bumper behind the hatch (Rötz & Kelkar, 2019). Moreover, Rötz and Kelkar (2019) found that a High Rhythmic sound was higher rated than the Low Rhythmic sound in respect to preference of the users and safety and appropriateness to the environment.

2.3 Road Safety and Statistics on Accidents

According to the Volvo Safety Report (Kockum et al.,2017) around 15% of all road fatalities in the EU are caused by HGVs, of which 32 % are accidents causing fatalities to vulnerable road users (Kockum et al., 2017).

The fatal accidents have been categorized and the most frequent accidents are the following:

- 30 % of accidents are related to a collision with VRU at intersection, moderate or high speed. VRU suddenly crosses the road in front of the truck, for example at crossroads.
- 20 % of accidents are related to a collision with VRU when turning (right in right hand traffic and left in left-hand traffic) at low speed. Front or side of the truck hits stationary VRU (often at red light or crossing) when turning or the cyclist comes at speed hitting the side of the truck.
- 15 % of accidents are related to collisions with VRU in lane at moderate to high speed, for example during lane exit, lane changing, merging or cutting in. Side of the truck hits VRU.

The three most frequent links to causes according to European Road Safety Observatory (European Road Safety Observatory, 2018) are:

- Faulty diagnosis – Information failure (between driver and traffic environment or driver and vehicle) with the frequency of 43 out of 195 links in total
- Observation missed – Permanent sight obstruction with the frequency of 23 out of 195 links
- Observation missed – distraction with the frequency of 13 out of 195 links.

Faulty diagnosis is an incorrect or incomplete understanding of road conditions or another road user's actions. Permanent sight obstruction refers to vehicle blind spots on these larger vehicles, where drivers cannot see part of the road infrastructure or other road users. (European Road Safety Observatory, 2018)

The common differences from a safety perspective between a car and a truck are:

- Trucks have much more blind spots
- Trucks are heavier
- Trucks' braking distance is longer
- Trucks' momentum is bigger
- Trucks are not as agile as cars.
- Driver fatigue – driving a truck requires much more workload

2.4 Noise pollution and Health Concerns

With the rise of electric vehicles (EVs), the amount of noise pollution produced by vehicles is on a decline as these vehicles produce significantly less noise in low speeds (Poveda-Martínez, 2017; European Commission 2019). Quieter vehicles are beneficial especially in regards to public health in urban areas, as a high level of noise pollution is closely correlated with a series of health problems including but not limited to cardiovascular diseases, cognitive impairment, sleep disturbance and tinnitus (World Health Organization, 2011). At the same time, with quieter vehicles on the roads. new challenges arise – particularly regarding the safety of the VRUs when EVs commute on noisy streets. In other words, quiet vehicles impose a risk for other road users such as pedestrians, cyclists and the visually impaired (European Commission, 2017) as they may not be made aware of the vehicle's presence through sound cues (European Commission, 2019). Moreover, the visually impaired can be especially impacted by this type of change as they solely rely on sound cues for detecting approaching vehicles.

2.5 AVAS Regulations

To address the arising concerns regarding quieter EVs and road safety, governing bodies such as European Commission have required manufacturers of hybrid and electric vehicles to implement Acoustic Vehicle Alerting Systems (AVAS) (European Commission, 2019). Likewise, the Department of Transportation in the USA have created similar regulations for electric vehicles. (Department of Transportation, 2019).

Such regulations and the demand on the car manufacturers consequently mean that several automotive manufacturers are now required to address the knowledge gaps in the field of electric and hybrid vehicles regarding AVAS and road safety.

Both regulations are relatively new and there are rather few cars on the streets that meet these regulations- meaning that there is a lack of data and accurate understanding on how effective these regulations are. As such, European Blind Union (EBU) and World Blind Union (WBU) have jointly lobbied for stronger requirements such as compulsory introduction of a stationary sound and an increase of the minimum sound level required by the regulations (European Blind Union, n.d.).

2.5.1 European Regulation

European regulations require all electric vehicles to automatically generate a sound from the start of the vehicle to the speed of 20 km/h as of 1 July 2021. The overall maximum sound level for AVAS is 75 dB(A) and the minimum sound levels at 10 km/h are 50 dB(A), at 20 km/h are 56 dB(A) and at reversing is 47 dB(A) (Table 2.1). The Vehicle Manufacturer is allowed to offer alternative sounds which can be selected by the driver. Each of the sounds must be in compliance and approved with the provision. AVAS must have at least two of the one-third octave bands according to Table 2.1 and at least one of these bands shall be below or within the 1,600 Hz one-third octave band. The regulation also requires a frequency shift to signify acceleration and deceleration (United Nations, 2017).

Table 2.1

Minimum Sound Level Requirement in dB(A) According to the United Nations

Frequency in Hz		*Constant Speed Test paragraph 3.3.2. (10 km/h)*	*Constant Speed Test paragraph 3.3.2. (20 km/h)*	*Reversing Test paragraph 3.3.3.*
Column 1	*Column 2*	*Column 3*	*Column 4*	*Column 5*
Overall		50	56	47
1/3rd Octave Bands	160	45	50	
	200	44	49	
	250	43	48	
	315	44	49	
	400	45	50	
	500	45	50	
	630	46	51	
	800	46	51	
	1,000	46	51	
	1,250	46	51	
	1,600	44	49	
	2,000	42	47	
	2,500	39	44	
	3,150	36	41	
	4,000	34	39	
	5,000	31	36	

Note. From United Nations (United Nations, 2017).

2.5.2 USA Regulation

The regulations created by National Highway Traffic Safety Administration (NHTSA) of the United States, requires that electric vehicles generate enhanced artificial sounds up to 30 km/h (see Table 2.2).

According to a statement by NHTSA in 2018: “hybrid and electric vehicles will have to meet a requirement based on sound level in either two or four one-third octave bands at the vehicle manufacturer’s option, and a vehicle may alternate between meeting the 2- band and 4-band specifications depending on test speed. Vehicles complying with the 4-band option must meet minimum sound pressure levels in any four non-adjacent one-third octave bands between 315 Hz and 5000 Hz, including the one-third octave bands between 630 Hz and 1600 Hz (these bands were excluded in the NPRM). Vehicles complying with the 2-band option must meet minimum sound pressure levels in two non-adjacent one-third octave bands between 315 Hz and 3150 Hz, with one band below 1000 Hz and the other band at or above 1000 Hz. The two

bands used to meet the 2-band option also must meet a minimum band sum level." (Department of Transportation, 2018, p.8186)

This was decided to give manufacturers more flexibility when designing AVAS. Additionally, NHTSA requires that "EV's of the same make, model and model year emit the same sound by specifying that those vehicles use the same alert system hardware and software, including specific items such as the same digital sound file to produce sound used to meet the minimum sound." (Department of Transportation, 2018, p.8186). Later on adding that "there would not be a limit to the number of compliant sounds a manufacturer could install in a vehicle." Later, adding that "there would not be a limit to the number of compliant sounds a manufacturer could install in a vehicle." (Department of Transportation, 2019, p. 48866)

In the latest version of Electronic Code of Federal Regulations, it is stated that: "Any two vehicles of the same make, model, model year, body type, and trim level [...] to which this safety standard applies shall be designed to have the same pedestrian alert sound when operating under the same test conditions and at the same speed including any test conditions and speeds for which an alert sound is required in Section S5 of this safety standard." (Department of Transportation, 2018, p. 8196). This suggests that as the regulations are changing and are open to discussions, manufactures are recommended to keep themselves up to date and suggest possible improvements. The table below (Table 2.2) displays the latest Minimum Sound Level Requirements for AVAS in dB(A) according to the Department of Transportation.

Table 2.2

Minimum Sound Level Requirements for AVAS in dB(A) According to Federal Motor Vehicle Standard No.141

Frequency in Hz		Stationary and constant speeds less than 10 km/h	Constant speeds greater than 10 km/h but less than 20 km/h	Constant speeds greater than 20 km/h but less than 30 km/h	Constant speeds between 30-32 km/h	Reverse
1/3rd Octave Bands	315	39	45	52	56	42
	400	39	44	51	55	41
	500	40	46	52	57	43
	630	40	46	53	57	43
	800	41	47	53	58	44
	1000	41	47	54	58	44
	1250	42	48	54	59	45
	1600	39	44	51	55	41
	2000	39	45	51	55	42
	2500	37	43	50	54	40
	3150	34	40	47	51	37
	4000	32	38	45	49	35
	5000	31	36	43	47	33

Note. From (Department of Transportation, 2019).

2.5.3 EU & USA Regulation Comparison

For the comparison of the European Union and the United States of America's regulations a table (Table 2.3) has been created.

Table 2.3

Comparison of EU & US Legislations for AVAS

Regulation	FMVS S141	UNR 138	FMVS S141	UNR 138	FMVS S141	UNR 138	FMVS S141	FMVS S141
1/3 Octave Bands	Reverse	Reverse	0-10 km/h	10 km/h	10-20 km/h	20 km/h	20-30 km/h	30-32 km/h
160		47 Overall		45		50		
200				44		49		
250				43		48		
315	42		39	44	45	49	52	56
400	41		39	45	44	50	51	55
500	43		40	45	46	50	52	57
630	43		40	46	46	51	53	57
800	44		41	46	47	51	53	58
1000	44		41	46	47	51	54	58
1250	45		42	46	48	51	54	59
1600	41		39	44	44	49	51	55
2000	42		39	42	45	47	51	55
2500	40		37	39	43	44	50	54
3150	37		34	36	40	41	47	51
4000	35		32	34	38	39	45	49
5000	33		31	31	36	36	43	47

The main differences between these regulations are:

- The UN Regulations has set the 1/3 Octave Bands to start from 160 Hz while the US Regulation starts from 315 Hz.
- The US Regulation defines the sound levels with a range, for example 10 - <20 km/h while the UN Regulations defines the sound levels and a constant speed
- The UN Regulations has the same minimum sound level for reverse, but the US Regulation sets the sound levels for reverse based on the 1/3 Octave band.

2.6 Sound as a physical phenomenon

In the following section, a series of properties related to sound are discussed. The following paragraphs describe important concepts in creating Acoustic Vehicle Alerting Systems and Take-off sounds for AVAS.

2.6.1 Physical Properties of Sound

There are several ways to examine sound; for instance, sound as a physical phenomenon or sound as perceived auditory information inside an individual's brain. Sound as a physical phenomenon consists of vibrations within materials that involve an exchange of energy (Farnell, 2010). When the sound wave travels through the air and reaches our ears, certain components of the ears vibrate in the same manner as the source of the sound (Cook, 2001). There are several factors contributing to how a sound is perceived – for instance, the distance between the source of the sound and our ears is an important factor in what we hear, as growing distance leads to the sound we hear growing weaker in loudness. The reason behind this phenomenon is the spherical shape of wave fronts – as the surface area of the wave front increases with the square of the radius, the intensity of a sound reaching the listener will decrease with the square of the distance between the source of sound and the listener (Cook, 2001)

As Cook (2001) mentions, different sounds produce various types of waves. For the sake of simplicity, let us think about a simple form of sound waves, called sinusoidal waves. These waves have certain physical properties which are characterized by three concepts, namely:

1. The maximum amplitude (measured in centimetres, volts, sound pressure etc.
2. The Frequency in Hertz (cycles per second).
3. Phase, which specifies the position when the sine wave reaches its peak amplitude.

For the purposes of this research, we will primarily focus on frequency and amplitude of sounds as physical properties since changes in phase are not important in how we perceive sound.

2.6.2 Amplitude (Sound Power and Energy)

The relative amplitude of sine waves is expressed in terms of decibels (dB) – which is always given in terms of decibels above a reference level. Amplitude is closely related to the power and energy a sound wave has; however, the peak of a sound wave is not very well perceived by human cognition as it lasts a very short while. As such, it is more relevant to speak about the power or the energy that a sound has regarding its perception of loudness, rather than its amplitude.

2.6.3 Frequency and spectrum

Frequency of a wave indicates the number of full cycles a wave completes within one second – that is, how many times a wave is repeated per second. Different frequencies have different effects on human cognition and certain frequencies have a higher perceived loudness due to evolutionary reasons. Coupled with this, is the concept of spectrum which refers to a full description of a wave form for each frequency which consists of two numbers, namely the amplitude and phase of each frequency in a certain sound (Cook, 2001).

2.6.4 Sound Perception and Psychoacoustics

Psychoacoustics is the field of science concerned with the physical effects of sound on biological systems (Berg, 2019). With the help of psychoacoustics and models offered by this field of science, the scientists can analyse how humans perceive, understand, and react to auditory information. The importance of psychoacoustics is crystalized when designing sounds containing important information such as the location of an object as it offers an understanding of which physical properties of sound can be perceived by humans.

The perception of sound, also known as audition, is a crucial sensory function of the primates. Audition is to a great extent comparable with vision from many perspectives: from sharing certain regions of the brain with the visual system, to being tasked with solving similar problems such as creating a spatial understanding of the world. Moreover, auditions are crucial for humans as it adds meaningful information about the world that the visual system cannot provide. For instance, vision is strictly limited to what the eyes are viewing and therefore we cannot see what is behind us; with the help of audition, we can retrieve information about objects and events behind us (Banich & Compton, 2018). The auditory system in us aims to solve the same type of problems as those of the visual system such as representing several features of the sensory world in a way that objects and their locations can be understood (Banich & Compton, 2018). Another similarity between the auditory and visual systems is the ability to distinguish between a figure from its background. For example, when looking at a specific vehicle, we are able to distinguish the vehicle from its background. Similarly, auditory perception allows us to distinguish a single sound stream such as a person's voice from the ambient background noise (Banich & Compton, 2018).

Auditory processing begins in the ear (Banich & Compton, 2018). When a sound wave travels from the source and reaches our ears, it produces vibrations in certain components of the ears similar to that of the sound source. Furthermore, different sensory features such as pitch, loudness and timing of sounds are processes to recognize various events (Banich & Compton, 2018) such as ringing of a bell, or the sirens of an ambulance.

2.6.5 Masking and least noticeable difference

Like human vision, the auditory system is not flawless in distinguishing different sounds. Take two close shades of colour like the green and blue next to each other in Figure 2.1: similar to the way that the visual system will have a hard time distinguishing the two colours, the auditory system will have a hard time distinguishing two sounds with close frequencies.

Figure 2.1

A Shade of Green and a Shade of Blue That are Close to One Another are Difficult to Distinguish

As the sound is analysed in the basilar membrane of the cochlea, a particular place along the basilar membrane is stimulated most strongly to a sinusoidal vibration of a specific frequency. Consequently, "while a sound of one frequency can mask a sound of a nearby frequency, it cannot mask a sound of widely separated frequency. Lower-frequency sounds can mask the sounds of higher frequency, but higher-frequency sounds cannot mask sounds of lower frequency." (Cook, 2001, p. 9).

2.7 Technical Implementation

The research team primarily used three software within the thesis to create the virtual environment, namely Unreal Engine, VCV Rack and Reaper. The following section introduces these software.

2.7.1 Unreal Engine

Unreal Engine 4 is an advanced real-time 3D creation tool which is not only used for creating games, but also designing high-fidelity visualization and immersive cinematic experience across different industries. UE4 is used by several different automotive and transportation companies such as Audi, Chevrolet, McLaren, Porsche and Volkswagen and enables designers and experts to communicate their ideas through rapid visual prototyping, collaborative design reviews, human-machine interaction testing, ergonomic studies and more (Epic Games, n.d. a). Unreal Engine 4 offers an extensive documentation with instructions and a marketplace with free assets to get started.

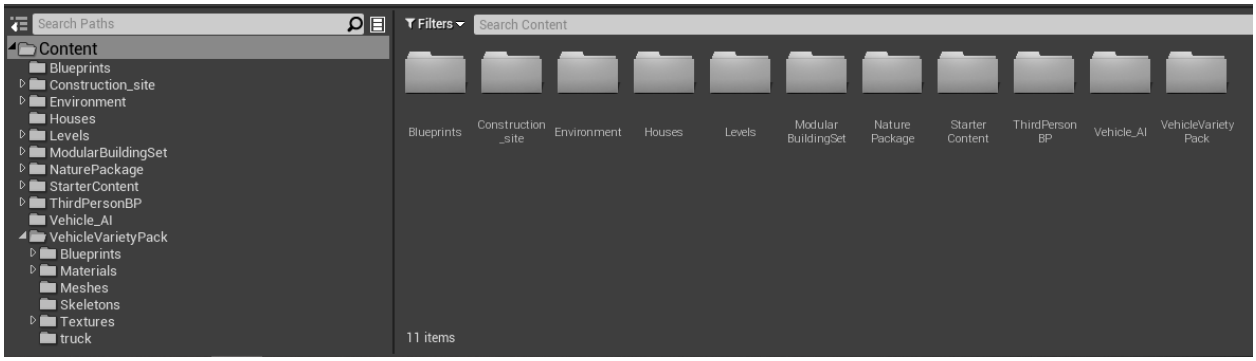
In the following paragraphs the concepts which are central to designing a virtual environment for AVAS using Unreal Engine 4 are briefly explained. Understanding these concepts will be useful further on in the report where technical implementation of the project is elaborated.

Project

A project includes all the content that make up the Virtual Environment. The project hierarchy tree (see Figure 2.2) in Unreal Engine 4 is used for structuring and navigating between content. New content such as images, 3D models and assets are imported to the project through the hierarchy tree.

Figure 2.2

Project Hierarchy Tree in UE4

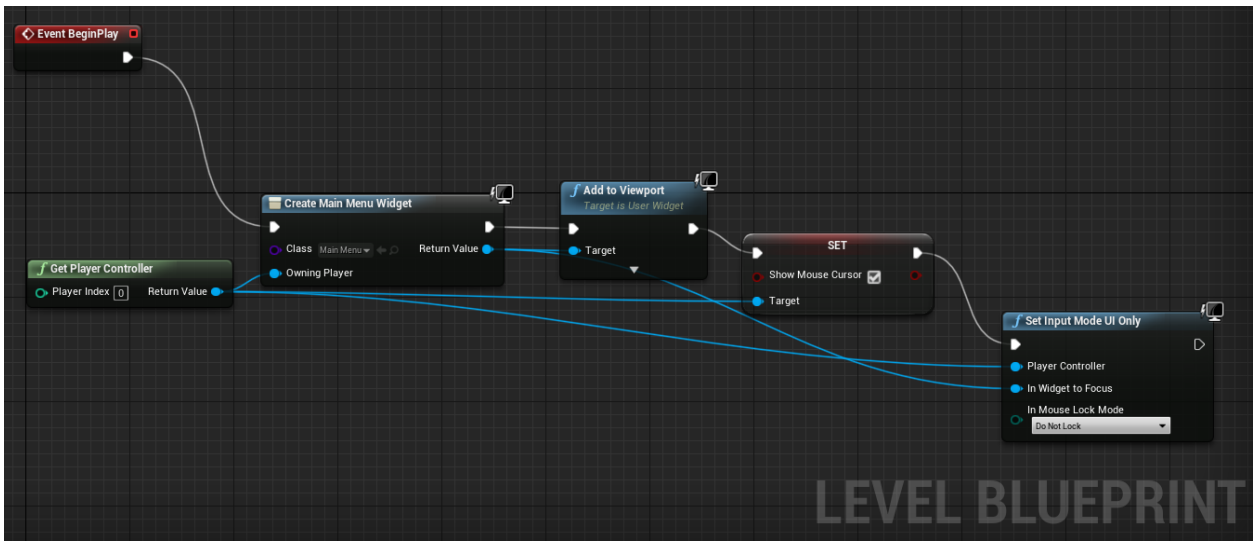


Blueprints Visual Scripting

Blueprints Visual Scripting system is a powerful and flexible tool for designers as it offers a range of tools generally only available to programmers (Epic Games, n.d. b). Blueprints Visual Scripting uses a node-based visual interface to define objects. This allows the research team to create elements and define objects without text-based coding (see Figure 2.3).

Figure 2.3

Blueprint Example of a Main Menu Being Loaded at the Beginning of the Virtual Environment



Marketplace

Epic Games has created a marketplace for Unreal Engine. This allows content creators to upload their products for purchase. The marketplace also includes free content that is made available for everyone. This allows new developers to use existing content and facilitate the learning experience.

2.7.2 VCV RACK

In order to generate the sounds used in this experiment, we used a virtual modular synthesizer called VCV Rack to program the sounds used in the simulation. This software offers a large range of settings through which one can change different properties of sound such as frequency, pulsation, amplitude, reverberation, attenuation and so forth.

2.7.3 REAPER

The research team used the software REAPER to record, edit and mix the sounds generated through VCV Rack for the experiment.

2.8 The Vision Zero

The Vision Zero is a multinational goal set-up initially in 1995 to prevent accidents resulting in fatality or life-long injuries in traffic by e.g. suggesting a reduced speed limit on certain roads (Trafikverket, n.d.; Action Vision Zero, n.d.). Naturally, to have safer roads, effective communication between different road users is necessary and a failure in communicating the intentions, actions and the type of road user can be detrimental in achieving Vision Zero.

3

Methodology

In the following paragraphs, a series of methods and how they related to this work of research are discussed. More specifically, the relation between sonification and interaction design, the research and evaluation methods used in this research, as well as design methods which this research benefited from are described.

3.1 Interaction Design and Sound

Studying and designing for disruptive technologies can be challenging as often, it is difficult to set boundaries and define the problem. This type of problem is known as wicked problems which can be understood as *underspecified* problems. A wicked problem is a problem that is complex enough so that there are no correct *a priori* solutions to it, and for which formulating the situation is a necessary part of addressing it (Gaver, 2012). As such, when researching underspecified problems, the theories produced by frameworks such as Research through Design are not falsifiable in principle (Gaver, 2012). In other words, theories produced in this type of work will have the form of *designing for X can lead to a successful outcome* where the argument is not that X will *always* result in successful design, which would be open to refutation (Gaver, 2012).

Deciding the boundaries and the type of evaluation in this type of problem can be challenging. Therefore, the researchers need to establish the boundaries by looking at the purpose of the research, which in turn stems from values (Wadsworth, 2011) that are established by the stakeholders and users. Thus, in order to begin the work of addressing the problem, the researchers need to empathize with users by steeping themselves in the data available, and talking to the users and stakeholders to gather information about their values (Preece, Rogers & Sharp, 2019; Wadsworth, 2011).

3.1.1 Auditory Displays

Auditory display researchers are interested in how the auditory system in humans can be used as the primary interface for communicating information (Serafin et al., 2011). In other words, Auditory Display “encompasses all aspects of a human-machine interaction system” (Serafin et al.,2011, p. 1) through exploiting the ability of the human auditory system to identify temporal changes and patterns (Serafin et al, 2011).

Using the auditory system as the primary interface of data transmission is derived from its ability to effortlessly perform complex tasks that even the most modern computers are incapable of reproducing (Serafin et al.,2011). The ability to identify sound sources, melodies,

or a basketball hitting the ground even in noisy environments are a few examples that demonstrate the power and complexity of the auditory system.

3.1.2 Sonification

Sonification as a subset of auditory displays is a means for transformation of information into perceived relations in form of non-speech audio signals for communication and interpretation. In other words, sonification aims to translate relationships in data into sounds perceived by humans in a way that the data relationships are understandable (Serafin et al.,2011).

3.1.3 Sonic Interaction Design

Sonic Interaction Design (SID) is an interdisciplinary field which combines the efforts of researchers and designers at the intersection of fields such as interaction design, human-computer interaction, sound and music computing, product design, music psychology, and music composition (Serafin et al., 2011). SID investigates how sound can be used to "convey information, meaning, aesthetic and emotional qualities in interactive contexts." (Serafin et al, 2011, p.87).

One of the benefits of using sound as means of interaction is due to auditory perception and action being naturally and closely coupled. Consequently, perceiving a sound not only gives the listener information about the nature of the object and event, but also may prepare them for reacting to the sound (Serafin et al, 2011). As such, SID is an area within Interaction Design that can offer invaluable insight in designing an acoustic vehicle alerting system for electric vehicles.

3.2 Research Methodology

In the following, a series of research methods are presented. These methods were used in the pre-study phase, as well as during the course of iterations in order to gather a better understanding of the subject-matter, as well as evaluating the products created during the course of this thesis work.

3.2.1 Benchmarking

Benchmarking in Interaction Design is used to test a prototype continuously over an extended period, in order to track the progress. It can also be used to compare products to other competitors' products (Interaction Design Foundation, n.d.). In this thesis, Benchmarking is used to compare existing products between to get better insight into the field and the related work.

3.2.2 Observation

Since the research area is a new area for the master thesis workers, observation may be a key method in defining the problem in the early stages (Preece, Rogers & Sharp, 2019; Martin & Hanington, 2012). Observational studies consist of two methods of observation, namely, semi-structured (casual) or structured (systematic) observations (Martin & Hanington, 2012).

As Martin and Hanington (2012) explain, this type of research method typically describes ethnographic methods in the exploratory phase of the design process. Therefore, this method may be useful in early stages where the focus is to immerse into the context and understand the user's needs. Moreover, Observational methods combined with Surveys help establish a good ground for making decisions regarding the convergence of context and ideas. In doing so, Observational methods provide the research team with information about how different parties behave in relation to each other and how the environment affects their day-to-day lives. This type of information can then be used in combination with Surveys, concept mapping and other design methods to create a series of scenarios (Preece, Rogers & Sharp, 2019) and context.

3.2.4 Surveys (Questionnaires)

Questionnaires are one of the main tools used to gather survey information which are often used to complement an observational study. This method allows the researchers to gather self-reported information about their characteristics, thoughts, feelings, behaviours and attitudes of the participants, which may in turn reveal invaluable information about the users which can then be used together with other methods (e.g. concept mapping, personas etc.) to build context and make design decisions (Preece, Rogers & Sharp, 2019; Martin & Hanington, 2012).

Questionnaires are often conducted with the help of online resources or software which make gathering and analysing of data much easier, however, extra attention should be paid to the wording of the questions as that is an important factor in securing a good response rate (Martin & Hanington, 2012).

Using Questionnaires as a survey method may have many benefits for the design process. Depending on the format of the questionnaire, the results may bring an evaluative, or explorative value. Questionnaires made up of close-ended questions are generally easier to numerically analyse and communicate and may consequently help designers base their decision on the target groups' preferences. Furthermore, by using open-ended questions the researchers provide an opportunity for the users to respond to the question in depth, which in turn may help explore the subject-matter and its relation to the users.

3.2.5 Surveys (Interviews)

As one of the two ways of carrying out a survey, interviews are used in combination with observations and questionnaires in order to verify and humanize the data collected (Martin & Hanington, 2012). Depending on the purpose of the research, interviews may be structured and strictly follow a script of questions, which in turn facilitates the timekeeping and analysing the answers. Alternatively, they may be unstructured which in turn allows for more comfortable and explorative settings (Martin & Hanington, 2012; Preece, Rogers & Sharp, 2019).

Using interviews can give us a better understanding of what different stakeholders, truck drivers, pedestrians and cyclists expect of an Acoustic Vehicle Alerting System. Moreover, unstructured interviews may prove to be more useful than structured interviews as they allow for exploration of ideas, context and situation, and the users' needs. However, structured interviews with certain stakeholders may be necessary in order to help keep the interview focused on a set of specific questions.

3.2.6 Research through Design

Although there is no single definition that all the disciplines using research through design (RtD) agree on, the core consensus is that RtD contributes with designerly activities and qualities as means of knowledge outcome (Stappers & Giaccardi, n.d.). In doing so, activities such as to introduce a prototype into the world, measure, analyse and discuss the effects can especially contribute to producing knowledge (Stappers & Giaccardi, n.d.).

As mentioned before, the theories produced in this type of work, namely using research through design, are such that a solution may sometimes lead to a successful outcome. This in turn, leads to an unfalsifiable assertion. Since in principle, the next try may lead to successful or unsuccessful outcomes, it is a difficult task to produce a controlled experiment where the results are useful for theory testing through design (Gaver, 2012).

Research through design is not concerned by comparison and refutation as is the case with Popper's epistemology but rather focuses on presenting an assertion to answer the question "what might be…" rather than "what is…" (Gaver, 2012). Therefore, in this thesis work, we do not aim to answer a falsifiable question, but rather to use design as a generative tool for exploration and conceptualization. Furthermore, the designers' concern is not that *"*design theory can sometimes generate bad designs [...] [rather] the concern is to sometimes create good ones" (Gaver, 2012, p. 4). By the same token, the goal of conceptual work in research through design is to develop theories that are sometimes right, rather than ones that are never wrong, through exploring and experiencing different approaches (Gaver, 2012; Preece, Rogers & Sharp, 2019).

3.2.7 Think-aloud protocol

Think–aloud protocol consists of participants articulating what they are thinking, doing and feeling as they complete a set of tasks that are aligned with the everyday goals. This method is a rather straightforward way of collecting information about the aspects of a product that delight, confuse and frustrate people (Martin & Hanington, 2012).

There are mainly two ways to conduct a think-aloud method – namely Concurrent Think-aloud and Retrospective Think-aloud whereas the users respectively either works through the tasks while articulating what they are feeling , doing and thinking, or they first go through the task in silence while they are being recorded and then comment on the process as they watch a replay of their experience.

This type of research may result in invaluable insight to how truck drivers and other road users operate, think and feel in a certain context. Consequently, think-aloud protocol may be a very useful method in early stages in order to identify aspects of driving trucks that may otherwise be unknown to the researchers. Furthermore, a concurrent think-aloud protocol is more suitable for this project as recording individuals in the manner required for a retrospective think-aloud is not a preferable option due to the GDPR and privacy policies of the company.

3.2.8 Thematic Analysis

Thematic Analysis consists of a collection of methods with a focus on identifying patterned meaning across a qualitative data set. Thematic analysis is commonly used to identify patterns

of themes in semi-structured interviews and generally consists of six steps (Mortensen, 2020; Blandford, n.d.):

1. Familiarize yourself with your data.
2. Assign preliminary codes to your data in order to describe the content.
3. Search for patterns or themes in your codes across the different interviews.
4. Review themes.
5. Define and name themes.
6. Produce your report.

After getting familiarized with the data, a phrase or a few words are used to summarize the insight. These words and phrases that specify the content are known as codes in this context. These codes will then be used to create categories, subcategories and so forth that result in the patterns and themes that are common throughout the data set. The themes will then be reviewed and analysed, and then described in the report (Mortensen, 2020; Blandford, n.d.).

This method focuses on the important and potentially interesting insights of a qualitative data set through the aforementioned steps as opposed to all available data. These insights ought to be in the areas that are important to the stakeholders, and the off-topic yet interesting insight should not be included in the same project (Mortensen, 2020).

3.2.9 Heuristic Evaluation

Heuristic Evaluation refers to an evaluation method which based on an agreed upon set of usability best practices helps detect and correct usability problems prior to having actual users test a product or system (Martin, & Hanington, 2012). This type of evaluation is often performed by members of the design team and experts and does not require actual users for its purposes, namely detecting baseline usability problems. This method is especially used in early and middle phases of design which in turn helps the designers to achieve a more user-centered design in a low cost and less resource intensive manner (Martin, & Hanington, 2012).

In this report, the agreed upon usability best practices are the ten principles developed by Nielsen (1994) which were then used in the second iteration of this research (see section 4.2.2.4)

3.2.10 Affinity Diagram

This method helps organize and cluster together related information and consequently leads to categorizing and synthesizing the information gathered through observed and learned insights (Martin & Hanington, 2012). Furthermore, this technique enables us to better understand the context in which AVAS is used, as well as leading to the emergence of a story about the users, their tasks and the nature of the problem (Martin & Hanington, 2012). This type of research usually takes observations retrieved from an interview as input and generate a qualitative result which can help build context for and around wicked problems.

3.2.11 Concept Mapping

A concept is “a well-understood idea, object, or event; usually a noun or noun cluster” (Martin & Hanington, 2012, p. 38). By connecting the concepts together through linking words (e,g, a

verb) a proposition is created. Some of these propositions will reflect upon relations that are already understood while others will generate new knowledge (Martin & Hanington, 2012). The purpose of concept mapping is to help the researchers make sense of a context where many ideas, objects, events etc. are connected to one another, through a visual framework that introduce new connections in the context of already understood information (Martin & Hanington,2012).

Constructing a concept map requires the researchers to have a good understanding of the domain (Martin & Hanington, 2012) therefore, this method will be a useful tool after having collected information about the domain and the target groups. Additionally, conducting the right focus question is an important aspect of using this method:"articulating the correct focus question is a key step that will provide context and structure to the map. 'How do people share pictures' and 'How do people want to share pictures' should lead to different maps: the former providing a listing of options, the latter, a more exploratory audit suggesting a range of opportunities." - (Martin & Hanington, 2012, p.38)

3.3 Design Methodology

In the following, a series of design methods are presented. The following design methods were used to create prototypes which were consequently evaluated through the research and evaluation methods.

3.3.1 Prototyping

Prototypes generate new knowledge in a different manner than most other methods; by introducing a prototype to the world, one can analyze, measure and discuss the effects of an artifact (Stappers & Giaccardi, n.d.). Moreover, "A prototype can also be a paper-based outline of a display, a collection of wires and ready-made components, a digital picture, a video simulation, a complex piece of software and hardware, or a three-dimensional mockup of a workstation." (Preece, Rogers, & Sharp, 2019, p. 422). Prototypes are excellent tools for communication among the team members, discussing ideas with stakeholders and exploring and testing out ideas. Prototypes come in different levels of fidelity where low-fidelity (LO-FI) prototypes are commonly used throughout early ideation process (in form of e.g. concept sketches, storyboards etc.). On the other hand, we have high-fidelity (Hi-FI) prototypes which consist of a more refined artifact that somewhat represents the look-and-feel and basic functionalities of a design.

One of the important benefits of using prototypes is that they allow the stakeholders to interact with a version of a future product to acquire some experience of using it in the context and environment it is meant to be used in, as well as exploring the supposed uses (Preece, Rogers & Sharp, 2019). As such, by using a limited version of a design, a prototype provides the researchers with an opportunity to better understand, experience, and envision what it would be like to have and use the product.
This method will be a crucial part of this research, as it offers a large array of generative insights and understanding. Furthermore, prototyping will be an important means of communicating ideas and concepts to the stakeholders, and team members.

3.3.2 Speculative Design

As we are designing for the future, one of the tools available to us in terms of design methodology is Speculative Design. More specifically, as our aim is to better understand AVAS and electric vehicles in respect to a future context, speculative design will enable us to not only better understand and design for the future, but also to critique the current practices (Auger, 2013). Speculative Design is a design methodology where the limitations imposed by the commercial sector which often lead to a normative design process are eliminated and instead the designers use prototypes as a core, and use fiction "to present alternative products, systems or worlds" (Auger, 2013, p 1).

What a speculative design approach brings to this research is the ability to generate ideas for the future. Furthermore, as opposed to associative design which gives way for experimentations within the field of conceptual art, speculative design explicitly focuses on science and technology to project scenarios of use (Malpass, 2018). By using a speculative design approach, we aim to gain a better understanding of the scientific theories and cultural implications related to AVAS and road safety in different ways. This gain in understanding in speculative design is due to the speculative design's encouragement of reconsidering the trajectory of present and how we might have the chance to change it (Malpass, 2018).

On the other hand, using this type of methodology to answer a wicked problem can be far from straight-forward. According to Auger (2013), and Malpass (2018), for a speculative design project to be successful, the speculations need to be carefully managed in order to offer plausible, reality-based, and feasible solutions. If the speculations are poorly managed and stray too far into the future or are too extraordinary – the audience will not be able to relate to, engage with or connect with the proposed solution (Auger, 2013). Furthermore, often, the contexts generated for speculative design have a dystopic subtext (Malpass, 2018) which may not be of much help in exploring a system such as AVAS. Moreover, speculative design often aims to reflect on the ethical and societal implications of applied science (Malpass, 2018) which is not the focus of this research but can prove beneficial to consider from a user experience standpoint.

3.3.3 Critical Making

Similar to critical design – a method commonly used in industrial design - Critical Making projects are thought to be particularly useful for issues in which no problem definition is agreed upon by the experts and researchers in the area (Ratto, 2011). This method is concerned with critical reflection on technology and society and works to blend and extend fields such as design, contemporary art, and technological development (Hertz, n.d.). In doing so, Critical Making merges two usually disconnected modes of engagement in the world, namely critical thinking, and making to address wicked problems. In critical making, the final prototypes are not intended to be the goal, rather they are a means to achieve value through joint construction, conversation and reflection (Ratto, 2011; Hertz, n.d.).

Despite the similarities between critical design, and critical making, there are several differences between the two. For instance, Critical making is much more focused on the constructive process of making as opposed to building an artifact, whereas critical design is more focused on build refined objects to criticize the traditional industrial design (Hertz, n.d.). In short, critical making, is explicitly concerned with making as an important part of the process. Moreover, "Critical making intervenes by giving designers and the public an

opportunity to break out of this cycle, step back, and mindfully reconsider a broader spectrum of human experience. it also strives to highlight people, perspectives and practices that are forgotten in conventional product development workflows: and consider the diverse complexities of what it means to be human." (Hertz, n.d.).

This method is a powerful tool for investigating the relationship between technology and society; therefore, the results produced can be the type of results that the stakeholders of this and similar research are interested in. Therefore, it is likely that this method will be used in this work of research.

3.3.4 Scenarios

Scenarios in interaction design are mostly used to explore and emphasize on the use of a possible future product from users perspective and understand the users behaviour (Martin, & Hanington, 2012). The research team created visual animations about high-risk situations in traffic to understand how road users view the danger of different accident scenarios between HGVs and VRUs. The scenarios were created from a neutral point of view, giving an overview from the top about the accident. This allowed us to use the scenarios with different road users. All the scenarios start with HGVs and VRUs crossing paths and end with a possible collision.

3.3.5 Sketching

Sketching is a common form of lo-fi prototyping (Preece, Rogers & Sharp, 2019). This type of prototyping can be utilized through methods such as storyboarding where the prototype may be a storyboard sketch consisting of things e.g. people, artifacts, etc. and actions such as find, listen, transfer, write etc. (Preece, Rogers & Sharp, 2019). Sketching as a method of prototyping is a useful tool for the purposes of this project as it provides the research team with economical, fast and simple means of ideation and prototyping.

4

Process

During the course of this project, a series of changes were imposed on the scope and the nature of this research project. Particularly, this research coincided with the COVID-19 pandemic and its outbreak in Europe, in early 2020. This in turn led to the shutting down of Volvo factories and offices in Sweden. This meant that the project's course was interrupted as the research team no-longer had access to most of the material and knowledge that Volvo had made available. Moreover, the Chalmers University of Technology took the necessary measures in order to limit the spread of the virus COVID-19. As such, the research team was recommended by the authorities and the stakeholders to work from home and minimize the exposure to other people through social distancing.

Consequently, the project's aims and goals were changed to match the new requirements and challenges. As such, the researchers were forced to scrap the previously planned Clinics, sprints and presentations accordingly and opted for a digital demonstration of the AVAS concepts through building a digital environment. To move forward with the project, the research team decided to use the previous research which was done prior to the COVID-19 outbreak and incorporate the scenarios and findings into a virtual 3D world built primarily in Unreal Engine 4.

Moreover, due to the COVID-19 pandemic, a great part of prototyping and evaluation took place remotely, and the evaluation of the concepts and prototypes created had to be reworked. As such, the researchers were forced to opt for a smaller, more homogenous sample size than initially planned for the clinic. Coupled with this, the research team were unable to perform the experiment in Volvo Group Trucks Technology buildings and instead were forced to perform the experiment in the available locations at Chalmers University of Technology at Johanneberg, and Lindholmen Campus in Gothenburg, Sweden.

The pandemic also meant that the researchers were no-longer able to benefit from the resources that Volvo Group Trucks Technology could otherwise provide, and even lost their mentor due to termination of consultancy contacts because of the circumstances. Further on, in late April, Volvo GTT informed the thesis workers that the company cannot provide them with any further support for the rest of the project's course, even though a gradual re-opening of the company was due to take place from the 4th of May 2020. This consequently meant that the thesis workers could not acquire a 3D model of a Volvo truck for the simulation in time and therefore opted for using free 3D models provided by Epic Games.

4.1 Pre-studies

In the following paragraphs, the initial research phase is elaborated. The purpose of the initial research was to provide the research team with a better understanding of the concepts, and knowledge gaps regarding Acoustic Vehicle Alerting Systems as well as truck drivers' and VRUs' behaviour in urban areas. Coupled with this, the initial research helped the research team map out the areas where AVAS is crucial to road safety and give them a better understanding of how and why fatal accidents involving HGVs and VRUs happen.

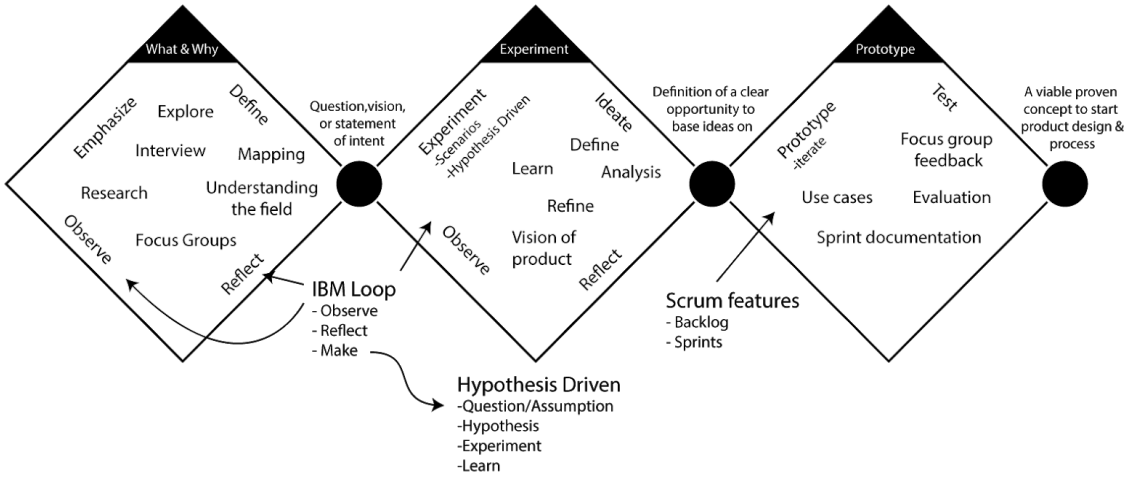
In order to get started with the project, the researchers received a series of material created and gathered by Volvo and the respective mentor for the project at the company. Consequently, this phase started with literature review where the research team familiarized themselves with the regulations and the research done in the field of AVAS. Coupled with this, the research team had the chance to be present in a couple of field-tests were prototypes made to address the regulations were tested by the Volvo function owners and experts. During this phase, the researchers got the chance to have a series of shorter co-rides with our mentor, during which several notes were taken and a think-aloud test was performed to better understand the truck users perspective, as they are operating a truck.

In addition to the above, the research team observed several different sites where HGVs were used, e.g. docking stations, urban areas, and goods terminals. The information collected was then analysed and categorised using affinity diagramming and story mapping techniques. Furthermore, during the initial phase of the project, we gathered data from experts and truck drivers - and got to interview some experts present at Volvo Trucks to better understand the concept, risks associated with driving heavy goods vehicles and the gaps in the field.

Lastly, in this phase, we conducted a planning report, which included the initial framework for the thesis, where we planned three iterations (sprints) during the project (see Figure 4.1).

Figure 4.1

Initial Framework used for the Thesis.



In the diverging part of each iteration, we used methods such as observations, surveys, sketching, scenarios and think-aloud protocol to gather data and expand our understanding

and focus. Subsequently, in the converging phase of each iteration, we used methods such as concept mapping, prototyping, experiments, affinity diagramming, heuristic evaluation, thematic analysis to delimit the scope and narrow down the focus of the research.

Moreover, each iteration will require a certain type of outcome. In the first iteration, it would be beneficial to create scenarios and personas in order to build a testable context where important safety aspects of AVAS will be outlined. To do so, the researchers will base the Scenarios and Personas on data gathered from the observational studies and surveys. Particularly, we aim to interview experts to identify the situations where the risk for VRUs are especially high. The identified situations then will be used in a questionnaire to be ranked and sorted by Experts, potential VRUs and Drivers. Then, the results of this will be used to conduct scenarios as the result of the first iteration. The outlined scenarios will then be presented to the stakeholders at Volvo Technology in order to make sure that the research is on the right track.

Subsequently, the results from the first iteration will then be fed forward to the second iteration where the research team will incorporate the findings into a new divergence phase where the research team gathers more information about the scenarios and the gaps they expose. Then, an experiment will be designed to test one or two scenarios. Furthermore, after an ideation session, a lo-fi prototype will be built to test in the scenario(s). At this point, we aim to use standardized protocols such as ISO to perform an evaluation of our prototype. The results from this evaluation will then be used as input for our last iteration where we incorporate the findings of our second iteration to refine our prototype. The refined prototype will then be evaluated again to conclude our findings.

After having finalized the planning report and having gathered enough information about the field, the research team made a scrum-board where the tasks for the next iteration were set up. It is noteworthy that the above-mentioned plan was disrupted by extraordinary circumstances due to the COVID-19 pandemic. These changes to the framework will be elaborated further on in the section Iteration II.

4.2 Design iterations

Iteration 1: Consists of observations, benchmarking of similar products, online questionnaire, and interviews with truck-drivers, bus drivers and VRUs. This iteration resulted in the researchers recreating some of the most dangerous scenarios as well as a scenario taken from our observations in the pre-studies, by animating a bird-eye view of the most critical situations which was consequently used in the online questionnaire in order to compare the statistics with the perception of danger by different road-users.

Iteration 2: Consists of creating a virtual environment in Unreal Engine 4 where the research team implemented different types of AVASes to be evaluated in an experiment. The primary purpose of this iteration was to design a realistic virtual environment that can be used as a replacement for the real-life environment which no longer was a viable option due to COVID-19 pandemic. After having built the virtual environment, the research team implemented a take-off scenario inspired by the Volvo Safety Report that best fitted the testing of a take-off sound. The research team then did a heuristic evaluation to remove the basic usability problems of the system and optimized the virtual environment for testing and evaluating different AVASes in the third iteration.

Iteration 3: Consists of the research team designing and programming different AVASes with the help of software such as VCV Rack, REAPER and Unreal Engine 4. This iteration was concluded by an experiment where nine participants underwent a series of tasks in the virtual environment and they answered a questionnaire (experiment questionnaire). Furthermore, the research team recorded each participants interaction with the simulation and interviewed them about their experience. The data gathered from the interviews was processed using thematic analysis. Lastly, the data gathered from the experiment questionnaire was processed and visualized in order to better understand how each AVAS was perceived in comparison to the others.

4.2.1 Iteration I

During the first iteration of this project, the researchers gathered data about different dangerous scenarios and gaps in the field, especially those related to AVAS by interviewing experts, VRUs, and truck drivers. In addition to this the researchers continued to observe different contexts such as terminals, urban areas, goods delivery trucks and vocational trucks in order to identify the risks associated with each context and use-case. In addition to this, the researchers benchmarked a number of similar products and analysed the results in regard to the regulations. Furthermore, the researchers held several interviews with electric bus drivers and Vulnerable Road Users in regard to electric vehicles and road safety.

4.2.1.1 Benchmarking

As a part of the research study, the research team decided that it is valuable to learn how the Acoustic Vehicle Alerting System for vehicles is currently implemented. In order to do that three different car dealerships were contacted in order to test AVAS in their electric cars. The research team decided to contact car dealerships because Volvo Trucks does not have AVAS implemented into their electric trucks yet.

Three cars were evaluated – Mercedes Benz EQC (see Figure 4.2), Audi e-Tron (see Figure 4.3) and Jaguar I-pace (see Figure 4.4). All three models are electric and have an AVAS system that meets the regulations. Mercedes-Benz and Jaguar already have AVAS fitted to all of their EQC and I-pace models. Audi has two types of E-Tron models – one without AVAS and the second with AVAS. Audi showroom in Gothenburg were certain that they gave us an E-Tron model with AVAS but later it turned out that they do not have any E-Trons with AVAS available yet. However, this made the benchmarking results more significant as E-Tron without an AVAS did produce a higher level of dB(A) than Jaguar I-pace in most instances, which consequently begs the question: how effective are the current regulations on AVAS in reality?

Figure 4.2

Mercedes-Benz EQC 400 4MATIC

Note. Photo by Macau Photo Agency on Unsplash.

Figure 4.3

Audi e-tron 55 quattro

Note. Photo by Thomas Hetzler on Unsplash.

Figure 4.4

Jaguar I-Pace

Note. Photo by Capritography on Pixabay.

We selected a large empty parking lot in a suburban environment in Högsbo to benchmark the three electric cars. A dB meter was used to measure the environment sound and the vehicle sound. The dB(A) was measured when the car is in standstill, reversing, and constant speeds at 10 km/h, 20 km/h and 30 km/h. The sound of the vehicle was measured from a two-meter distance. The research team also examined whether AVAS is turned on in different vehicle functions, such as Standstill while the car was in D gear or when the vehicle is turning.

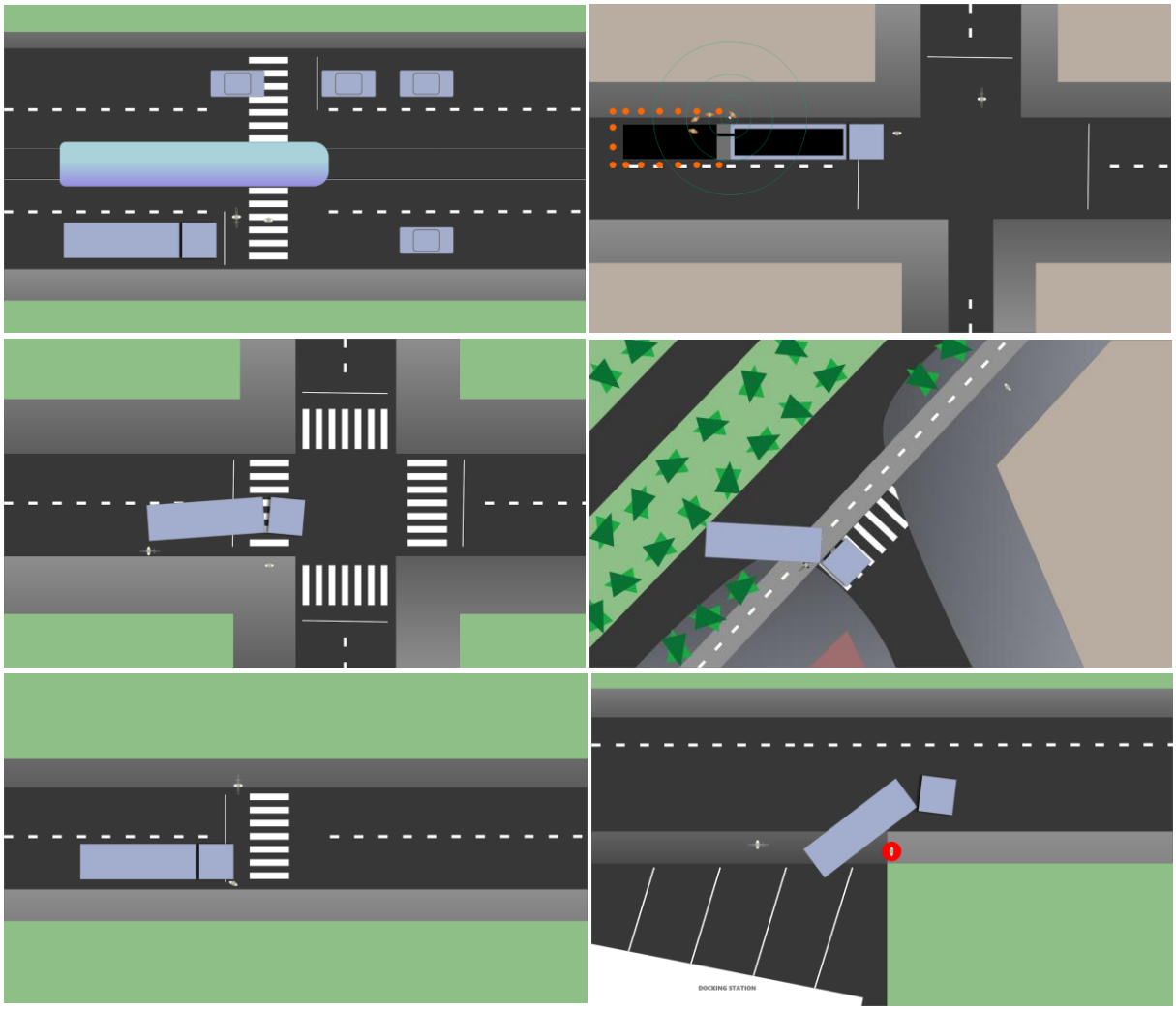
4.2.1.2 Scenarios

Animated scenarios were used to represent dangerous situations between HGV currently on the roads and VRUs such as pedestrians and cyclists. The scenarios were inspired and created based on the research team's understanding of the statistics from The Swedish Transport Agency, Volvo Safety Report (Kockum et al., 2017) and the observations from the pre-studies. The scenarios generated were used in an online questionnaire (see Appendix B) to understand how different road users rank the danger of each scenario, in order to compare their understanding with the statistics reported by Kockum and colleagues (2017) as well as the Swedish Transport Agency. As such, six animated scenarios were created (Figure 4.5), namely:

- Truck taking off from standing still
- Remotely controlled truck at construction site
- Truck driving parallel with a VRU
- Truck turning right at an intersection
- Truck driving at a constant speed
- Truck reversing

Figure 4.5

Six Animated Scenarios Created in Adobe XD



Note. 1) Truck taking off from standing still [Top left]; 2) Remotely controlled truck at construction site [Top right]; 3) Truck driving parallel with a VRU [Centre left]; 4) Truck turning right at an intersection [Centre right]; 5) Truck driving at a constant speed [Bottom left]; 6) Truck reversing [Bottom right]. Scenarios were generated as the results of the pre-studies, statistics provided by the Volvo Safety Report (Kuckom et al.,2017), Swedish Transport Agency, and observations.

4.2.1.3 Interviews with bus drivers

In this iteration, the researchers interviewed a number (N=6) of bus drivers who had experience in driving hybrid and electric buses in Gothenburg. The interviewees were contacted and asked to be interviewed in person by the research team at the electric bus terminal located in Lindholmen, Gothenburg during Spring 2020 before the COVID-19 pandemic. The electric bus terminal was selected to target Electric bus drivers.

The purpose of the interview was to gather insight about driving quiet heavy vehicles in general as well as exploring safety related issues that the bus drivers might have experienced. Questions such as “What are the biggest differences between an electric bus and a combustion engine

bus?" and "What are the scenarios where extra attention should be paid to HGVs and their interaction with buses?" were asked (Appendix F).

4.2.1.4 Interviews with the VRUs

The researchers interviewed a number (N=5) of VRUs (pedestrians and cyclists) who mainly commute by foot or bike. The interviewees were randomly contacted and asked to be interviewed in person by the research team on the ferry between Lindholmen and Stenpiren in Gothenburg during Spring 2020 before the COVID-19 pandemic. The Lindholmen ferry was selected because it is popular amongst pedestrians and cyclists for commuting. The ferry is a good location for the Research team to contact the interviewees because they are waiting to cross the river.

The purpose of the interview was to gather insight about VRUs concerns regarding everyday commuting in urban areas as Vulnerable Road Users. Questions such as "Which scenarios involving trucks are the most dangerous for you in your opinion? "and "Do you know where the blind spots of a truck are? If so, are you actively aware of them when commuting?" were asked to focus on HGVs and VRUs communication (Appendix G).

Understanding VRUs concerns regarding everyday commuting enabled the research team to focus on the scenarios that are the most dangerous in VRUs opinion and acknowledge how well VRUs perceive the dangers associated with HGVs. The interview was a part of the pre-study for the Online Questionnaire.

4.2.1.5 The Swedish Transport Agency

The Swedish Transport Agency was contacted and interviewed by the researchers. The outcome of this contact was a series of randomized and anonymized descriptions of the accident involving HGVs and VRUs in recent years, as well as statistic data related to factors such as the geographical distribution of accidents, weather, lighting conditions, and types of accidents (i.e. HGV vs pedestrian, and HGV vs cyclist).

4.2.1.6 Online Questionnaire

During the analysis of the gathered data from the pre-studies, the research team noticed a gap between the experts' view on the topic of blind spots and safety versus that of pedestrians and cyclists. More specifically, the VRUs did not know about the blind spots of a truck, whereas the experts at Volvo and truck drivers were naturally more aware of these blind spots.

The knowledge gap led to an online questionnaire (see Appendix C) being conducted to explore the contrast between the knowledge of road-users about the risks associated with each scenario and the statistics as to which scenario is more likely to lead to a fatal accident. The reason behind collecting data about how VRUs associated different levels of risk with each scenario was to identify areas where there is a dissonance between what VRUs identify as a high-risk scenario versus the statistics on the subject matter. Understanding this gap, would then enable us to study whether AVAS should be tasked to compensate for the lack of knowledge, in order to increase road safety. This could be done in a similar manner as warning signage (see Figure 4.6) - conceptually - and consequently AVAS would be tasked to give audio feedback to other road-users about entering a truck's blind-spots.

Figure 4.6

A Visual Display Warning VRUs to be Aware of the HGV's Blind Spot

The online questionnaire was then published on social media such as Facebook, Reddit (e.g. subreddits for joggers, truck drivers and cyclists), as well as truck related forums as part of the end results of the first iteration.

4.2.2 Iteration II

This iteration coincided with the COVID-19 outbreak, and as such, the research team was forced to migrate the experiment to a virtual environment to test different types of AVAS, as opposed to a series of physical prototypes mounted on Volvo electric trucks.

The researchers studied the different available simulation engines and decided to create a virtual environment in Unreal Engine 4 (UE4). The reasons behind this choice was the flexibility and ease of use of UE4. Coupled with this, was the availability of free resources and support online, which under the circumstances, would facilitate the construction of the virtual environment. Furthermore, as UE4 offers a visual method of coding through *blueprints*, it would not require the thesis workers to learn a new programming language. Lastly, the researchers chose to use Unreal Engine 4 as during the earlier stages of the thesis work they had discussed using a simulation tool with one of the experts in charge of the simulators used at Volvo GTT, where a possibility of using Unreal Engine 4 in the near future was brought up and discussed.

4.2.2.1 Technical Implementation of the testing platform

The Virtual Environment, where the experiment is carried out, was made using Epic Games' 3D creation platform Unreal Engine 4.24. The research team compared Unreal Engine and Unity platforms and chose Unreal Engine 4 since it has a built-in visual scripting system and therefore would not require learning a new programming language. Furthermore, the research team compared the two platforms and deemed that it would be more time-efficient, and more comfortable to learn to build a high-fidelity 3D virtual environment in UE4 than in Unity.

Process

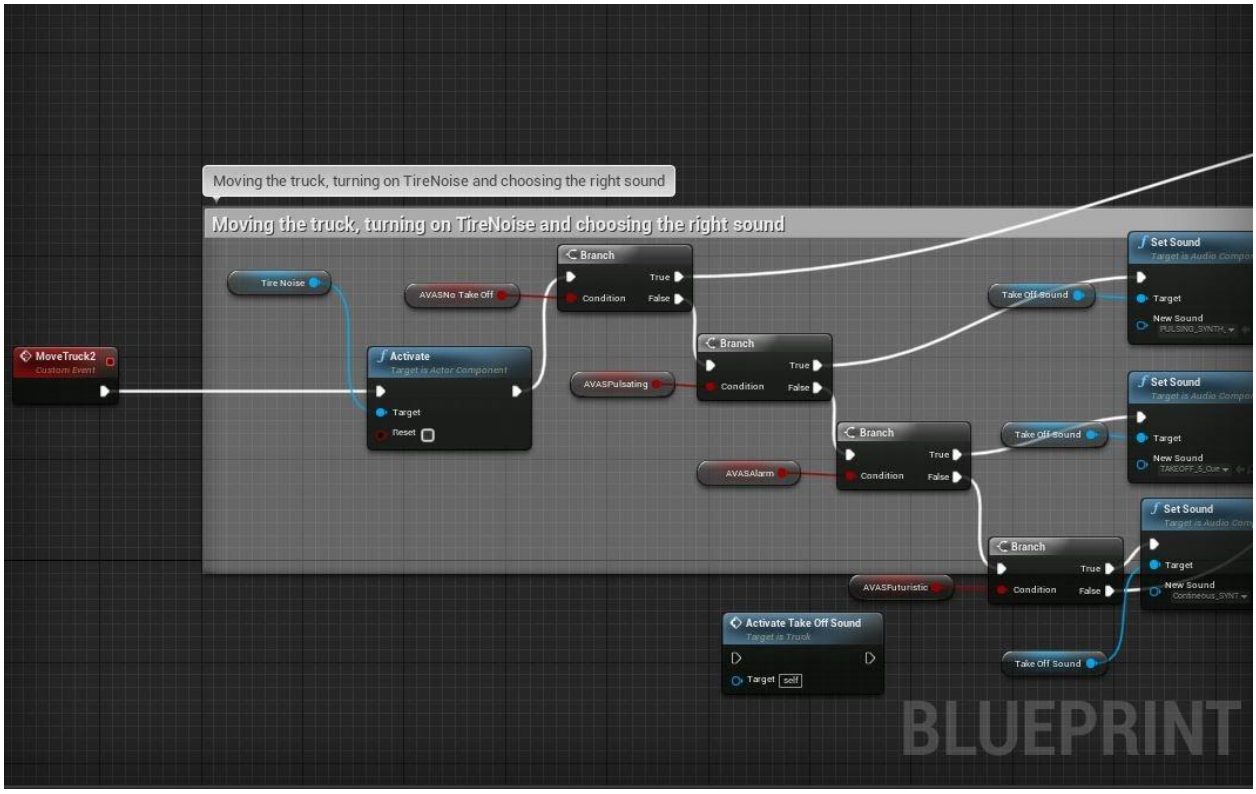
The research team made the Virtual Environment solely by using free content created by different content creators and putting them together to create a Virtual Environment. The assets from different asset packs were selected to fit into the Virtual Environment. Often, an asset pack was acquired only to use one object from the asset pack.

Scripting

To create an interactive and immersive experience, the researchers used the *Blueprints Visual Scripting* system or Blueprints for short (see Figure 4.7). By using this feature, the thesis workers were able to animate movements of the truck and implement the different AVAS systems into the simulated vehicle as well as construct the UI necessary for using the virtual environment.

Figure 4.7

Coding with the Help of Blueprints Visual Scripting System in UE4



4.2.2.2 Content in the Virtual Environment

A new project was made in Unreal Engine 4 to create a suitable Virtual Environment for prototyping and experimenting.

The Virtual Environment project was created and categorized into 6 main content types:

- Vehicles
- City Environment Design
- Main menu
- Character
- Movement
- Sound & Sonification

Vehicles

The research team aimed to fit A 3D model of a Volvo truck into the Virtual Environment. Due to the aforementioned COVID-19 pandemic, the 3D model could not be acquired from Volvo Trucks, so an alternative was chosen from Unreal Engines Marketplace namely Vehicle Variety Pack created by Switchboard. The Asset pack includes multiple vehicles, most importantly a truck, which was implemented into the Experiment in the Virtual Environment. Other vehicles such as the sportscar, SUV, pickup and a small car were placed into the parking lot in the virtual environment to make it look more realistic.

The Virtual Environment also features a small Easter egg. By pressing T, the user can take control of a parked truck and drive it around. The purpose of the Easter egg is to show that the experiments made in the virtual environment do not only have to be from the Pedestrians point of view. The experiments in the Virtual Environment can also focus on truck drivers.

City environment design

The goal was to create an urban city environment with high to medium sized buildings and complement the environment with detailed road markings, lamp posts, bus stops and other assets that are common in the urban environment.

The city environment (see Figure 4.8) was created by using multiple different asset packages acquired from Unreal Engines Marketplace. A wide range of different asset packs allowed the research team to create a rich environment. It was important to select asset packages that have assets that fit together with each other and unify the city environment. Default daytime lighting was applied to the world for less shadows.

Figure 4.8

Screenshot of the City Environment in the Virtual Environment

The environment has multiple subenvironments such as a parking lot, road construction, building construction, garbage alleys, office buildings etc.

The skyscrapers taken from a package called City 16 asset pack created by Unreal Environments - Speed Level Design were resized in order to prevent a size difference between different buildings from various asset packs. Resizing the buildings made the city feel unified. In order to fill the city with more unique houses, the research team acquired an asset that allowed creating buildings with different building blocks. The buildings from City 16 asset pack did not have physical properties, so invisible walls (invisible volume used to block other actors) had to be fitted in so that the character would not be able to walk through the buildings.

The construction sites (see Figure 4.9) in the virtual environment were created by using construction Site VOL. 1 - Supply and Material Props and Construction Site VOL. 2 - Tools, Parts, and Machine Props created by Dekogon Studios. During observations (aforementioned in pre-studies of the thesis) construction sites were inspected and the construction sites in the virtual environments were inspired by construction sites in Gothenburg, Sweden.

Figure 4.9

Road Construction in the Virtual Environment

The necessary assets for the road (see Figure 4.10) were acquired from the Modular Building set asset pack created by PurePolygons. The look and feel of the roads in the virtual environment were inspired by the American and European roads to be familiar for the stakeholders. Google maps was used to get inspired and create realistic road markings.

Figure 4.10

Road Markings in the Virtual Environment

Main Menu

A main menu for the Virtual Environment is created as a separate level in the world. It is primarily created to make the Virtual environment look & feel more complete. The main menu has multiple blueprints that are connected to Tutorial & Experiment levels. This is necessary to allow the research team to select suitable options for the scenario faster during the experiment. For example, one of the main menu's blueprints is connected to the Truck's blueprint and sends requests to the trucks blueprint in order to change the take-off sound of the truck based on the selected options from the main menu.

Chalmers University of Technology, Volvo Trucks logos and the authors names are represented in the main menu to show who are involved in this project. The background image (Range of Volvo Electric Trucks) from Volvo Truck Image and Film gallery (Volvo Truck Corporation, 2018) was used to show the focus (Electric trucks) of the experiment (see Figure 4.11). The colour of the buttons is selected from the trucks and the Volvo font is used in the title of the main menu.

Figure 4.11

Main Menu for the Virtual Environment

Character

The character was initially designed as a test dummy and the user could control it from a third person view. The test dummy design on the character was not realistic so the research team decided to make the character look as a real person. In order to do that, skins were acquired from Scanned 3D People pack by Render People (see Figure 4.12).

Figure 4.12

The Character Equipped with a Skin from Scanned 3D People Pack by Render People.

Movement

The third person view and PlayerController blueprint were imported from Third person blueprint by Unreal Engine. The movements of the character were adjusted in the PlayerController blueprint to fit our experiment. The character from the Third person blueprint by Unreal Engine had running as the default movement forward. Running movement was disabled as a default and a walking movement was made the default movement forward. The speed of the movement was also slowed down in order to make the experiment more realistic and controlled. The third person view was later changed to first person view for a more realistic experience.

The animation of the truck, which was a vital part of our experiment, was generated by creating an AIController Blueprint class, which forwards instructions to the Truck asset within the rendered world. The animation of the truck was the following:

- The truck started moving when the instructions for the game were closed
- The truck followed a predefined path and stopped once it reached the pedestrian crossing.
- Take-off from standstill was activated when the user-controlled character stepped on the crossroad.

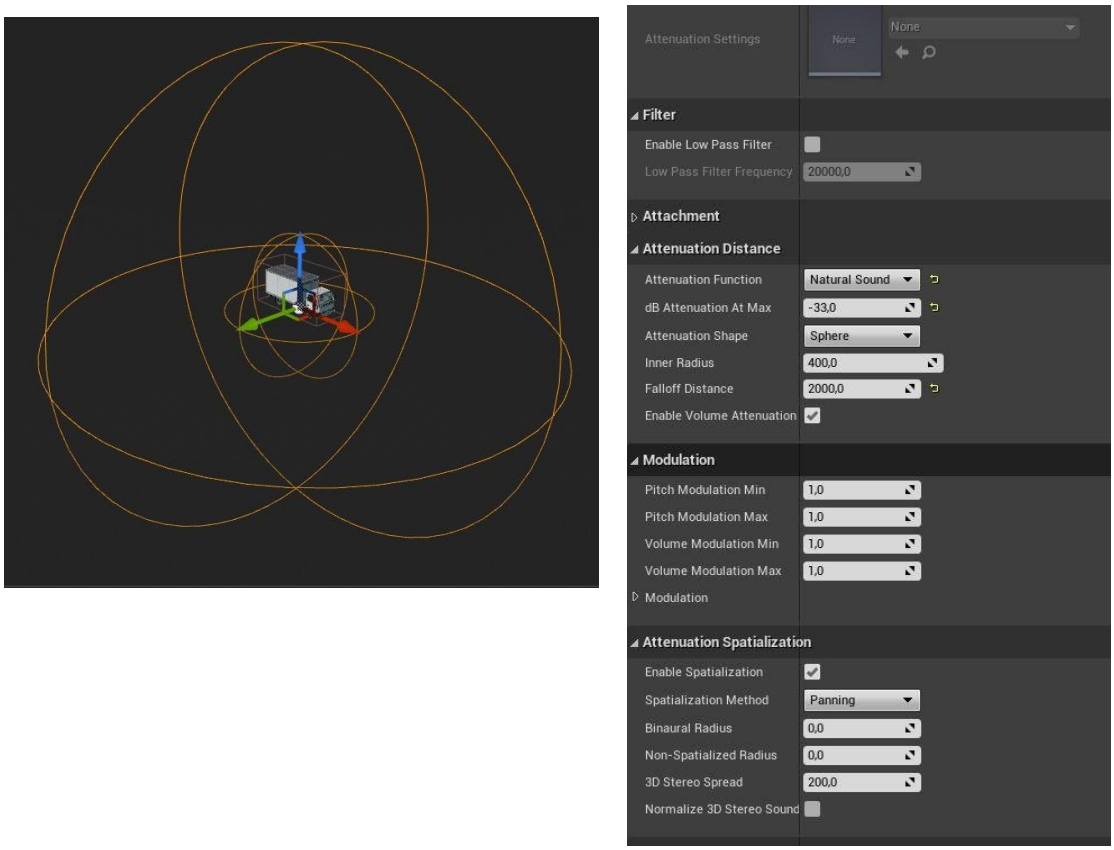
Sound & Sonification

UE4 offers a powerful set of features for managing sound in the virtual environment. More specifically, this tool allows for 3D spatialization and movement of sound sources through easy to use settings that do not require any coding (see Figure 4.13). Furthermore, UE4 offers an automated attenuation feature where the designers can both visually and numerically set the parameters for the decay of the sound, as well as offering different mathematical functions for determining the quality of attenuation.

The research team recorded samples of environmental sounds in Gothenburg urban areas and implemented them into the virtual environment for a realistic sound. The selected environment sound in the virtual environment was recorded in Annedal, Gothenburg near Brunnsgatan tram stop. The Electric Truck engine imitation sound and the take-off sounds were created by the research team using software namely VCV Rack and REAPER.

Figure 4.13

UE4 Offers Easy to Use Visual and Numerical Settings for Adjusting Sound Behaviou.



4.2.2.3 The Take-off Scenario

The scenario implemented in the virtual environment was inspired by the Volvo Safety Report (Kuckom et al., 2017). The selected scenario is responsible for 5% of all fatal accidents involving HGVs and VRUs. This scenario was chosen as it best fits a situation where a take-off sound is needed and can be tested. Furthermore, although there are three scenarios that account for a higher risk of fatality, this scenario still ranks as the fourth cause of fatality in accidents involving HGVs and VRUs, whilst it was ranked as the least dangerous scenario out of six, in the online questionnaire conducted during this project, and therefore it is important to avoid taking scenarios like this one for granted.

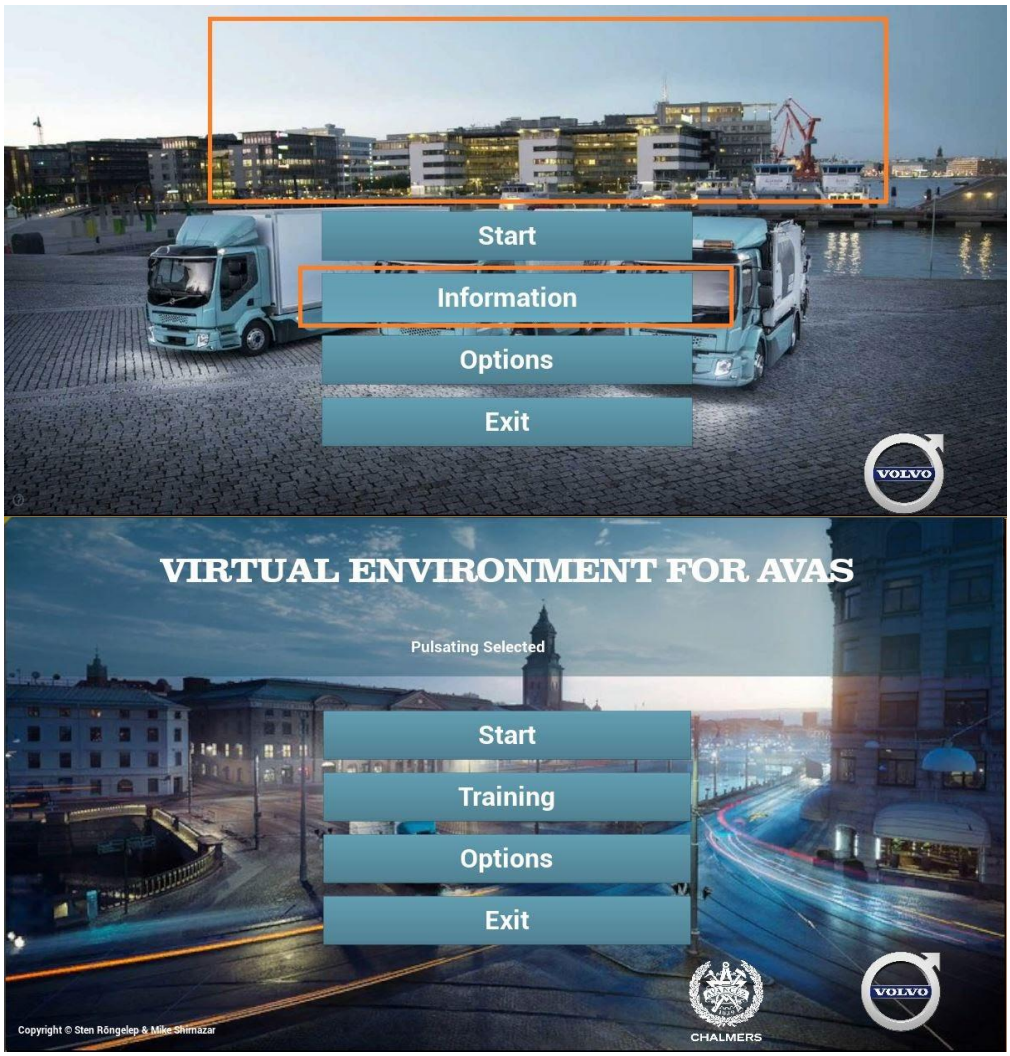
4.2.2.4 Troubleshooting and Heuristic Evaluation

To finalize the iteration and evaluate the simulation the research team performed a heuristic evaluation where the simulation and the user interface was evaluated and adjusted to best fit the purposes of the experiment (see Figure 4.14). In doing so, the research team used Nielsen's

(1994) ten principles for interaction design to help detect the usability problems of the virtual environment and its respective UI. In the following paragraphs, these ten principles are named, followed by a description of how these principles related to the produced virtual environment.

Figure 4.14

Main Menu Usability Problem



Note. The information button would never be used. Additionally, it is unclear which AVAS mode is chosen [top]. As such, the "Information" button was replaced by "Tutorial", and a text showing which AVAS was chosen was added to the main menu [bottom].

VISIBILITY OF STATUS: We identified a need to include a text indicating the chosen AVAS mode in the main menu in order to show the status of the system.

MATCH BETWEEN SIMULATION & REAL WORLD: In regard to this principle, the simulation appeared acceptable, however for a more immersive experience, we added background noise, and used animated trees and grass patches instead of static lo-fi 3D models. Furthermore, we decided to not only change the appearance of the character used to a more realistic character, but also to change the view from third-person's perspective to first-person's perspective (see Figure 4.15).

Figure 4.15

Changes Between Second and Third Iteration of the Testing Platform

Note. A screenshot of the product by the end of the second iteration [top]. The mannequin was changed to represent a person and the lo-fi trees were replaced by hi-fi and animated meshes. Furthermore, the perspective was changed from third person's perspective to first-person's perspective for added immersion [bottom].

USER CONTROL & FREEDOM: In respect to user controls and freedom, we limited the controls to WASD for movement and Spacebar for jumping. Although the jumping was never used in the scenario, we decided to include it to give the user a relative freedom of movement. Additionally, we decided not to include sprinting as it could affect the experiment's course if a participant crosses the street too fast.

ERROR PREVENTION: To prevent errors in the experiment the participants were asked to strictly follow a series of instructions to avoid situations where they trigger the truck's movement before it arrives at the crossroad

CONSISTENCY AND STANDARD: The product had an acceptable level of consistency and followed the standard controls used for video games. Furthermore, we noticed the lack of a pause key which would allow for accessing the main menu after having started the simulation. Lastly, we decided to use the same instructions for all the scenarios to establish a standard for the experiment's course.

RECOGNITION RATHER THAN RECALLING: The simulation in general consisted of a good level of recognition as not much recalling was required of the user to navigate and recognize the elements of the virtual environment such as a crossroad.

FLEXIBILITY AND EFFICIENCY OF USE: The simulation allows for easily changing between different AVAS systems. The simulation also allowed for a rather efficient testing of the scenario as it would take less than a minute for each participant to perform the tasks and complete each scenario. Furthermore, the level of flexibility that the virtual environment offered was deemed acceptable as the user could easily move around and go through each scenario at their own pace.

AESTHETIC AND MINIMALIST DESIGN: In regard to aesthetics of the simulation, we decided to abandon the previous assets and replace them with more realistic ones (see Figure 4.15). Furthermore, the UI of the main menu was revised for excess and the research team decided to only include necessary buttons in the main menu, as opposed to buttons that could show that which can be done using UE4 (e.g. choosing character, choosing scenario, etc.).

HELP USERS RECOGNIZE, DIAGNOSE, AND RECOVER FROM ERRORS: We decided to make the simulation as error-free as possible. As such, there were no instances where the user would face any errors, nor would they have to recognize or diagnose one.

HELP & DOCUMENTATION: A set of instructions were put in the top left corner of the screen to assure the user remembering the controls. Additionally, we deemed that given that during the course of the experiment a series of instructions printed on a paper will be present, no additional help would be necessary.

4.2.3 Iteration III

During this iteration, we gathered the results of the heuristic evaluation and implemented the improvements that could help the participants experience immersion in the virtual environment. Coupled with this, the researchers designed and generated the sound cues needed for the take-off as well as the base AVAS sound used in the experiment. This iteration was concluded with an experiment where nine participants (N=9) were asked to follow a set of instructions (see Appendix E) while performing a think-aloud protocol.
The take-off scenario helped the research team get a better understanding of what is wanted from such a future product. In the take-off scenario, we had participants follow a set of instructions and think-aloud their thoughts.

4.2.3.1 Sonification and choosing sound for AVAS and take-offs

During this phase, the research team decided to have three types of sound to test. The reason for choosing three types of take-off sound was to limit the length of the experiment as well as to avoid overloading the participants' memory during the course of the experiment.

Firstly, an Alarm sound which refers to one short, high-pitched sound which was similar to that of a bell, or an error message on the computer. The reason for this choice was for the research team to be able to see whether an attention demanding, and sharp sound would be acceptable by the users despite being contrary to the findings of Rötz and Kelkar (2019), and Hwang (2016). Additionally, a high-pitched sound was chosen in order for it to be clearly heard and stand out in the noisy virtual environment. This would in turn guarantee that the sound is heard and would in turn notify the participants of an attention-demanding event happening in their vicinity.

Furthermore, the research team decided to design a Pulsating sound with two consecutive short and high-pitched sounds in order to explore the perception of a pulsating sound in regard to the intentions of the truck, namely moving forward. One reason for choosing to have the same sound consecutively being played was the idea that "SIMILAR ACTION IS SYNCHRONIZED MOTION" (Kövecses, 2010, p. 165). In other words, when the same sound is being played successively, it metaphorically indicates a requirement for synchronized action (Kövecses, 2010) - which in this case would be a synchronized action between the truck (taking-off) and the VRU (stopping). Coupled with that, the "SPEED OF ACTION IS THE SPEED OF MOTION" (Kövecses,2010, p. 165) which in this case would mean that the speed of the sounds heard, is telling the other road-users about the speed of motion - and that the vehicle is no longer standing still. Lastly, as two successive sounds indicate progress, and progress is conceptually mapped with movement, the research team deemed it necessary to include a pulsating sound in the experiment.

Finally, the researchers designed a "Futuristic" sound which was a low-pitched sound inspired by Shepard tone (gradually increasing in pitch) which would in turn mimic the sound emitted by the acceleration of the engine of ICE vehicles. The reason for choosing a lower-pitched sound was that a lower-pitch often represents a heavier object and a higher pitch often presents a lighter object, and therefore, a low-pitched sound could better represent the physical properties of the vehicle. Furthermore, one can consider frequency as a representative of the speed of action, which in turn, based on the metonymy of "SPEED OF ACTION IS THE SPEED OF MOTION", would seem like a good fit for indicating motion. Naturally, an increase in frequency means an increase in the speed of motion as frequency represents a full cycle of events.

The researchers also generated and designed a base AVAS sound which was in turn made very similar to the sound of an internal combustion engine without the increase in the pitch. In creating this sound, the researchers decided to have a very fast reverberation in the sound to mimic the vibrations caused by the explosions in the engine of ICE vehicles. In order for this base sound not to interfere with the take-off sounds, the research team decided to keep the pitch and amplitude of this sound at a constant level to better observe and study the effects of the different take-off sounds.

4.2.3.2 Technical Implementation of Truck Sounds in the Virtual Environment

To implement and design sounds the research team used VCV Rack and REAPER.

VCV Rack

The software VCV Rack was used to generate sounds for AVAS. The research team designed and programmed four sounds with the help of the modules provided in VCV Rack.

The concepts created and tested in this study were:

I) AVAS with a humming sound that was similar to that of a combustion engine at standstill (aka AVAS with no take-off sound).
II) AVAS with Alarm take-off sound.
III) AVAS with Pulsating take-off sound
IV) AVAS with a Shepard tone inspired take-off sound (aka AVAS with Futuristic take-off sound).

These concepts were then implemented in the virtual environment and then evaluated using a questionnaire and a semi-structured interview.

REAPER

The sounds generated in VCV Rack were then modified, mixed, and recorded in the software Reaper because VCV Rack does not support recording. The recorded sounds were then trimmed as well as exported in .WAV format, and then imported and implemented in Unreal Engine.

4.2.3.3 Alpha testing

Prior to the experiment, the research team carried out an alpha testing of the environment and the experiment with one participant to assure that the experiment questions are understandable, the sequence of the experiment is logical and practical, and correct any potentially missed usability errors of the product. As there were no significant errors reported by the alpha-tester, the research team deemed that the experiment was acceptable, and the instructions were clear. Coupled with this, alpha testing helped the researchers to rehearse their parts in accordance to the step-by-step walk-through which further on facilitated the performing of the actual experiment. The main outcome of alpha testing was that the researchers ought to be more vigilant in reminding the participant to perform the think-aloud protocol as he or she is performing the designated tasks.

4.2.3.4 The experiment

The experiment was conducted in 13 steps. To assure that each experiment is performed correctly, the researchers conducted a *walk-through* of the experiment (only seen by the researchers) that was strictly followed in order to guarantee the success of the experiment as well as the safety of the participants and researchers in regard to the COVID-19. The step-by-step walk-through of the experiment was the following:

1. The Participant is given a consent form to sign
2. The Participant is given a paper with instructions where they are asked to perform a think-aloud as well as the steps they need to take.
3. The Researcher runs the simulator.
4. The Participant starts the tutorial and tries out the think-aloud method.
5. When the participant feels comfortable, the researcher takes over and goes to the main menu.
6. The researchers start the recording of the screen (Xbox game bar) as well as the audio (combined with video) of the think-aloud
7. The Researcher chooses the AVAS settings according to the order from options.

8. When the scenario has ended (the AVAS has been played) the researchers ask the participant to answer the questionnaire.
9. In the meanwhile, the researchers put on the next scenario according to the order. (Repeat from step 7 for each AVAS/scenario)
10. After going through all scenarios, the researcher starts recording for the interview (phone) and initiates the interview.
11. After the interview save the recordings with the appropriate name [code] and collect the questionnaire and code it depending on the order of AVAS played.
12. After the participant has left, the keyboard, mouse, pen, headset and surfaces must be cleaned.
13. Great job! Next participant can come in.

Furthermore, in order to balance the data gathered and counter the biases that can emerge from a learning curve, the researchers decided to use an experimental research method similar to an incomplete repeated measures design (Shaughnessy, Zechmeister, & Zechmeister, 2014). As such, the participants went through each condition (i.e. the scenario with a specific type of AVAS) once in a semi-randomized order. More specifically, the researchers decided to have all the participants start with the AVAS with no take-off sound in order to become acquainted with the scenario, and then based on a randomized code, they were presented with a certain order of conditions to undergo. The research team reasoned that some level of learning could benefit the experiment in terms of the participants getting to know what is expected of them and since the main focus of the research is the take-off sounds, the research team deemed it reasonable to only have the order of take-off sounds changed for counterbalancing the learning curve, to an acceptable degree.

As mentioned in the walk-through, after having gone through each condition, the participant was presented with the experiment questionnaire (see Appendix C) and were asked to rate their experience on a Likert-scale of 1-7, in regard to Noticeability, Safety, Pleasantness and Representativeness. The data gathered through the questionnaire were visualized through a radarchart (see Figure 5.22 and Appendix A).

After having gone through the four conditions of the experiment (i.e. different AVASes created), the participants took part in a semi-structured interview (see Appendix D) to freely elaborate on their experience and express their opinion. The data gathered through the interviews and the think-aloud protocol was then processed using the thematic analysis. The research team transcribed the important input brought up by the participants and assigned preliminary codes to each of the data points. After reviewing the codes, a series of changes were made to the wording of the codes for more consistency. This was done through discussing and reviewing the transcriptions which then lead to grouping them into sub-subcategories, subcategories, categories, and themes, all of which were reformulated and reviewed for consistency a handful of times. Moreover, the research team used Excel, and Adobe XD to facilitate and structure the analysis, and visualize the thematic analysis respectively (see Figure 5.10, Figure 5.11, Figure 5.13, Figure 5.14, Figure 5.16, and Figure 5.17).

5

Results

In the following we state the results of our research and evaluations derived from interviews with bus drivers and VRUs, the online questionnaire, benchmarking, and the experiment's think-aloud protocol, questionnaire, and interviews.

5.1 Interviews with electric bus drivers

After having interviewed the electric bus drivers, we learnt that the experienced bus and truck drivers need to keep a steady nerve as they are operating in urban areas. When asked about the measures they take regarding driving safely, they unanimously mentioned that as long as the driver keeps the right speed, and is patient, there is no danger. All bus drivers from the interview agreed that the most stressful part of their work is traffic and situations where the bus breaks down.

When the research team asked the bus drivers about the differences between combustion engine versus electric buses in regards to the latter being far quieter, they did not believe that there are any differences in terms of safety for VRUs, yet some remarked their surprise by the VRUs not noticing the heavy vehicles and not being aware of the dangers of them. The use of earphones amongst VRUs was brought up as a reason for this. Furthermore, it is difficult for the bus drivers to notice cyclists using a segregated lane (even when they are sitting lower than truck drivers) which was further stressed upon in the results of the online questionnaire.

Additionally, bus and truck drivers mentioned that a large part of the danger is in regard to car drivers, which is outside the scope of this project. Based on the interviews with electric bus drivers and a pilot test conducted by Volvo Trucks about electric trucks (Volvo Trucks, 2019), the research team learned that Electric heavy vehicles will improve the drivers well-being in general as there is less noise. Naturally, this will result in the driver being less stressed and fatigued, which consequently enables them to have more mental resources to focus.

Current electric buses without AVAS are very quiet and the bus drivers have to be more cautious with VRUs. Bus drivers believe that splitting the traffic (segregated lanes) would be a good idea, while people using segregated lanes (cyclists) are extra cautious because of bad experience.

5.2 Interviews with VRUs

After having interviewed the VRUs, we learnt that 4 out of 5 participants have not noticed electric trucks in Gothenburg. The participants were asked to name dangerous situations with trucks, and they were the following:

- VRUs who are not attentive when crossing the street during heavy traffic.
- Electric vehicles (cars, buses) masked by high environment noise.
- Commuting with earphones in streets with limited visibility.
- Crossing intersections with a bicycle.

A cyclist mentioned that they have never thought about the dangers of trucks. However, multiple participants raised concerns about communicating with truck drivers (eye contact), because the Cab of the truck is higher compared to other vehicles. Cyclists mentioned that they actively think whether a truck driver notices them or not. The interview revealed that the participants lack information regarding the blind spots of the truck. The blind spots at the front, rear and back were partly mentioned but none of the participants had a clear understanding of all the trucks blind spot. As a solution one of the participants suggested that the truck manufacturers should inform the public better about their products. The interviewees would like the electric trucks to have directed sound and to improve the communication between VRUs and HGVs in general. None of the interviewees had experienced dangerous situations with trucks.

5.3 Benchmarking

The data from the benchmarking of three electric vehicles resulted in the comparison tables below. Even though the tables reflect that the vehicle sound is louder than the environment sound, the research team did not notice a significant difference between the environmental noise and sound emitted from the vehicles' AVAS.

As shown in Table 5.3, we can see that Audi e-tron without AVAS emitted more sound in most cases than the Jaguar I-pace with AVAS. Mercedes-Benz had the highest dB(A) levels and was heard the most.

In general, none of the cars were clearly heard in our selected environment. This indicates that the regulations for AVAS are not effective as AVAS is being masked by the environmental sounds, and that the sounds emitted from the EVs' movements (wind, tire noise) are louder than the required levels by the regulations and consequently mask AVAS.

AVAS sounds in the three models were low pitched and thus were mostly masked by the environmental sounds. Mercedes-Benz and Jaguar had fitted a higher pitched reversing sound which was clearly heard by the research team inside and outside the vehicle even though it had a lower dB(A) than when vehicles drove forwards at constant speed.

The general information about the vehicles was gathered from the representatives of the vehicle brand in the showrooms (see Table 5.1). Table 5.2 and Table 5.3 were created by the research team to show the results from the benchmarking. The sound levels were measured by a sound meter – which was provided by Volvo Trucks - from a two-meter distance. The sound levels

were a result of tire noise and AVAS as it is practically impossible to remove the tire-noise wholly in a real-life setting.

None of the vehicles had a stand still sound, this is most likely because the automotive companies wish to produce cars that contribute minimally to noise pollution, as well as the AVAS regulations not requiring a standstill sound.

Table 5.1

General Information About Electric Vehicles Used in Benchmarking

	Mercedes	Audi	Jaguar
Speaker position	One at the front, second at the back	Front right- tested model didn't have AVAS	Front Grille
Number of speakers	2	1	1
AVAS activated	Up to 30 km/h, starts to fade at 20 km/h	up to 20 km/h	Up to 20 km/h
AVAS availability	Standard equipment	Standard equipment	Standard equipment
VRU detection	Sensor proximity detectors	-	-
Does it meet the regulations	Yes	No	Yes

Table 5.2

Table Showing Vehicle Functions and if they Have an AVAS Sound

	Mercedes	Audi	Jaguar
Standstill P	No	No	No
Standstill D	No	No	No
Standstill R	Yes	No	Yes
Take-off	No	No	No
Acceleration	Yes	No	Yes
Constant speed	Yes	No	Yes
Slowing down	Yes	No	No
Turning	No	No	No
Reversing	Yes, changes frequency according to speed	No	Yes
Parking	No	No	No

Table 5.3

Sound Levels of the Environment Sound and Electric Cars Performing Various Activities

	Mercedes		Audi		Jaguar	
	Environment sound dB(A)	Vehicle passing from a 2-meter distance dB(A)	Environment sound dB(A)	Vehicle passing from a 2-meter distance dB(A)	Environment Sound dB(A)	Vehicle passing from a 2-meter distance dB(A)
Stand still	-	-	-	-	-	-
Reversing	57	60	55	60.3	54.5	56.5
Constant speed at 10 km/h	58.5	61	55	59.4	55	60
Constant speed at 20 km/h	57.3	65.3	56.6	62.3	55.3	60.5
Constant speed at 30 km/h	57.5	68.5	56.2	66.6	57.3	64.3

5.4 Online Questionnaire

The age mode for our online questionnaire was 26-35 years (Figure 5.1). Most participants were from Sweden or USA (Figure 5.2).

Figure 5.1

Age Groups of Participants in the Online Questionnaire

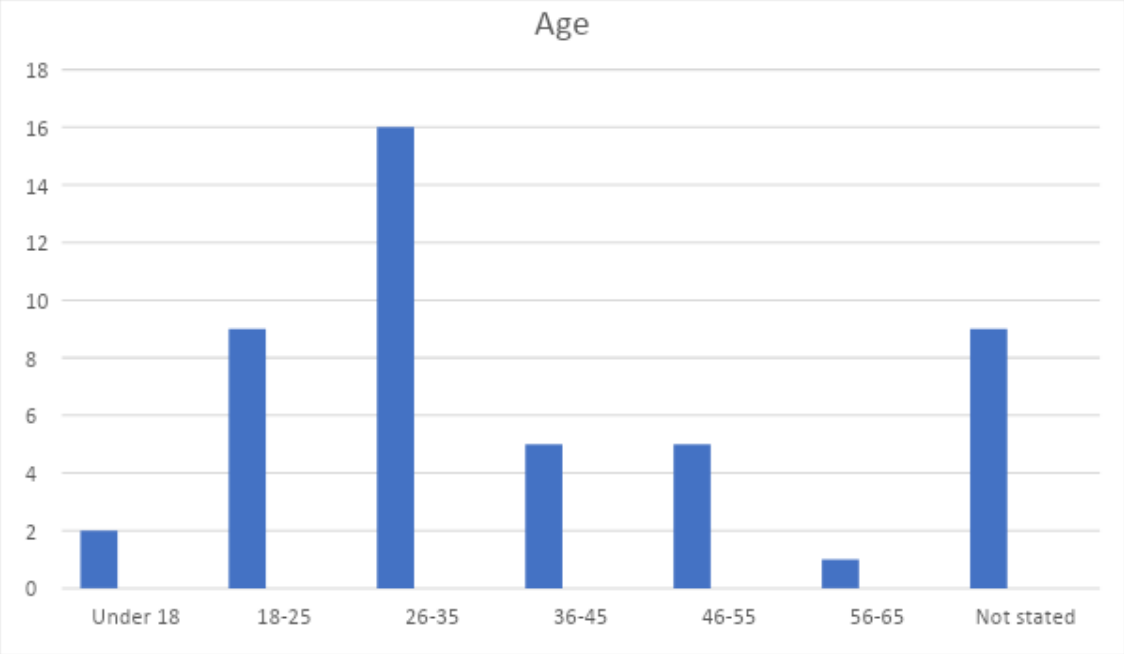
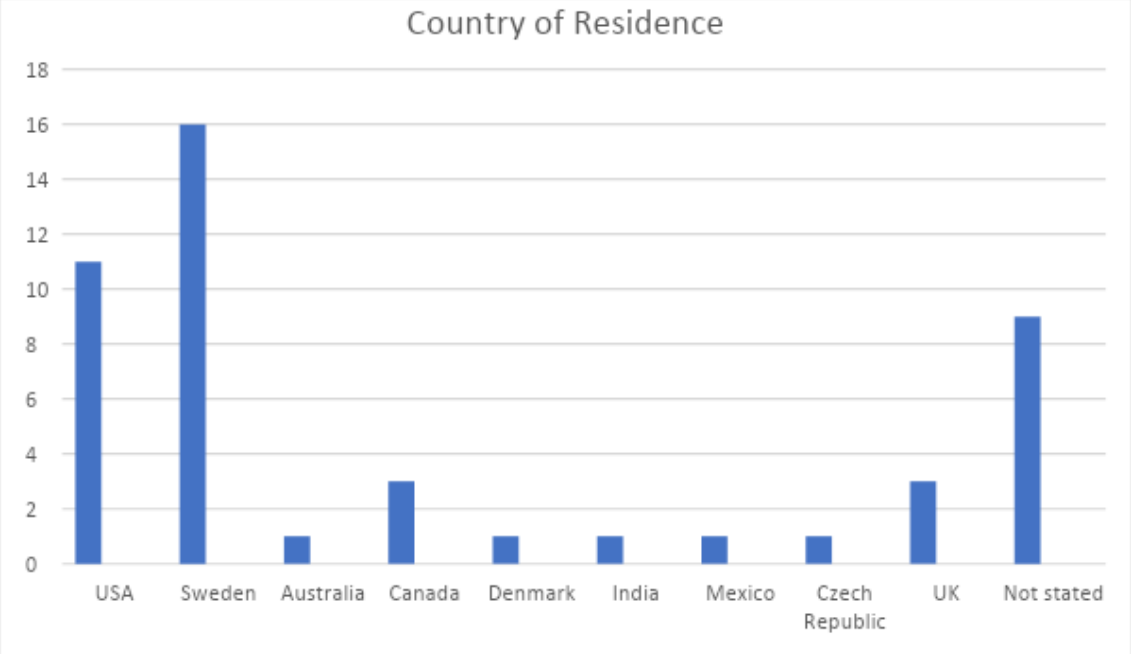


Figure 5.2

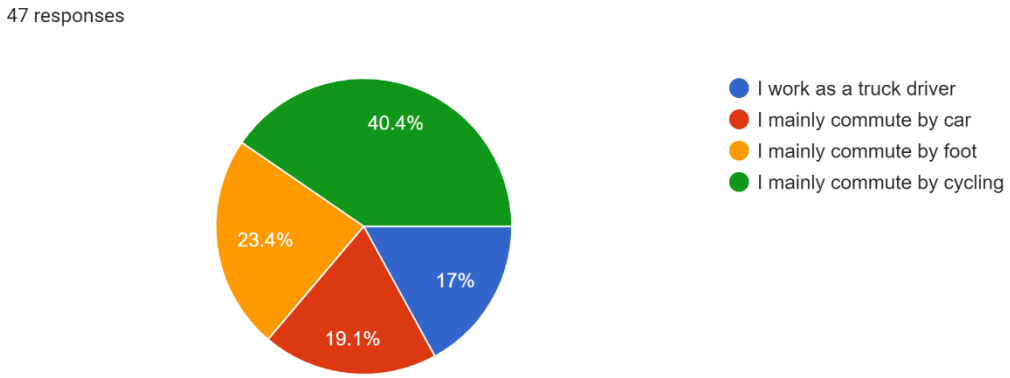
Online Questionnaire Participants Country of Residence



In total there were 47 participants of which 40.4% mainly commute by cycling, 23.4 % commute by foot, 19.1 % by car and 17% are truck drivers (see Figure 5.3).

Figure 5.3

Pie Chart of Participants Main Commuting Type



The participants were asked to rank the danger of six different accident scenarios. The scenarios were inspired by the Volvo Safety Report (Kockum et al., 2017), benchmarking different electric cars and interviews conducted with electric bus drivers and VRU's.

5.4.1 Truck taking off from standstill

Car drivers, cyclists and truck drivers rank the "Truck taking-off from standstill" scenarios danger similarly, as moderate danger. Pedestrians ranked the danger much lower (Not dangerous at all). Seemingly, participants have a different understanding of who is responsible for the accident in this scenario.

Pedestrians believe that due to the low speeds in this scenario, the truck driver has a clear view and the driver must ensure that it is safe to take-off. A truck driver commented that pedestrians sometimes ignore traffic rules & lights which makes this scenario very dangerous.

Cyclists mention that eye-contact with the driver is necessary and that they are aware of the blind spot in front of the truck. Cyclists have contrasting opinions about this scenario, some cyclists along with car drivers believe that due to low speeds the likelihood of a serious accident is lower. Other cyclists believe that it is dangerous since the impact is direct.

5.4.2 Remotely controlled truck at a construction site

Car drivers and cyclists believe that it should not be possible to control the truck remotely. Car drivers and truck drivers rank the danger of the construction site similarly whereas cyclists believe that this scenario is slightly more dangerous.

Pedestrians believe that this scenario has a high-risk factor but have different opinions about how dangerous it is. Most pedestrians ranked the danger of this scenario relatively low, which might be because of inexperience, which is reflected by participants' comments about this scenario where they say that they have not experienced this scenario in real life.

5.4.3 Truck driving at constant speed

Car drivers have contrasting opinions for truck driving at a constant speed scenario. Most car drivers and cyclists agree that it is the pedestrians' fault if this accident would happen and it is a very unexpected accident causing serious injuries for the pedestrian. Car drivers rank the danger of a truck driving at constant speed much more dangerous than truck drivers. Although a truck driver mentioned that this scenario is: "Very common and dangerous when there's parked cars along the road". Cyclists have different opinions about truck driving at a constant speed. The mode is very dangerous, meaning most cyclists ranked the scenario as very dangerous as did most car drivers.

Pedestrians have contrasting opinions about this scenario, the mode is Not dangerous at all but there are rankings from low danger to very high danger. Most pedestrians believe that this accident is fatal for the pedestrian. One pedestrian believed that the truck driver has plenty of time to see the pedestrian approaching the road.

5.4.4 Truck driving parallel with a VRU

Cyclists rank Truck driving parallel with a VRU scenario as one of the most dangerous scenarios. From the comments it is clear that cyclists are aware of the high death toll due to these accidents and try to be very careful in such situations. Reading the trucks movement constantly is mentioned multiple times as a solution. Most cyclists rank this scenario as very dangerous but there are a few cyclists who gave it a low rank in danger.

Truck drivers rank Truck driving parallel with a VRU scenario as more dangerous than car drivers. A truck driver said that: "Cyclists who don't pay attention or ignore traffic rules makes these situations dangerous, but the driver has a responsibility to make sure it's safe to turn". Car drivers think that it is the cyclists' fault as they should be more aware of the situation and how the trucks move.

Pedestrians agree with Car drivers and believe that the cyclist should take precautions in this scenario. When precautions are taken, pedestrians believe that this scenario is less dangerous. In general pedestrians rank the danger of this scenario lower than other road users in the online questionnaire.

5.4.5 Truck turning right at an intersection

Cyclists ranked and commented Truck driving parallel with a VRU and Truck turning right at an intersection scenarios very similarly. Both scenarios are ranked as the most dangerous. Cyclists are aware that it is hard to communicate between the cyclist and truck driver in this scenario which according to the Volvo Safety Report is one of the most common accidents causing fatal casualties between HGVs and VRUs (Kockum, et al., 2017). Amongst cyclists, Truck turning right at an intersection is considered more dangerous while driving on a separate lane than Truck driving parallel with a VRU in the same lane. Truck drivers agree with cyclists and rank Turning right at an intersection scenario as more dangerous than car drivers.

Cyclists also mention from experience that segregated lanes can often be even more dangerous due to lack of visibility and that it is bad engineering. Car drivers agree that separated lanes are more dangerous as it is even harder to notice VRU's. Cyclists are aware that the truck should yield, but due to experience they are cautious. Cyclists rank the Truck turning right at an

intersection scenario to be much more dangerous than car drivers & truck drivers. Pedestrians and car drivers agree that it is hard for the truck driver to notice cyclists from the edge of driver's field of view, but that is why pedestrians and car drivers believe that truck drivers should be extra cautious.

5.4.6 Truck reversing

Car drivers and pedestrians agree that when the truck is reversing the truck driver has very limited visibility and VRU's might have difficulty understanding the direction where it is reversing. Truck drivers rank the danger of the Truck reversing scenario much higher than car drivers. Most cyclists rank the danger of the truck reversing similar to truck drivers, but there are some who believe that the danger in this scenario is low. Cyclists are also aware that the truck driver has very limited visibility but believe that low speed will give the pedestrians plenty of time to get out of the way. Pedestrians ranked the danger of this scenario much higher than car drivers but slightly lower than truck drivers and cyclists.

Summary of ranking the danger in different scenarios by each road user category in the online questionnaire are (See Figure 5.4, Figure 5.5, Figure, 5.6, Figure 5.7, Figure 5.8, Table 5.4, Table 5.5, Table 5.6 and Table 5.7):

Table 5.4

Summary of Car Drivers Ranking the Danger of Six Scenarios

	1	2	3	4	5	6	Mode
Truck taking off from standing still	1	3	3	1	1	0	2,3
Remotely controlled truck at construction site	1	2	3	2	0	1	3
Truck driving parallel with a VRU	0	0	0	3	2	4	6
Truck turning right at an intersection	0	0	0	3	3	3	4,5,6
Truck driving at a constant speed	0	1	0	2	2	4	6
Truck Reversing	0	0	4	2	1	2	3

Figure 5.4

Car Drivers Rank the Danger of Six Scenarios

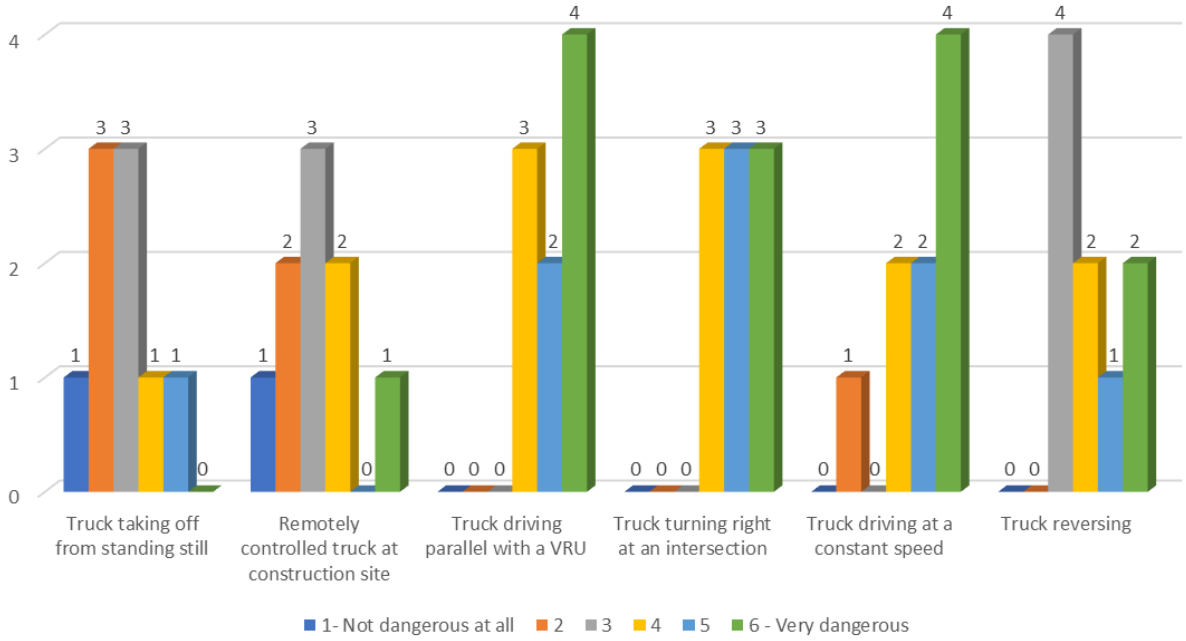


Table 5.5

Summary of Truck Drivers Ranking the Danger of Six Scenarios

	1	2	3	4	5	6	Mode
Truck taking off from standing still	1	3	3	1	0	0	2,3
Remotely controlled truck at construction site	1	1	3	2	0	1	3
Truck driving parallel with a VRU	0	0	0	1	2	5	6
Truck turning right at an intersection	0	0	1	2	1	4	6
Truck driving at a constant speed	0	0	4	2	0	2	3
Truck Reversing	0	0	1	2	2	3	6

Figure 5.5

Truck Drivers Rank the Danger of Six Scenarios

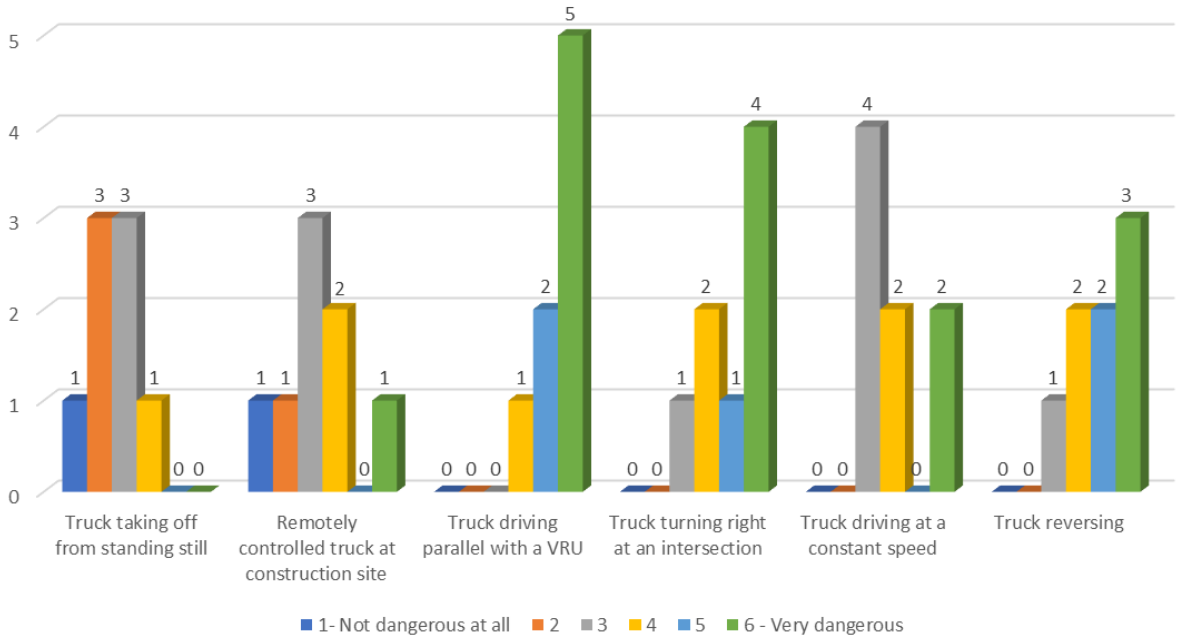


Table 5.6

Summary of Cyclists Ranking the Danger of Six Scenarios

	1	2	3	4	5	6	Mode
Truck taking off from standing still	0	6	6	4	2	1	2,3
Remotely controlled truck at construction site	0	2	8	4	3	2	3
Truck driving parallel with a VRU	0	2	1	3	2	11	6
Truck turning right at an intersection	0	1	0	3	3	12	6
Truck driving at a constant speed	1	4	4	0	4	6	6
Truck Reversing	0	1	4	5	3	6	6

Figure 5.6

Cyclists Rank the Danger of Six Scenarios

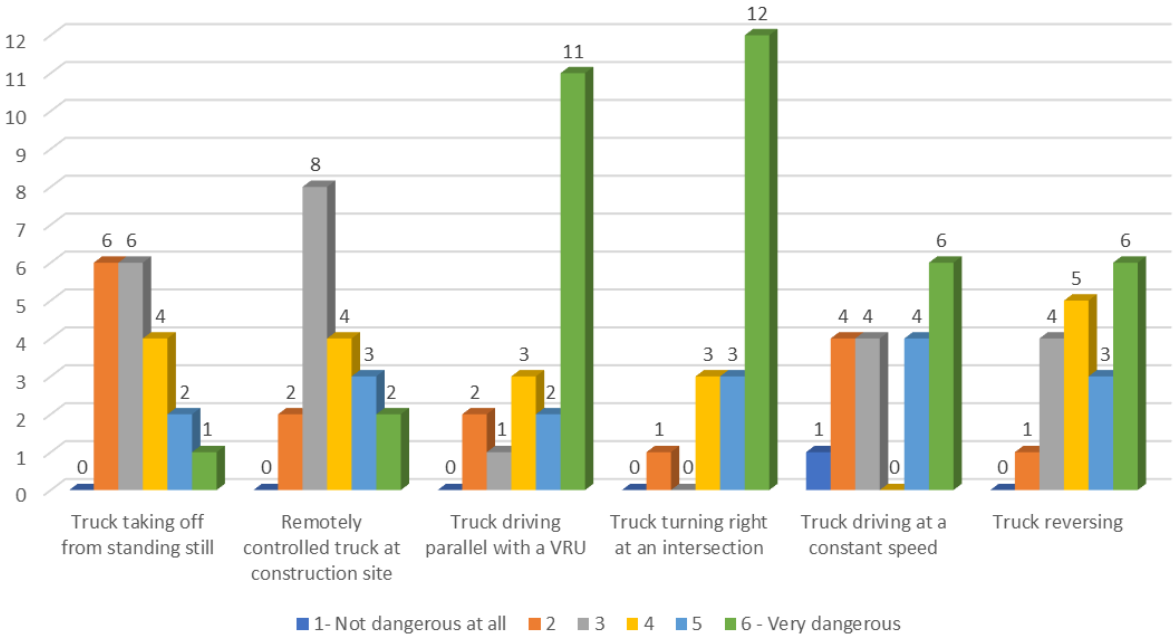


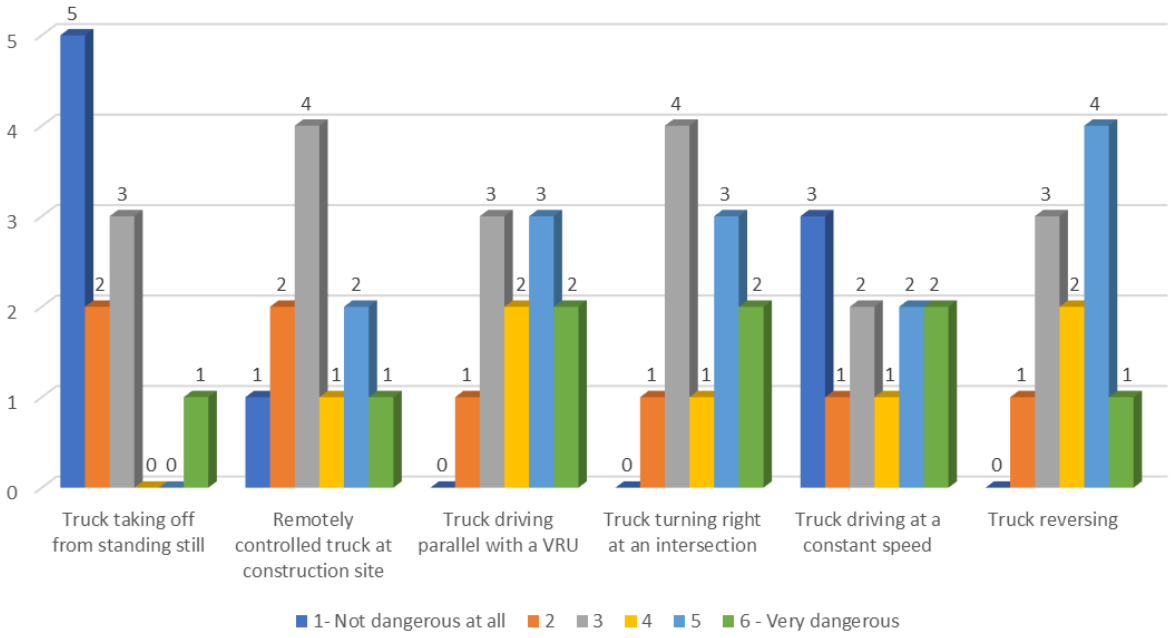
Table 5.7

Summary of Pedestrians Ranking the Danger of Six Scenarios

	1	2	3	4	5	6	Mode
Truck taking off from standing still	5	2	3	0	0	1	1
Remotely controlled truck at construction site	1	2	4	1	2	1	3
Truck driving parallel with a VRU	0	1	3	2	3	2	3,5
Truck turning right at an intersection	0	1	4	1	3	2	3
Truck driving at a constant speed	3	1	2	1	2	2	1
Truck Reversing	0	1	3	2	4	1	5

Figure 5.7

Pedestrians Rank the Danger of Six Scenarios



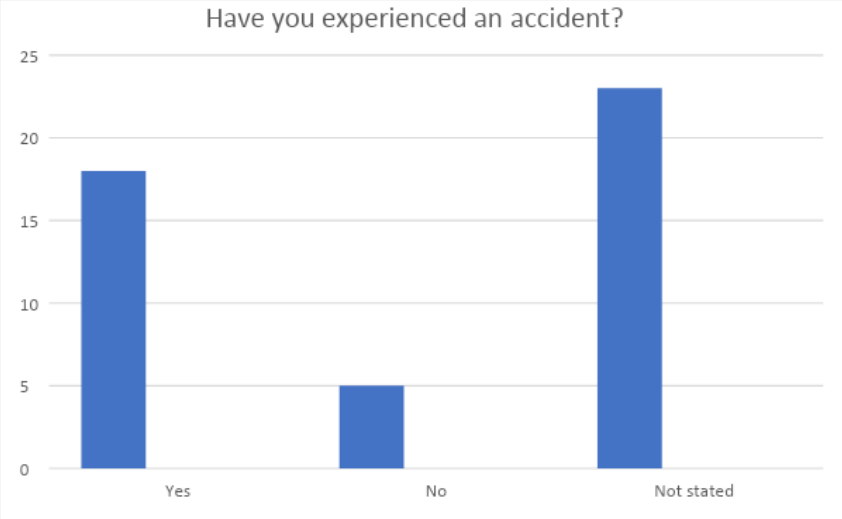
The participants were also asked for other dangerous scenarios that should be looked into and here are the participants suggestions:

- Different times of day
- Round-a-bouts that lead straight into pedestrian crossings
- Downhill
- Curves
- Driving from side roads onto main roads
- Narrow streets
- Vehicles overtaking cyclists before road narrowing
- Include motorcycles
- Illegal U-turns
- A truck and a cyclist parallel to each other, but both stopped at the stop line of a red light. Truck turns right, kills cyclist proceeding forwards.
- Lane Changes in mixed traffic

The participants were also asked if they have experienced an accident (Figure 5.8).

Figure 5.8

Online Questionnaire Participants Involved in Accidents



5.5 The Virtual Environment

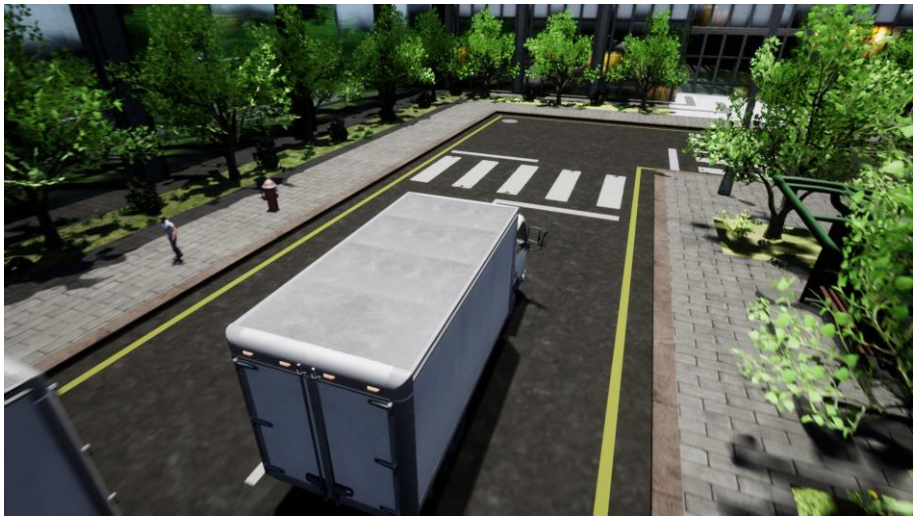
In this project, a virtual environment for testing AVAS concepts was created. This environment was created in Unreal Engine 4 and consisted of an urban environment with roads, intersections, high-rise buildings, low-rise buildings, a parking lot, a construction site and animated environmental elements such as trees and patches of grass. A series of personal vehicles were placed in the parking lot and a couple of trucks were also placed on the streets of this environment, one of which helped us recreate the scenario in which the experiment took place.

In addition to the virtual environment, a graphical user interface (GUI) was put in place to help the users choose different types of AVAS, and start the experiment. This GUI consisted of a main-menu and an options menu. In the main menu a total of four buttons (i.e. Start, Training, Options, and Exit), and in the options menu, a total of five buttons (i.e. AVAS NoTakeOff, AVAS Pulsating TakeOff Sound, AVAS Alarm, AVAS Futuristic, and Back) were placed to increase the usability of this product. Although this product is not a finished product, it is a useful minimum viable product to use as a proof of concept and help us investigate the different AVAS concepts generated for the purposes of this study.

Furthermore, two easter-eggs were placed in this platform where the user could drive a truck by pressing the T key on the keyboard. Moreover, although the running was disabled as the default mode of movement, it was still kept in the virtual environment as a second easter-egg and could be activated by holding down the Shift key. However, none of these two easter-eggs were revealed to the participants during the experiment as they could potentially break the course of it.

Figure 5.9

Driving a Truck as an Easter-Egg in the Virtual Environment



In addition, a series of environmental sounds such as wind and a noises from a construction site were placed in the virtual environment, where the wind would be heard equally in every part of the environment, but the contruction site was tied to a specific location (i.e. the construction site) and would grow weaker in intensity (i.e. volume) as the character moved away from the sound source.

Although only one scenario was implemented in this virtual environment, it offers the space and environment for recreating several more scenarios such as a remotely controlled truck at a construction site, or a truck moving forward in a constant speed.

Figure 5.10

Construction Site, High-Rise, and Low-Rise Buildings in the Virtual Environment

5.6 Thematic Analysis

The data set created from the interviews and the think-aloud protocol resulted from 150 codes. Three themes, 11 categories, 11 subcategories and nine sub-subcategories were generated and defined. The research team then defined the themes and categories to produce the results of the thematic analysis and graphs were created to visualise the results of the thematic analysis (see Figure 5.12). A legend has been created for the thematic analysis (see Figure 5.11).

Figure 5.11

The Legend for the Thematic Analsysis

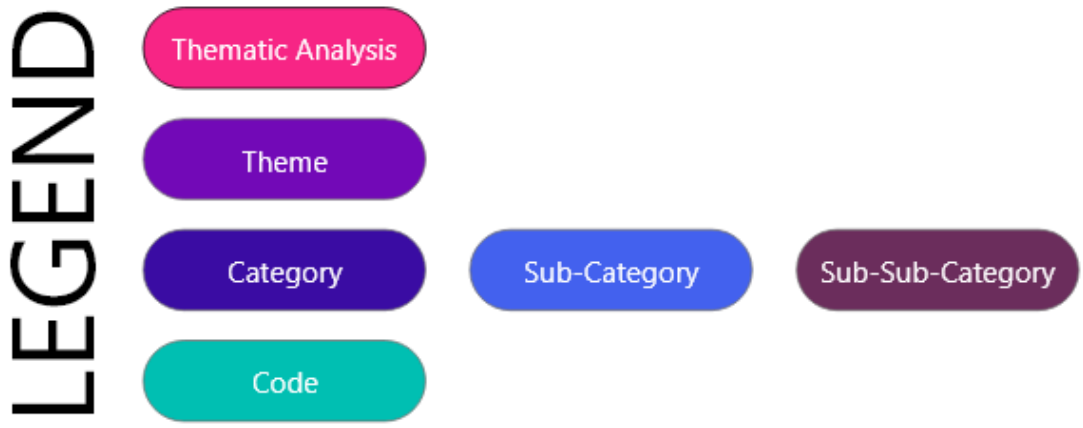
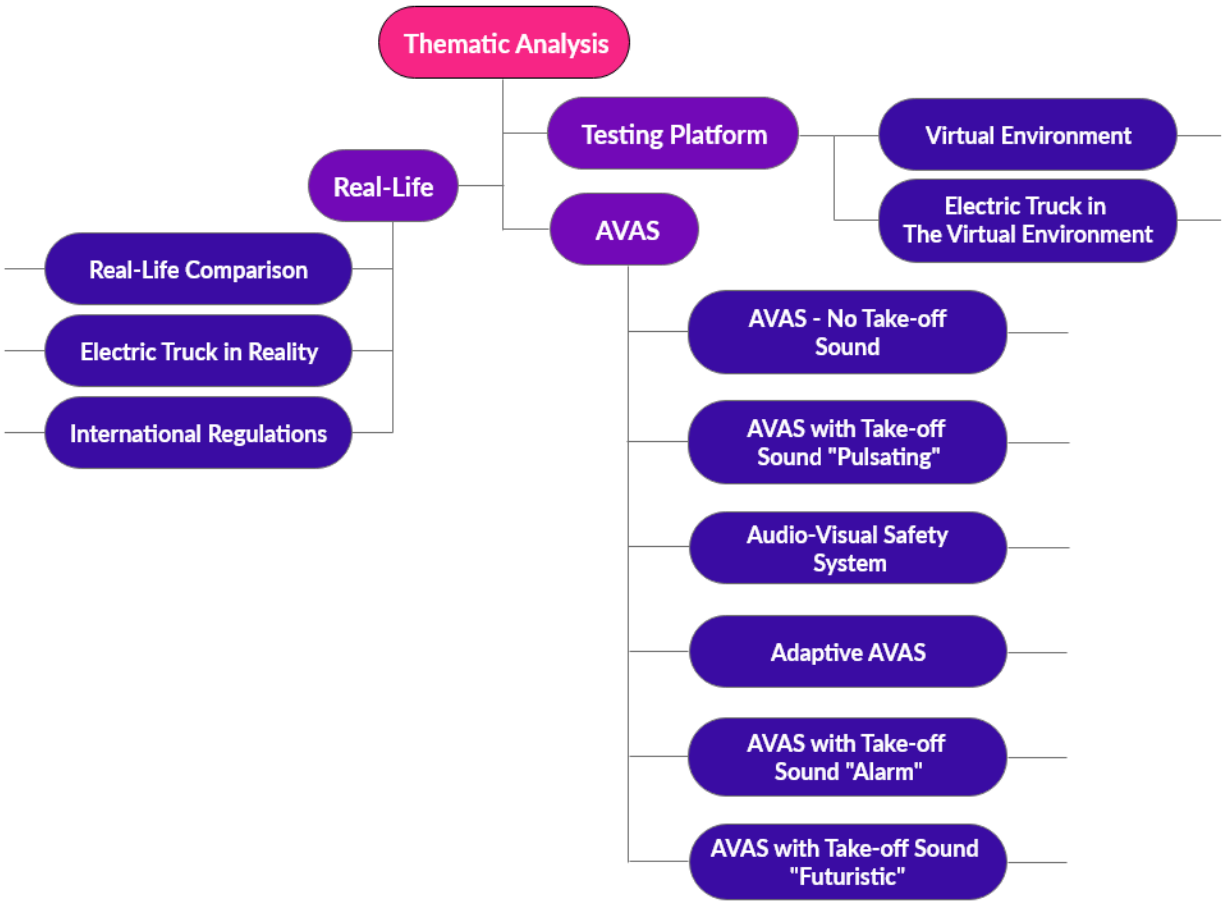


Figure 5.12

All the Themes and Categories That Emerged as a Result of the Thematic Analysis



5.6.1 Real-Life

Real-life as a theme refers to the sum of codes and categories that relate to the physical world as opposed to the virtual world. This theme consists of three categories, namely International Regulations, Real-life Comparison, and Electric Truck in Reality (see Figure 5.13). In the following, we explain each category in more detail.

International Regulations

International and global regulations requiring electric vehicles to emit a take-off sound would result in a conventional understanding and expectation of take-off sound by Vulnerable Road Users. Learning to associate a certain sound with a certain event was mentioned by several participants, however one participant mentioned the importance of international regulations in order to achieve a global consensus on the meaning of sounds. The research team deemed this insight as an important factor in this context and therefore decided to include this insight as a category under the theme Real-Life.

Real-Life Comparison

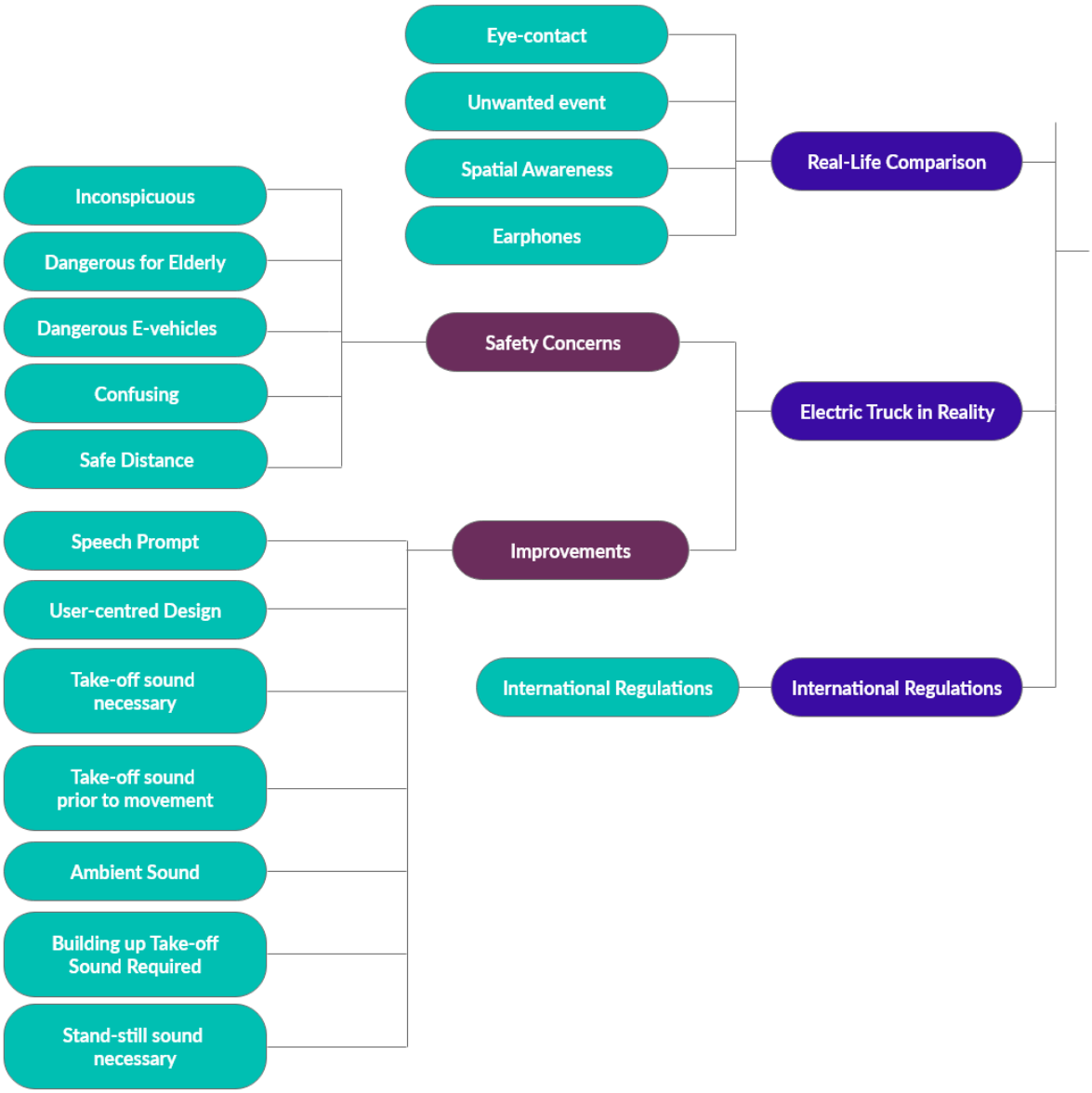
Referring to the comparison of a real-life situation to undergoing the experiment, this theme consists of a series of points raised by the participants in regard to their behaviour in real life which were not possible or implemented in this simulation. These points consisted of the ability to be more spatially aware of the surroundings in real-life, having eye-contact with the driver, wearing earphones (especially noise-cancelling earphones) to listen to music.

Electric Truck in Reality

This theme consists of a series of safety concerns and suggested improvements for Electric Trucks in reality - as opposed to in the Virtual Environment. The safety concerns raised by our participants consist of the vehicle being inconspicuous in urban areas which would pose a threat to the safety of VRUs and especially the elderly. Our participants also raised concerns over not understanding the intentions of quiet electric vehicles, as well as misjudgement of distance between an approaching electric vehicle and pedestrians due to lack of noise. To address these, certain improvements and requirements were suggested by the participants. Among these were a necessity for e-trucks to emit “standing still sounds”, and “take-off sounds”. According to the data gathered, a take-off sound implemented in a truck in real life ought to be played prior to movement and have a build-up in terms of pitch that mimics the sound of engine acceleration in ICE trucks. Furthermore, one participant suggested that, in reality, the truck’s behaviour should be altered in accordance with VRU behaviour as opposed to VRUs altering their behaviour in accordance to that of the truck (User-centred Design).

Figure 5.13

The Categories Belonging to the REAL-LIFE Theme Consisting of Real-life Comparison, Electric Truck in Reality, and International Regulations



5.6.2 Testing Platform

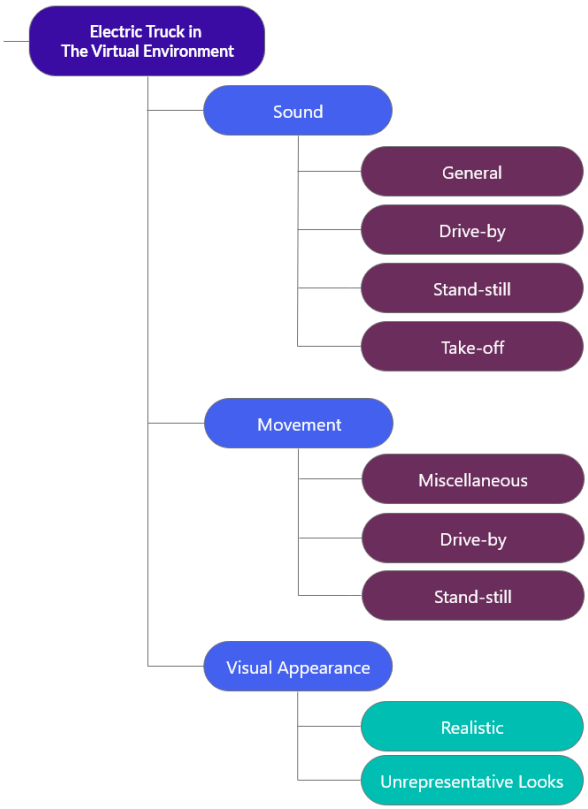
The following categories emerged in the thematic analysis. These categories together were labelled as the theme Testing Platform since they relate to the virtual environment in which the experiment took place.

Electric Truck in the Virtual Environment

One of the themes that naturally emerged from our experiment was concerned with the Visual Appearance, Movements, and Sounds of the *simulated* truck in the virtual environment (see Figure 5.14).

Figure 5.144

The Category Electric Truck in the Virtual Environment Under the Theme TESTING PLATFORM



Visual Appearance: Although the majority of the participants believed that the visual appearance of the truck was realistic, some pointed out the mismatch between what they expected of an electric truck and the mule truck used in the experiment (Figure 5.15).

Figure 5.15

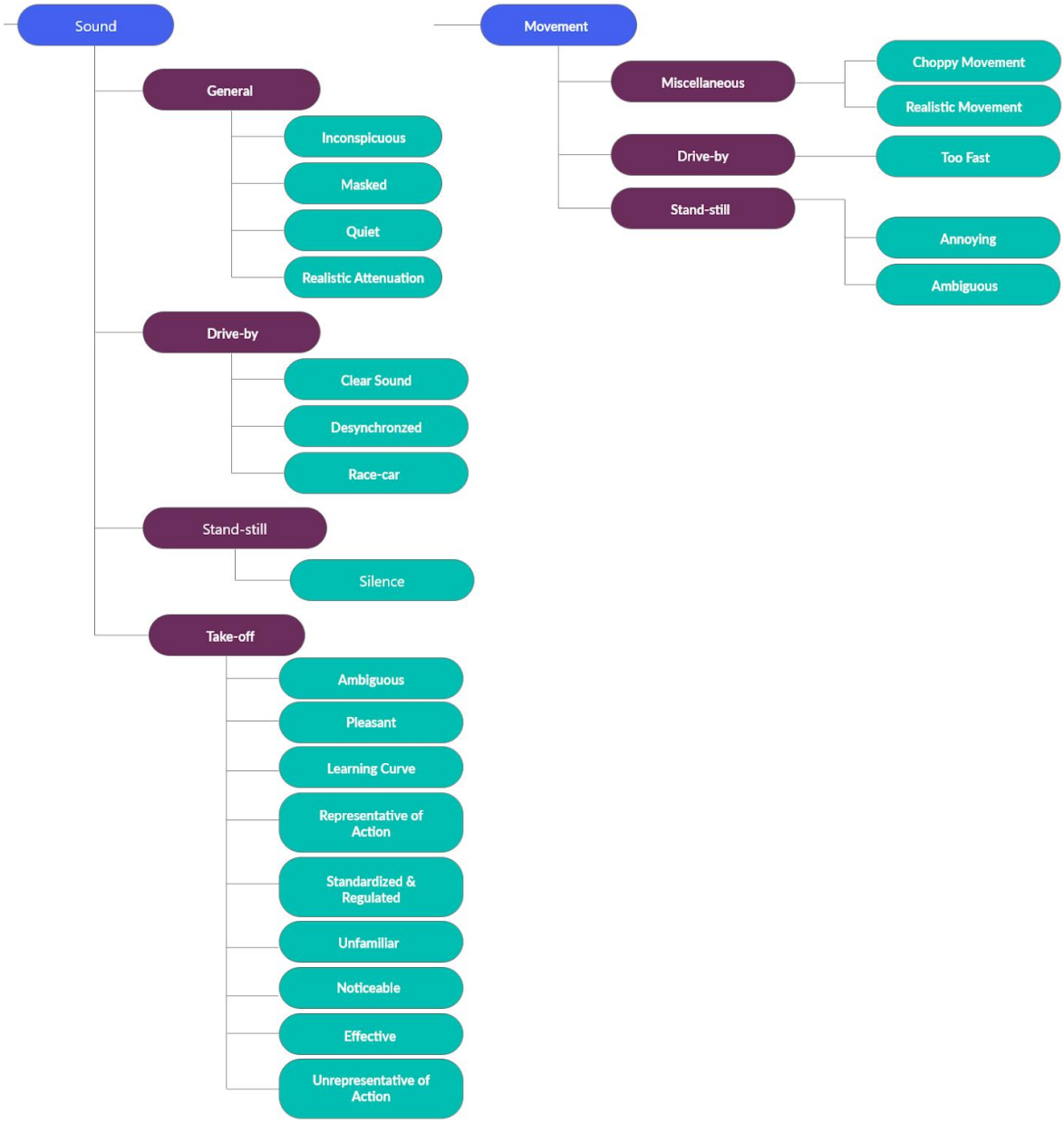
The Truck Used in the Simulation

Movement: The movements of the truck was seen as natural and realistic by the majority of the participants, however a few of the participants believed that at points the movement was "choppy". Furthermore, some mentioned that the truck's "drive-by" [prior to coming to full stop at the crossroad] was faster than expected. Additionally, some participants noted that they were annoyed by the truck waiting at the crossroad as they did not understand the intentions of the truck (see Figure 5.16).

Sound: The majority of the participants pointed that the sound generated by the simulated truck was rather realistic in terms of attenuation and that they did not notice any incoherent sound spatialization. Additionally, several participants mentioned that the environmental sounds masked the sound of the truck and therefore making the truck relatively inconspicuous. In regard to the take-off sounds, several participants noted that although a take-off sound was unfamiliar and ambiguous in terms of the intentions of the truck, the take-off sound was representative of some type of action and would be an effective means of demanding attention and addressing safety concerns. The majority of the participants also mentioned that they would be able to learn to associate a sound with take-off if such sound was standardized and regulated (see Figure 5.16).

Figure 5.16

The Subcategories and Codes Belonging to the Category Electric Truck in the Virtual Environment



Virtual Environment

The virtual environment (see Figure 5.17) built in Unreal Engine 4 for the purposes of this experiment was labeled as realistic, impressive, effective, and likeable as a whole. The character movements were perceived as realistic, and the environmental sounds were perceived to be rather realistic for the scenario.

One of the shortcomings of the virtual environment that was mentioned in the data gathered during the interviews consisted of the lack of traffic and other people in the scenario presented. Coupled with this was short-comings in the soundscape of the scenario where one participant

expected to hear several more background noises (e.g. children playing, bikes passing by, sirens, traffic etc.) in the urban environment in addition to the wind and construction background noise that was already implemented in the simulation.

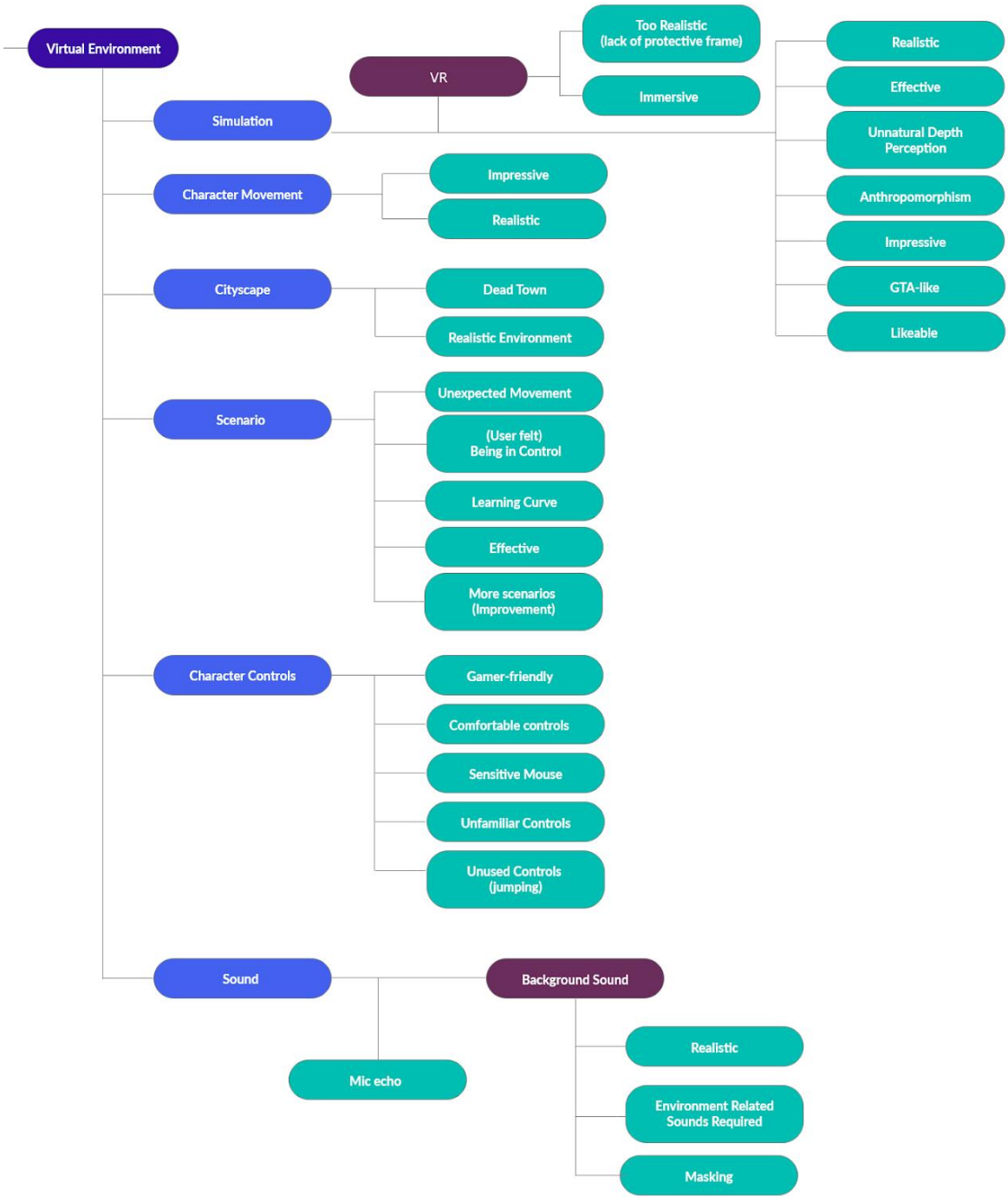
Figure 5.17

The Virtual Environment

The controls (W,A,S,D) were familiar and comfortable for most participants, especially those who had some gaming experience. On the other hand, a couple of the participants preferred less sensitive mouse controls. One participant also noticed an echo of their own voice through the microphone of the headset used for the experiment which they described as slightly annoying. Lastly, most participants felt immersed in the virtual world, two of which suggested using VR for more immersion (see Figure 5.18).

Figure 5.18

The Category Virtual Environment Under the Theme TESTING PLATFORM



5.6.3 AVAS

The following categories were merged together to form the theme “AVAS”. These categories include the AVASes that were designed and tested, as well as Adaptive AVAS and Audio-visual Safety System (see Figure 5.19).

AVAS - No Take-Off Sound

This category consists of the input regarding the base AVAS, namely an imitation of engine sound without any take-off sound. This sound was clearly heard by the participants and the participants were able to naturally map this sound to the vehicle's engine sound. However, in comparison to the other Acoustic Vehicle Alerting Systems with a take-off sound it was perceived as ambiguous regarding the intentions of the truck. Coupled with that, this type of AVAS was perceived as more inconspicuous in comparison to other AVAS with take-off.

AVAS with Take-off sound "Pulsating"

This category refers to AVAS with a pulsating [two consecutive short high-pitched sounds] take-off signal. This sound was perceived as a distinct and alerting yet familiar sound that represented some type of action by most participants. The pulsating take-off sound was perceived as a friendly and pleasant sound by several participants. However, it was not very representative of the physical properties of a truck and many participants associated this sound with lighter or smaller vehicles. Furthermore, this sound was ambiguous of the intention of the truck (take-off) and was associated with reversing by several participants.

AVAS with Take-off sound "Alarm"

This category refers to AVAS with one short high-pitched take-off signal. This sound was identified as clear, attention-demanding, friendly, and representative of the intentions of the truck or some type of action. On the other hand, some participants perceived this signal as unrepresentative of the truck and associated it with lighter vehicles (e.g. E-Scooter) as it was a rather high-pitched sound. As such, some participants found this signal ambiguous and did not naturally map it to a truck. What is more, some perceived this signal as inconspicuous and quiet while one perceived it as “scary”.

AVAS with Take-off sound "Futuristic"

This category refers to AVAS with a continuous Shepard tone inspired (increasing in pitch) take-off signal. This sound was identified as a sound that was representative of the truck (/light truck) which best represented acceleration in relation to the other two take-off signals. Coupled with that several participants reported that this sound was representative of the intentions of the truck (taking-off).

On the other hand, several participants perceived this signal as inconspicuous, annoying, too quiet and ineffective. Coupled with this, a few participants believed that this sound better represented a race-car and did not naturally map it to a heavy truck. Additionally, one participant thought that the signal was too short and high-pitched.

What is more, this sound was labelled as “industrial”, and one participant even associated this with e-scooters, and labelled this sound as the worst practice in relation to the other take-off sounds.

Adaptive AVAS

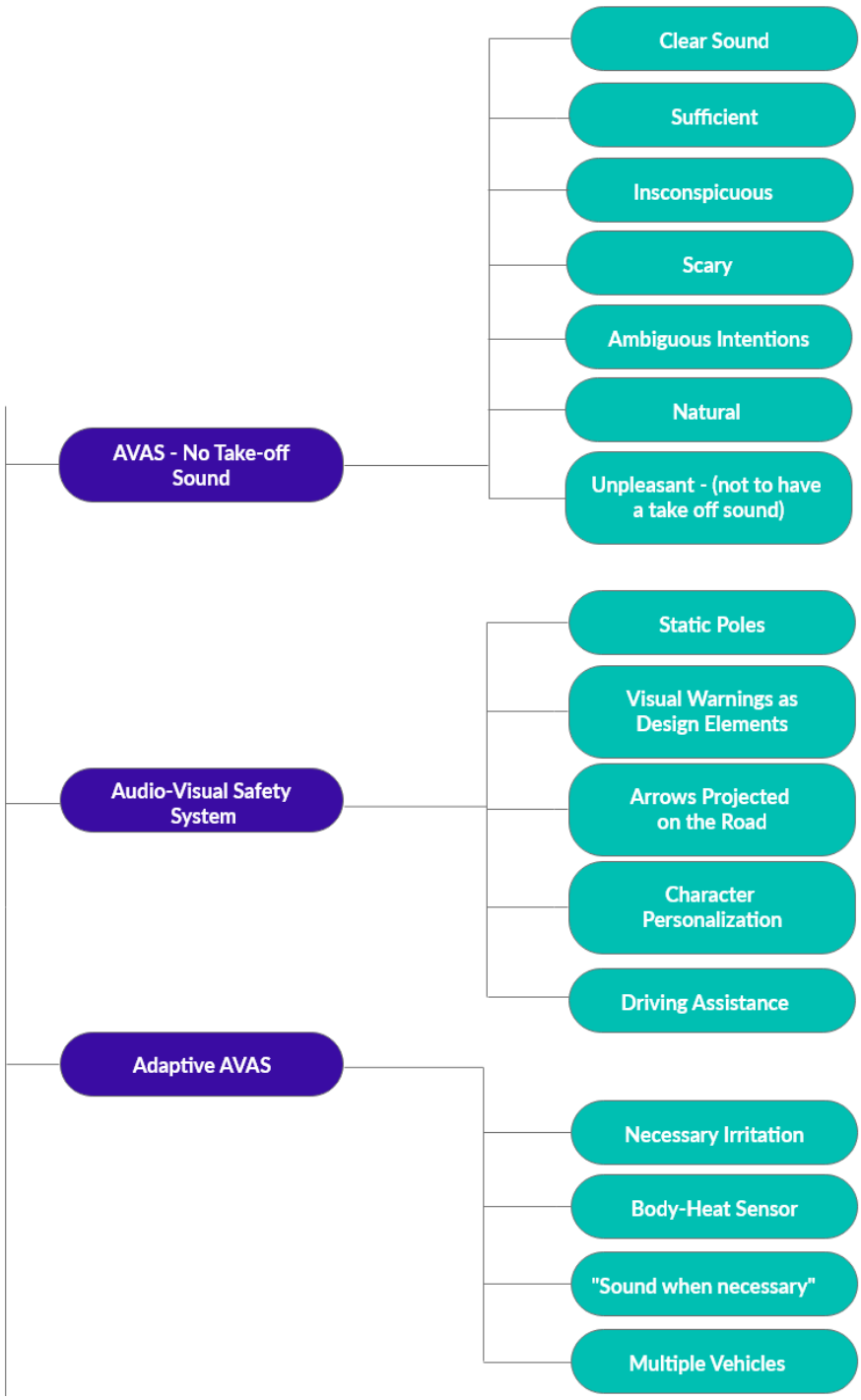
This category refers to an AVAS that adapts to the situation, and other road users. Such a system can adapt to different situations e.g. adapting the AVAS pitch to avoid the emitted sound being masked by the environmental sounds or to produce a unique and distinguishable sound when there are several different vehicles in the vicinity, producing the same type of sound. This theme emerged from the comments and suggestions from several participants during the interviews. Many of our participants brought this up as a means of achieving a balance between safer roads, and quieter urban areas. Additionally, the participants showed a desire in implementing such a system in order to make the HGV smarter and consequently safer through e.g. body-heat sensors which would read the presence of a VRU to emit a warning sound in case of a looming dangerous situation. Coupled with this, some participants suggested that this type of AVAS may be able to alter the sound to demand more attention in critical situations where the risk of a fatal accident is high.

Audio-Visual Safety System

This category refers to a warning system that combines visual and audio cues to warn VRUs of the intentions of a truck. When asked how they would have wanted to be warned several ideas came up, most notably combining AVAS with a projection of arrows on the road to indicate the direction in which the truck is about to move. One participant mentioned that such a visual cue can have a dual purpose as it may act as a driving assistance to e.g. help the driver keep in lane.

Figure 5.19

6 Categories of the Theme AVAS



Note. Consisting of AVAS w/ no take-off sound, Audio-visual Safety System, and Adaptive AVAS (top) as well as AVAS with Futuristic, Alarm and Pulsating take-off sounds (bottom) and their respective codes.

5.7 Experiment Questionnaire

The questionnaire (Appendix C) conducted for the experiment consisted of four general questions about noticeability, safety, pleasantness and representativeness of the AVASes in regard to the virtual truck. The reason for choosing four questions was the simplicity of answering a low number of questions while the memory of the sounds perceived was still fresh. Moreover, the research team decided to ask a question about the noticeability of the sound cues, as it is crucial for AVAS to be noticeable despite the environmental noise. How well the participants understand the intentions of the truck is considered to be tightly related to the safety aspects of the AVAS implemented, as a failure in communication of the intentions of HGVs is thought to lead to fatal accidents especially in the chosen scenario. Moreover, the research team deemed the pleasantness of the perceived sounds as an important deciding factor in choosing a sound for AVAS, and take-offs and as such, a question was dedicated to gathering data on the pleasantness of the emitted sounds. Lastly, as sound often gives the hearer rather important clues about the nature of events and the physical properties of objects, the research team decided that it is crucial that the sounds emitted by AVAS, in fact, represents the physical properties of the respective vehicle. As such, a question about the representativeness of the sound cues in regard to the physical properties of the vehicle was asked in the questionnaire in order to determine if any of the sounds designed for the purposes of this experiment better represents these properties.

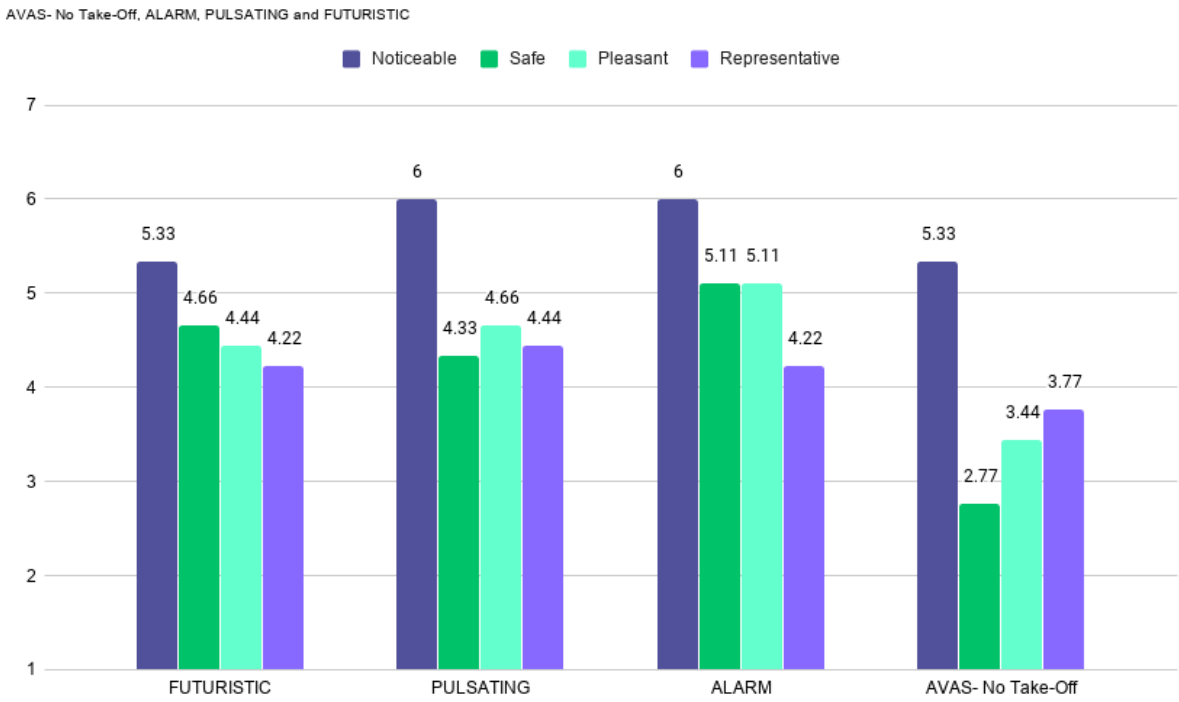
The analysis of the questionnaires filled by the participants shows that AVAS with no take-off sound was as noticeable as AVAS with the Futuristic take-off sound, and AVAS with the Alarm take-off sound was on par with AVAS with the Pulsating take-off sound in that regard. Furthermore, the two latter AVAS were perceived as more noticeable in comparison to the former two.

In terms of safety, the Alarm take-off sound was more effective and attention demanding than the other alternatives, second by the AVAS with Futuristic take-off sound. Coupled with that, the Alarm take-off sound was perceived as more pleasant by the participants than the other alternatives, second by the AVAS with Pulsating take-off sound.

According to the data gathered, the acoustic vehicle alerting system that best represented the physical properties of the truck in the simulation was the AVAS with the Pulsating take-off sound. Furthermore, the AVAS with the Alarm, and Futuristic take-off sounds mutually shared the second place in terms of being representative of the physical properties of the truck. The results of this questionnaire are shown in Figure 5.20, and Figure 5.21

Figure 5.20

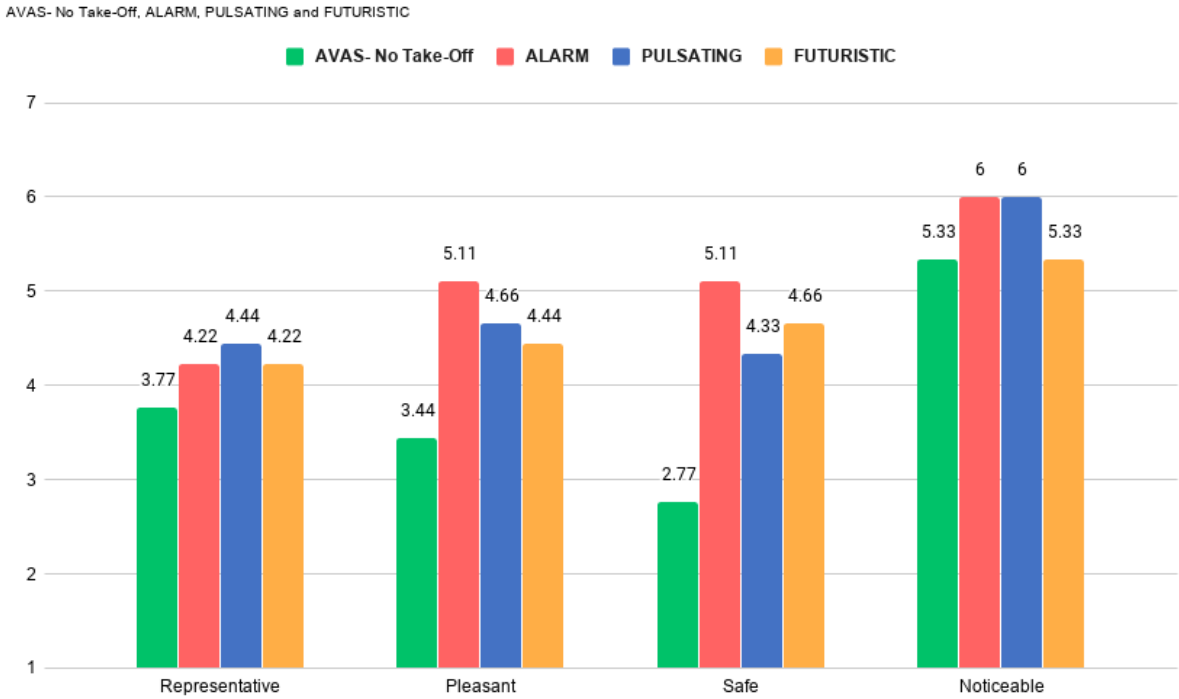
Experiment Questionnaire's Results Categorised per AVAS



Note. The numbers represent the mean value of the scores given to each system in terms of being Noticeable, Safe, Pleasant and Representative on a Likert scale of 1 to 7.

Figure 5.21

Experiment Questionnaire's Results Categorised per property

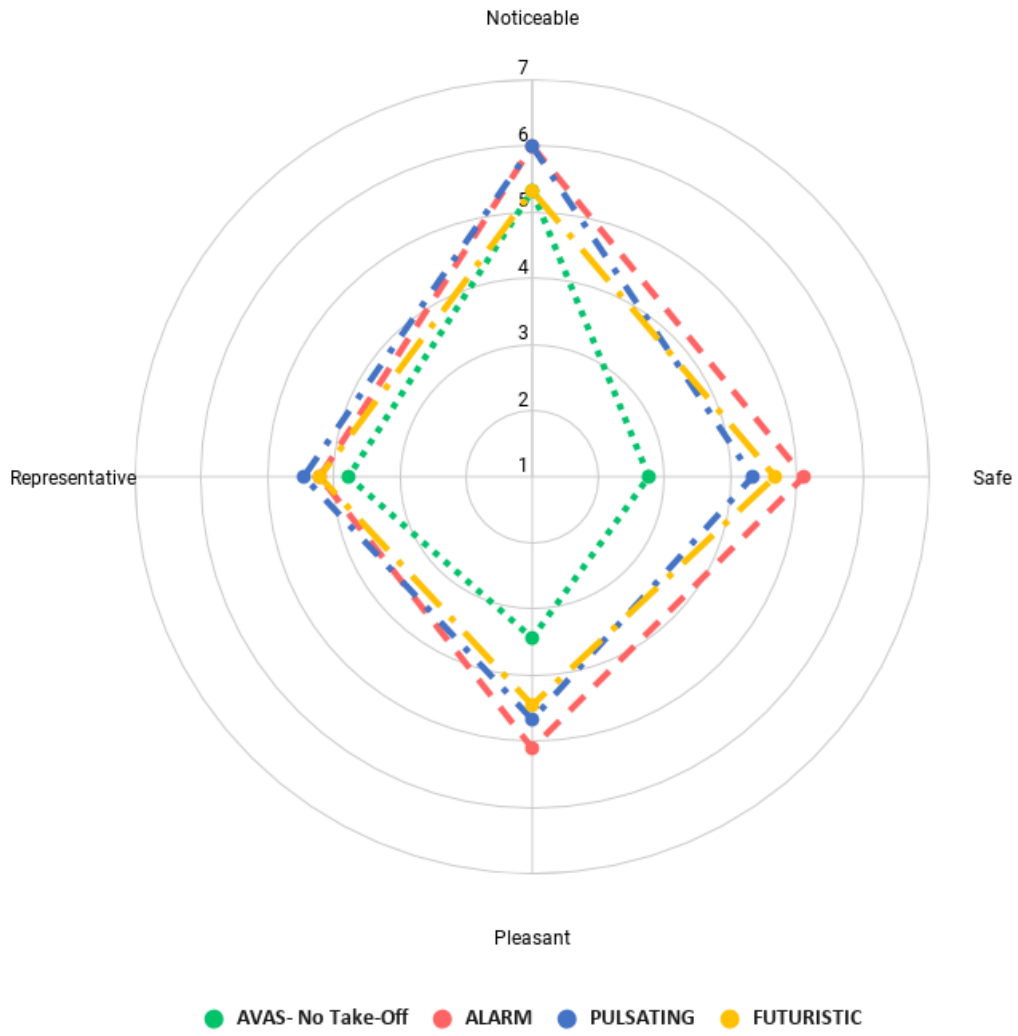


Furthermore, the results of the experiment questionnaire indicate that an AVAS without any take-off sound received a lower or similar score in each of the four categories, namely

Noticeable, Safe, Pleasant and Representative. Although in terms of noticeability, and representativeness, the AVAS without a take-off performed closely to its counterparts, this sound was clearly inferior in terms of safety and being pleasant to AVAS'es with a take-off sound.

Figure 5.22

Summary of The Questionnaire in the Experiment



Note. The area occupied by AVAS with no take-off sound is clearly smaller than the areas occupied by its counterparts. For seeing the radarchart results of each AVAS see Appendix A.

In terms of safety, and being pleasant, the Alarm take-off sound performed marginally better than the other two take-off sounds. Additionally, the Alarm take-off sound was on par with the Pulsating take-off sound in terms of noticeability whereas the Pulsating take-off sound was perceived as marginally better than the other take-off sounds.

5.8 Guidelines

Throughout our design and research process we learned several important take-aways. Both in regard to designing AVAS, and in regard to designing a virtual environment for testing AVAS. The take-aways were not only a result of our experience during the process, but also brought up the participants of our experiment, questionnaires, and interviews.

Designing AVAS requires some basic understanding of how we perceive sound as humans. For instance, knowing that certain frequencies are perceived louder than the others with the same amplitude can help you find a balance between the volume and frequencies used. Using these basic principles will help you with designing useful yet pleasant AVASes by putting the users' needs and desires in focus. During this process, we learned that using metaphors can help you reason about why a certain sound makes more sense than others.

You may feel that building a virtual environment is a big task especially if you are not familiar with simulation software and game engines. Although it greatly depends on the purpose of your research, building such environments are made easier and easier by the day as there are many resources that one can use to build a good-enough platform. In our experience of building a platform for testing AVAS, using animated assets such as trees with moving leaves can help greatly with creating an immersive experience for the participants of your experiment. For instance, as we learned during an interview with a participant, they thought that the sound of wind that they heard was a result of the wind blowing through the trees. Additionally, during some of the interviews where we asked about the virtual environment, participants mentioned that there is a lack of other actors such as cars and people. As such, we learned that including more animated elements could help us improve the environment in terms of being realistic.

To sum up, certain incidents made, and some broke our experiment and research along the way. As such we have composed a series of guidelines based on our experience as designers as well as the results of the experiment to help with designing and performing tests on AVAS, especially in a virtual environment. These guidelines are as follows:

5.8.1 Guidelines for Designing AVAS

After having studied and designed AVAS, we created a series of guidelines to help the future researchers and designers working with AVAS to reach their goals. The guidelines for designing AVAS are as follows:

1. **Learn about psychoacoustics:** based on our experience, this understanding is crucial to designing AVAS. If you don't know how the human auditory system works, it will be very difficult to maintain a user-centered design when designing AVAS. Having a user-centred design is very important in design, and designing AVAS is no exception. As one of our participants said in the interview conducted after the experiment "[an electric truck should] be more adaptive to people rather than having people adapt to it". By not having a user-centred design approach, you may focus too much on the technical aspects of sound and miss the bigger picture: namely that the VRUs need to recognize and distinguish the sounds emitted, even though there may be several sources of sound around them. Moreover, certain phenomenon such as masking are tightly related to psychoacoustics and understanding the "whys" and "hows" behind them will be crucial in countering such issues when designing safety systems such as AVAS.

2. **Learn about the physical properties and the anthropological importance of sound.** Learning the theoretical concepts such as amplitude, frequency, resonance, and masking are

rather crucial in designing AVAS. During this project we encountered several misconceptions about these properties of sounds by some of the stakeholders who were not sound designers but were working on the subject matter: an example of these misconceptions was that a high-pitched sound has more energy than a low pitched sound: this is simply not the case as it takes more energy to create longer wave lengths than it takes with shorter ones. Additionally, understanding these concepts in theory will help you navigate and find the right settings when designing sound for AVAS via software e.g. VCV Rack, as most of the settings in these software are labelled with technical terms and require a good understanding of the concepts relating to the physical properties of sound. Having a good understanding of the anthropological importance of sound is also highly recommended as it may strengthen your reasoning by relating your design choices to cultural and/or universal interpretations of the sounds. This aspect of sound is especially beneficial when communicating your ideas to your teammates and stakeholders and will give you an additional tool to have them better understand you through metaphors, similes and analogies. For example, as we explained in the section 4.2.3.1, using metonymies such as SPEED OF ACTION IS SPEED OF MOTION will help you bridge the physical, real-life events to the minds of your target group, by using rather universal ways of understanding the world.

3. **Experiment with frequency and amplitude.** In our experience, a bodily understanding of how sounds different frequencies and amplitudes are necessary to compliment the description of these concepts when designing AVAS. For example, when we experimented with different sounds in VCV Rack and implemented some of the sounds created in the virtual environment, we realised: given the fact that there are several different sounds present in the environment, a change in tone can be crucial in avoiding the masking of AVAS. We also noticed that by doubling the amplitude of a sound, we do not hear the sound double as loud, whereas a change in pitch increased the perceived volume of the sound cues drastically. In other words, merely knowing the basic definitions of frequency or amplitude will not suffice when designing AVAS. An ability to hear the differences in tone and amplitude of sounds will help you better understand why certain sounds work better than others in a given context.

4. **Consider designing an Adaptive AVAS:** Based on the results of our experiment, as well as our interviews with experts and other stakeholders, there is a desire for electric vehicles to be “smart”, and an Adaptive AVAS is simply expected of them. Several participants in our experiment showed a desire for having some form of Adaptive AVAS. For example one participant said “[An Adaptive AVAS] could only make a take-off sound when a person/animal is close to it using bodyheat sensors.”. Furthermore, during the interviews with the experts at Volvo Trucks, one of the co-authors of the Volvo Safety Report mentioned that AVAS may benefit from some type of geo-tagging of the location it is operating in. This expert mentioned that “for example maybe the truck can adjust [accordingly] when they are operating near a school – for example when they are delivering food [to the food court].”. Therefore, an Adaptive AVAS that adjusts its behaviour to the environment is an ideal form of AVAS that was brought up by several different stakeholders in our study and should be considered when designing such systems.

5. **Consider matching the sounds for AVAS to the physical properties of the vehicle:** As we learned during our pre-studies and the reviewing of literature, sounds communicate a lot of information about the nature of events and the physical properties of the agents involved in that event (see section 2.5.1). As such a representative sound will give the VRUs an immediate idea about the weight and type of vehicle approaching them. In the interviews conducted in the experiment, participants mentioned that e.g. “A darker tone could be more suitable for the

electric truck. Big and slow, dark beeps would be more connected to the truck [and] faster lighter beeps to smaller cars.", "As a truck is a heavy object you need a heavier sound to it.", "A truck needs more depth and a lower pitch", and "[a take-off sound] might have benefitted from being a lower sound, not in volume but in pitch, just to show the weight, the momentum and inertia of getting such a big car to drive". These quotes suggest that a darker tone, i.e. lower in pitch is naturally mapped to heavier vehicles such as trucks, and a lighter tone, i.e. higher in pitch suits the lighter vehicles. As such, it can be beneficial to communicate the size and weight of the vehicle with adjusting the pitch of the tones used in AVAS in order to make the VRUs more aware of the physical properties of the vehicle you are designing for.

6. **Implement a take-off sound.** As the results of our study shows, a take-off sound can improve AVAS (see figure 5.22), especially in terms of safety. In fact, all of our participants agreed that a take-off sound improves the safety of the roads. For example the participants said that "[Take-off sound] will make the streets much more safe", "The take-off sound is necessary especially for heavy vehicles. Even with personal vehicles it is hard to notice electric cars, especially old people will get confused and be a bigger risk in dangerous situations.", and "Take-off sound would definitely make the streets safer. I'm really used to the trams, and their 'take-off sound' and I always listen to it. I've also noticed that other people listen to it. If trucks would have a similar sound, I'm sure people would react to it.", to quote a few of their inputs.

5.8.2 Guidelines for Designing a Virtual Environment for Testing AVAS

As previously mentioned, we spent a reasonably large portion of this project designing a virtual environment where ideas for AVAS can be tested and communicated. As such, we have created ten guidelines to help researchers and designers to create a platform where they can test and communicate their ideas effectively. The ten guidelines for designing a virtual environment for testing AVAS are as follows.

1. **Use common and intuitive controls.** In our experience, by having commonly used means of navigation and movement you save valuable time both during troubleshooting of the environment (see chapter 4 section 4.2.2.3), as well as during the actual experiment. This helped us reduce the time spent on explaining the controls to the participants, and only one person said "For me the keys WASD were on the wrong side, [as I am used to the arrow keys]" whereas most participants said that the controls were easy to master; for example one participant said "It was comfortable to control the character, as I'm used to playing games.", and another said that "The movement and controls felt natural.". As such, we would like to encourage using commonly used and intuitive controls as means of movement in the simulation.

2. **Spend some time optimizing the movement of vehicles and other moving objects:** as we asked our participants about the virtual environment, we learned that although most participants gave comments such as "The simulations was realistic, everything was very lookalike as a real world. The approaching of the car was realistic." and "Movement and simulation was pretty realistic", some of the movements had more room for improvement. For instance, one of our participants mentioned that "the movement of the truck wasn't extremely physically correct – it was a bit choppy". As such, we recommend spending time on the realistic movement and animation of the vehicles and other moving objects in your simulation to make it more realistic. Based on our gathered data, having the moving objects translate smoothly in the environment will make the simulation more realistic and immersive, and failing to do so may break the feeling of presence in the simulation.

3. **Record and include environmental noise in your simulation.** During our pre-studies and observations, we noticed that the environmental noise forms a large part of the soundscape in which trucks and other vehicles are used. During this phase, we recorded a one-minute long sound clip in Linnéstaden in Gothenburg when observing truck behaviour in this urban area. Later on, this sound clip proved to be useful as when added to the simulation, it increased the realism of the simulation. Several participants marked this; for example, one participant said "you even had some city noise back there" when talking about how realistic the simulation was in general, and another . As such, it is necessary to include this type of sounds to make a realistic and immersive experience in your simulation. Also, add tire-noise to your vehicles as it is not possible to remove that type of noise from the future electric cars or trucks.

4. **Implement and adjust sound related settings, especially attenuation.** Intuitively, sound properties such as attenuation to your environment will make your simulation more realistic and immersive. The results of our interviews show that most participants considered the sound behaviour as realistic and seamless as they did not notice any inconsistencies with the sound behaviour in the simulation when asked about it. For instanece, one participant said that "The distanced sound of the truck was realistic, I could notice that the wind was taking over from the sound of the car.". Furthermore, one participant said that "Since I didn't think about [the sound], I think it flowed well" and another mentioned that "The environment sound was seamless, created a feeling that I was in the environment. The sound was well done for an urban environment." when asked about the auditory aspects of the simulation. In this regard, seamlessness of the sound behaviour is an indication of it not breaking the feeling of presence in the simulation.We believe that having implemented sound-related settings such as attenuation have lead to our experiment being perceived as more realistic as a whole as the participants did not seem to notice any anomalies in regards to the sound behaviour of the environment – barring the take-off sounds which were meant to stand out.

5. **Add NPCs and other vehicles to your scenarios**. This was brought up by a few participants during the experiment as a suggestion. For instance one participant mentioned that "it felt like the town was very dead; not much going on there in terms of other people and vehicles". Another participant mentioned that " The virtual environment felt like a real city like New York, Montreal), so there should be more city sounds [like] children playing, people, cars honking and there should be more traffic, [and] people.". In other words, the participants believed that adding more assets such as children playing will lead to a more realistic urban environment by creating a sense of liveliness in the simulation.

6. **Use life-like characters and avoid using unrealistic skins and body-shapes**: this point was brought up by our supervisor when we showed him the environment in the second iteration. After having discussed this point, we added a life-like skin to the standard mannequin provided in Unreal Engine 4. Although we opted for a first person's perspective later on, this lead to the character being more relatable as the participants could see different body parts such as hands and legs (see Figure 4.15). Based on our discussions, and a rather intuitive understanding of how the simulation would be perceived, this reduced the "gamey-ness" of our simulation and most likely helped the participants feel more present in the simulation. We believe that using a superhero-like appearances may have caused our participants to take more risk than they would in reality as they would likely feel more invincible controlling a robot-like character than a human like character.

7. **Use animated assets**: in our experience using animated assets such as rustling trees and grass, flashing shop signs etc. will help you create a more realistic simulation. One of our participants said "I hear the wind passing through the trees" during the think-aloud that he was performing as he went through the experiment. This clearly indicates that he – and perhaps more participants, strongly associated the sound of the wind implemented in the simulation with the rustling of the trees assets. This in turn is a sign of having succeeded to create a consistent and believable environment and as such, we would like to encourage an implementation of animated assets in the environment.

8. **Use the virtual environment for rapid Prototyping:** In our experience developing AVAS related features and testing them can be costly and communicating the ideas about sound is generally a difficult task. This was made clear to us as we tried to pitch different ideas to our mentor and the team involved. We also noticed that it is especially difficult to prototype different concepts as Volvo Trucks could not provide us with a workshop nor material as doing so would require us to take part in safety educations and reserve the workshop which was almost always fully booked with the nearest available time sometimes being months ahead. Additionally, during this project we came across several ideas that we could not explore due to not having access to vehicles, and testing platforms that would be available on short notice. In fact, at points, our mentor would notify us that he had found a truck that had been available for testing AVAS due to other planned tests being postponed or cancelled due to e.g. weather conditions. However, as we created the virtual environment, we found ourselves very much capable of implementing and prototyping most of the ideas we previously had. For instance, a take-off sound was now easily possible to prototype without much engineering and the implementation of sophisticated software and hardware. Software products and platforms such as Unreal Engine are also powerful and easy to use means of realizing your conceptual work and communicating your ideas to your team members and stakeholders. And therefore, we recommend using these platforms before a physical prototype is made.

9. **Take advantage of well-known usability principles and frameworks**: in our experience (see chapter 4 Process section 4.2.2.3), using design principles such as Nielsen's (1994) ten principles of usability will make the product you are working on much easier to use. During the evaluation phase of the second iteration, we noticed a number of usability problems e.g. a lack of "pause" button to exit the simulation which if not identified would have made our experiment more cumbersome and time consuming. Anchoring your design choices into the standards used to match and shape our expectations will save you valuable time and minimize the risk for confusing your participants during the experiment. Furthermore, as we did not face any critical usability issues during the experiment, we believe that following these principles will likely help you produce a product with minimal usability issues as well.

10. **Use VR if possible but be careful:** based on our interviews, we found that a desirable improvement to virtual platforms for testing AVAS would be implementing a VR version where the participants can almost fully immerse into the virtual environment. One of our participants of the experiment said "it would be easier to immerse myself [in the simulation] if it was in VR" which was . However, as one participant mentioned during the interview, if you decide to use VR for your experiment, make sure to have a safe environment and avoid collision with the vehicles. Another participant who also mentioned using some type of AR and/or VR in the interview said "[I] propbably would [have] a heart attack when standing next to a car during take-off [in VR]" which indicates how the experience of collision in VR - albeit not being real, can have negative psychological effects on the participants.

6

Discussion

During this thesis work, we have explored a series of questions in regard to a wicked problem, namely designing an AVAS for Volvo electric trucks. These systems are meant to compensate for the lack of engine noise in electric vehicles and are crucial in warning pedestrians, cyclists, and the blind of the presence of an electric vehicle.

Through numerous interviews with experts and non-experts (e.g. Electric bus drivers, VRUs, safety experts at Volvo GTT), questionnaires, observations and literature studies we identified a series of scenarios where the risk for fatal accidents was high. In our study, we also noticed that there is a disconnect between the perception and recognition of a fatal scenario by vulnerable road users (i.e. pedestrians and cyclists) versus the statistics on those accidents. In other words, we believe it might be so that fatality rates are higher in these situations partially due to a failure in recognition of dangerous situations by pedestrians and cyclists, but also car and truck drivers.

The aim of our study was to design and test an Acoustic Vehicle Alerting System on Volvo Trucks. However, due to unforeseen and unprecedented circumstances, namely the COVID-19 pandemic, we were forced to change the course of our project and adapt it to a new world where physical meetings had to be restricted and Volvo Trucks was temporarily shut down. As such, instead of implementing a physical prototype and evaluating the design with a large number of participants, involving both the youth and the elderly, we were forced to implement our ideas in a virtual world and test our design using fewer participants. Additionally, due to the restrictions of this new world and the crucially important health measures, we did not have the chance, nor the desire to involve the elderly in this study. Rather, we opted for a rather uniform set of participants in terms of age group and occupation. This decision may have weakened the validity of our study as the sample size is not a good representative of the population in general. However, due to the health concerns regarding COVID-19, this was the safest way to perform an evaluation of the concepts created.

6.1 The Analysis of the Experiment

The new circumstances imposed by the outbreak of COVID-19 lead to creating a virtual environment for testing and evaluation of our design concepts. Interestingly enough, this enabled us to test more concepts than initially planned, and resulted in the production of an environment that greatly facilitates and improves the communication of ideas regarding AVAS.

6.1.1 Experiment questionnaire

To evaluate the aforementioned concepts, a questionnaire was created where we focused on four main properties of these sounds, namely:

I) Noticeability.
II) Safety.
III) Pleasantness.
IV) Representativeness.

Noticeability refers to how well the sound was heard despite the incorporated background noise in the virtual environment.

Safety refers to how well the sound informed the participants of the intentions of the truck.

Pleasantness refers to the general impressions of the participants of the sound cue heard, in terms of annoyance vs pleasantness, and

Representativeness which refers to how representative of the (assumed) physical properties of the truck a sound was.

After having gathered insights about these aspects of the concepts through questionnaires and interviews in the final experiment, we can conclude that having a take-off sound leads to AVAS becoming better in all of the aforementioned aspects, and therefore a take-off sound will most assuredly improve AVAS (see Figure 5.22).

As the main results of our study shows, and is illustrated in Figure 5.22, the take-off sounds will likely improve AVAS in terms of Safety and Pleasantness the most, whereas the difference it may make for AVAS in terms of representativeness and noticeability may be statistically insignificant.

Representativeness

It is worth mentioning that during our interviews, several participants mentioned that a low-pitched sound better represents the physical properties of HGVs, whereas a high-pitched sound - such as the Alarm take-off sound was a better representative of much lighter vehicles such as e-scooters. However, it is important to keep in mind that although low-pitched sounds may better represent the physical properties of a HGV, they are more susceptible to being masked by the environmental noises and as such, a balance between or combination of high- and low-pitch frequencies may help future researchers in designing a representative sound that is not masked by the environmental noise.

Safety vs Pleasantness

The primary goal of AVAS ought to be to help make roads safer in the first place, and secondly, it ought to help reduce noise pollution. In other words, an AVAS needs to be primarily concerned with risk reduction and reduced noise pollution, and likeability should be secondary to designing this system. This is not to undermine the importance of likeability and pleasantness of a product as it greatly overlaps with risk reduction and reduced noise pollution, rather, the pleasantness of an AVAS ought not to be more decisive of a factor than its consequences in regards to noise pollution and safety.

6.2 How Can the Results Be Used to Design AVAS

In general, the results of this study can be used in several different ways for designing AVAS. The results from our benchmarking research indicates that a major factor to have in mind is the background noise and the soundscape of the context in which a vehicle is to be used. For instance, an AVAS which reaches 60 dB(A)s and is clearly noticeable in a lab or quiet suburban area will be nearly impossible to notice in a construction site where the sound levels may reach up to 80-90 dB(A)s (Zitzman, 2018). As such, we suggest that the designers and researchers map out situational dependencies and requirements especially in regard to masking. Additionally, we would like to encourage the automotive manufacturers and especially our stakeholders at Volvo Trucks to consider producing noticeable sounds as opposed to focusing on dB(A) levels. The reason for this encouragement is that although a louder sound may stick-out in many situations, the power and amplitude of the sound is not the only factor that makes a difference in how noticeable a sound is. Coupled with that, exposure to a high level of dB(A) can lead to irreversible health problems, and consequently merely increasing the power of the sound to counter masking effects of the environmental noise is not the way to go.

Several other techniques can be used to generate recognizable sounds that stand-out better than others with no apparent change in dB(A) levels. Sound properties such as timbre, rhythm, and using tonal components are a few factors that can play a crucial role in countering the masking effects of the environmental noise. Coupled with that, we would like to encourage automotive manufacturers and the governing bodies to research masking as an important topic in regard to AVAS. Furthermore, there is a dire need to develop methods that help designers and

researchers, as well as decision makers to study, understand and resolve issues in regard to masking in different environments.

6.2.1 Informing the public

Furthermore, based on our interviews with VRUs and HGV drivers, there seems to be a gap in understanding and recognizing the factors (e.g. truck's blind spots) and scenarios (e.g. turning at intersections, take-off after coming to full-stop, etc.) that can result in fatal accidents. As such, it is important that the general public is kept informed and reminded of the contributing factors, and scenarios with a high risk of fatality.

As the results of a mean value ranking of the answers shows, both pedestrians and cyclists identified the most dangerous scenario (Kuckom et al.,2017) as the fourth most dangerous scenario. According to the results of the online questionnaire, the top three most dangerous situations identified by the VRUs are "Truck turning right at an intersection", followed by "Truck driving parallel with a VRU" and "Truck reversing" which - barring the "Truck moving forward at constant speed" – was in accordance with the Volvo Safety Report (Kuckom et al., 2017). Furthermore, the results of the online questionnaire show that the perceived danger associated with the "Truck taking off from stand still" was ranked as the least dangerous scenario, even lower than the "Remotely controlled truck at construction site". Although the Volvo Safety Report does not explicitly mention the construction site, the research team believe that this might be due to a near-zero or zero rate of fatality in this scenario. In any case, one thing is clear; the scenario "Truck taking off from standstill" is one of the main scenarios that have caused a significant number of fatalities in accidents involving VRUs and HGVs. In the following, we have created two tables, namely Table 6.1 which shows the description and ranking of the dangerous scenarios in the Volvo Safety Report and their corresponding code in the online questionnaire, as well as Table 6.2 which is created for the purpose of camparison of the Volvo Safety Report, and the perception of danger in VRUs according to our online questionnaire.

Table 6.1

The Ranking of Fatal Accidents Based on the Statistics in Volvo Safety Report, and the Corresponding Naming of Each Scenario in Our Online Questionnaire

RANKING	VOLVO SAFETY REPORT (2017)	Corresponding Code in Online questionnaire
1st	Collision with VRU at intersection, moderate or high speed. VRU suddenly crosses road in front of truck, for example at crossroads.(C3)	Truck driving at a constant speed
2nd	Collision with VRU when turning (right in right hand traffic and left in left-hand traffic) at low speed. (C4)	Truck turning right at an intersection
3rd	Collision with VRU in lane at moderate to high speed, for example during lane exit, lane changing, merging or cutting-in. Side of truck hits VRU (C5)	Truck driving parallel with a VRU
$4^{th}/5^{th}$	Collision with VRU during low speed reversing. Impact with rear of truck or trailer. Typically distribution trucks when delivering goods, or refuse collectors (C2)	Truck reversing
$4^{th}/5^{th}$	Collision with VRU during low speed manoeuvring or starting at crossroads or pedestrian crossings. Impact with front of truck. (C1)	Truck taking off from standing still
N/A	N/A	Remotely controlled truck at construction site

Table 6.2

A Comparison of the Ranking of Fatal Scenarios Based on (Kuckom, et al.,2017) vs the Results of the Online Questionnaire Conducted by the Researchers

	Volvo Safety Report (2017) Scenario (% of all fatal accidents)		**Online questionnaire Scenario (Average score on a scale of 1-6) given by VRUs)**
1st	Truck driving at a constant speed (30%)	**1st**	Truck turning right at an intersection (4.87)
2nd	Truck turning right at an intersection (20%)	**2nd**	Truck driving parallel with a VRU (4.70)
3rd	Truck driving parallel with a VRU (15%)	**3rd**	Truck reversing (4.33)
4th	Truck reversing (5%)	**4th**	Truck driving at a constant speed (3.80)
4th	Truck taking off from standing still (5%)	**5th**	Remotely controlled truck at construction site (3.40)
		6th	Truck taking off from standing still (2.87)

6.3 Using Virtual Environment for Communicating Ideas

To communicate ideas about sound and new concepts can be a difficult task for designers and engineers. This becomes more difficult if their primary topic is not sound design and/or engineering. As such, we would like to encourage using virtual environments as a means for rapid prototyping and communication of ideas and concepts, especially in regard to AVAS. One of the noteworthy take-aways of our project was that, despite the pandemic and the restrictions imposed on us, we were able to not only test one, but several different concepts in a rather short time. Additionally, we were able to test these ideas without environmental factors (e.g. the weather conditions) affecting the timing nor the quality of our evaluation of these concepts.

Building a virtual environment where different interactions and sounds can be tested will in all likelihood decrease the time, money and resources expenditure. In addition to that, platforms such as Unreal Engine 4 enable the team of developers, designers and engineers to collaborate and jointly review the designs from the comfort of their desks or even homes. This in turn, can be a relatively perfect solution for situations such as the COVID-19 pandemic where a large part of the team is required to stay at home.

Additionally, these simulations can be simply exported in HTML5 and run on a server, which in turn would allow for the experiments and evaluations to be carried out online. Coupled with this, simulations built in Unreal Engine 4 can be rather easily turned into VR experiences, which can in turn boost the immersion of the participants and provide the automotive manufacturers and researchers with reliable results without a need to rebuild a VR specific

version of the environment. As one of our participants pointed out during the interview, when using a VR setting, it is important to keep in mind that, near collisions and collisions may have devastating psychological effects on the participants and as such, appropriate measures must be taken before the implementation of such means of evaluation.

6.4 Improved Regulations

Developing new methods and techniques to understand the needs in regard to AVAS, and masking ought to be done on both a regional and global level. We believe that merely setting up a range of frequencies and a minimum of dB(A) levels are not enough for making roads safer in the absence of engine sounds. Rather, the governing bodies and decision makers ought to set up requirements that correspond to the context in which a type of vehicle is primarily used.

Furthermore, the governing bodies and decision makers ought to establish a consensus in regards to masking and set up a clear definition for what is and what is not an acceptable level of masking measured by a clear method of calculation, Furthermore, it is important that rigorous testing and evaluation of sound perception is performed in order to produce guidelines that are in line with the Vision Zero and similar regional and global goals.

6.5 Adaptive AVAS

Throughout our research, the idea of an Adaptive AVAS has been brought up on multiple occasions. From our discussions with Volvo GTT experts, to the interviews conducted during the experiment. This concept refers to an Acoustic Vehicle Alerting System that can primarily read the surroundings and *adapt* its behaviour accordingly. Although realising such a design is out of the scope of this paper, it is a concept worth exploring as it can be rather easily prototyped and implemented in the virtual environment using Unreal Engine 4.

Adaptive AVAS can be achieved by several means, depending on the extent of its adaptiveness. For instance, considering that different landscapes such as suburban versus urban areas, the needs for AVAS varies. Naturally, the sound cues emitted by the AVAS can be easier heard in a Swedish suburban area where there is a minimal environmental noise versus downtown Berlin where heavy traffic, construction, music and more may be heard. As such, an Adaptive AVAS can use the location of the truck to recognize its entering to urban areas with a larger amount of noise pollution and adjust the sound levels or the type of sound emitted, to keep a certain level of noticeability. Coupled with that, this type of geo-fencing can help with producing the adequate sound when entering more specific types of areas such as schools or construction sites where the needs for the type of sound emitted may vary.

Similarly, an Adaptive AVAS can consist of a series of sensors that read the environmental noise emitted by other vehicles, the construction, wind etc. and adjust the sound cues emitted. This type of Adaptive AVAS (using microphones) may be the best option for countering the masking effect of the environmental sounds as it can offer the best level of adaptiveness and re-adjust its behaviours in real-time. Coupled with that, this type of Adaptive AVAS can read and interpret the frequencies and the amplitude (as well as other properties of the soundwaves) of the background noise and re-adjust the AVAS based on properly engineered models to generate a sound that is not masked by the other sounds in the environment.

Another type of Adaptive AVAS can be connected to heat-sensors around the vehicle which would in turn read the environment and activate the AVAS in case a person or animal is present. This would in turn mean that the AVAS in low speeds can be more effective in reducing noise pollution, which could prove to be useful in e.g. urban areas at night when there are fewer VRUs in traffic. This type of Adaptive AVAS can also benefit from being connected to the active safety systems implemented in vehicles, especially the autonomous driving vehicles that have cameras and proximity sensors, in order to complement these systems.

Last but not least, an Adaptive AVAS can be - and perhaps should be - merged into one larger, more comprehensive safety system that incorporates audio and visual cues together to ensure the safety of the roads. In that, such Audio-visual Safety System (AVSS) - for trucks can consist of an Adaptive AVAS that reads the environment and adjusts the sound cues accordingly, while giving visual feedback in forms of projection of visual cues on the street (e.g. arrows that with the help of a well-trained AI predict and indicate the direction in which the driver is about to drive). This type of cues may not only be used by VRUs in order to better understand the intentions of the truck, but also by the drivers as some type of driving assistant that helps them with e.g. keeping in lane. Alternatively, the visual cues can be incorporated on the body of the truck, in form of e.g. LED lights or screens which can add an exciting design element to the vehicles. The latter type of visual feedback is most likely the better option as the lights will be easier to spot for instance during a sunny day, than their projected counterparts. Furthermore, the design element that comes with them can be used in several ways for branding, and anthropomorphism in order to increase the likeability of the vehicle.

6.6 Limitations

In this research we faced a series of setbacks and limitations, most importantly the COVID-19 pandemic which halted the operations of Volvo Trucks and consequently, the research team lost all support that may have otherwise been provided by Volvo GTT.

6.6.1 The COVID-19 Pandemic

As previously mentioned, this project coincided with the outbreak of COVID-19 in Europe. As such, the research team was forced to abandon the planned clinics and evaluations. This resulted in a change in the nature of the research as well as the design process. Consequently, a virtual environment replaced the real-life settings and a rather homogenous sampling of participants in terms of age and occupation was the only viable option as only nine participants - mostly students in their 20s - had the possibility of taking part in the experiment. Furthermore, the small sample size meant that the experiment needed to be balanced in terms of quantitative and qualitative data gathered. As such, the researchers opted for gathering both types of data through the think-aloud protocol, a questionnaire, and semi-structured interviews to ensure the reliability of data gathered.

Furthermore, in late April the research team was informed that Volvo GTT will not provide any more support for the project. As such the research suffered from a shortage of appropriate resources and material such as adequate and engineered sounds to be used for AVAS, and 3D models of Volvo electric trucks to be used in the simulation.

The sounds used in this experiment were programmed, edited, and mixed by the master thesis workers who despite having some experience with sonification, are not sound designers.

Furthermore, a great amount of time and effort was put into learning to work with software such as VCV Rack and REAPER.

A lack of access to a realistic 3D model of a Volvo electric truck meant that the researchers were forced to use free material provided by Epic which was in clear contrast to the visual appearance expected of an electric truck. This was brought up by some participants but might not have had a significant impact on the core results of the research.

6.6.2 Virtual Environment

It is important to mention that although the simulation was seen as realistic in most aspects, by the vast majority of the participants, the thesis workers had a relatively limited experience and knowledge of using Unreal Engine 4 prior to the pandemic. This consequently meant that the thesis workers had to change focus from AVAS-related design work to building the virtual environment. In addition, due to the lack of knowledge and expertise in building virtual environments, it is difficult to argue that the sound parameters used in the simulation exactly match their respective parameters in reality from a phenomenological perspective. Rather, the thesis workers had to greatly rely on their personal and subjective experience as well as the functions, material and knowledge provided by Unreal Engine 4 and their community, to create a believable and realistic experience. Moreover, due to lack of resources, the researchers opted for using headsets for an immersive experience and accurate hearing of the sound cues. The use of headsets is clearly not optimal and future research in virtual environments may benefit from carefully setting up loudspeakers in the environment to create a more reliable and realistic 3D spatialization of sound.

Furthermore, due to the time constraints imposed by the circumstances, certain aspects such recreating and testing all scenarios, having a large number of non-player characters or NPCs for short (i.e. computer controller cars and individuals commuting in the virtual environment) and some finer details had to be deprioritised. The research team strongly recommends implementing NPCs for a more realistic experience.

6.6.3 Experimental Research Design

In regard to the experimental research design, a main factor that can have contributed to the results being skewed in favour of AVAS with a take-off sound was the semi-randomized counterbalancing. As previously mentioned, the experimental research design of this project was a version of incomplete repeated measures design where the AVAS with no take-off sound was always presented in the beginning of the experiment whereas the order in which AVASes with some type of take-off were presented was randomized. This can have skewed the quantitative data gathered due to the learning curve of what is expected of the participants. As such, future research may benefit from examining these concepts in a true incomplete or complete repeated measures design where all conditions are randomized and counterbalanced for a learning curve. Furthermore, future research of this topic can benefit from acquiring a larger and more representative sample size where the elderly, teenagers, the blind and possibly construction workers are included.

6.7 Consequentialism & Ethics

In discussing the balance between the likeability of a sound cue and risk reduction, an undeniably important and relevant topic is the ethics of the design. In this context, ethics can be used as a general compass which can provide the designers with direction and motivation for their design decisions. One of the historically important and still popular theories in ethics is known as consequentialism. Consequentialism is simply based on the intuition that what is best, or right is that which makes the world best in the future (Sinnot-Armstrong, 2019). As two of the three core values of Volvo consist of safety, and environmental care, it is fully plausible to use consequentialism as a means to reach these values when designing AVAS for Volvo Trucks. As such, it is of great importance to design a system that leads to risk reduction and safety, as well as reduced environmental noise.

7

Conclusion

To conclude, during the course of this research, a conceptual Acoustic Vehicle Alerting System with a humming sound was implemented and tested in a virtual environment. Together with that, three types of take-off sounds were implemented atop of the AVAS and tested as well. The result of this study shows that including take-off sounds clearly improves the Acoustic Vehicle Alerting System in terms of noticeability, safety, pleasantness and representativity of the physical properties of the truck. The three implemented take-off sounds consisted of a short and high-pitched sound (Alarm), two consecutive short and high-pitched sounds (Pulsating), and lastly, a Shepard-tone inspired sound (Futuristic) which imitated the engine acceleration of the combustion engines. According to the results of this study, the Alarm sound was perceived as the safest and most pleasant, and together with the pulsating sound was identified as the most noticeable. Moreover, the pulsating sound was identified as the most representative of the physical properties of the truck among all the aforementioned AVASes, including the AVAS with no take-off sound.

To better understand the perception of dangerous situations by vulnerable road users, that can be addressed by AVAS, an online questionnaire was conducted and compared with the Volvo Safety Truck (Kuckom et al., 2017). The results of this questionnaire show that although pedestrians and cyclists show a very good understanding of most fatal situations, they failed to recognize the number one scenario resulting in fatalities - namely moving forward in constant speed (e.g. at crossroads) and in fact, this scenario was ranked as the fourth dangerous among all scenarios by the participants that identified themselves as VRUs.

In addition, this research coincided with the COVID-19 pandemic, which in turn impacted the research in several ways. Most noticeably, a virtual environment was created in order to compensate for the lack of access to workshops, and vehicles that would have otherwise been offered by Volvo Trucks. However, the creation of the virtual environment brought many insights into this research, most importantly that this type of environment can be simply used for rapid prototyping of otherwise hard to implement or imagine concepts. Furthermore, a virtual environment can facilitate collaboration among the team members tasked with creating and implementing new features in the automotive industry. Moreover, using virtual environments can reduce the costs of designing, and developing conceptual work and will likely prove beneficial in rapid testing of these concepts in a simple or complex situation.

Moreover, the research team deem the regulations as insufficient. As the results of the benchmarking of EVs with AVAS that satisfy the requirements set up by regulations shows, the vehicles will be hardly heard in the presence of background noise as unavoidable factors such as wind can fully mask the sound of AVAS completely, given that the regulations do not increase the dB(A) levels. Furthermore, we have identified a gap in understanding,

consideration and methods regarding masking of the sound, especially in urban areas where the environmental noise can e.g. reach up to 80 dB(A) at the construction sites.

Last but not least, a series of guidelines were created to help the future researchers in the automotive industry who are designing or researching AVAS. These guidelines can be useful in the automotive industry where researchers are focused on designing AVAS, and a virtual environment for testing AVAS. A list of these guidelines can be found below:

Guidelines for designing AVAS

1. Learn about psychoacoustics.
2. Learn about the physical properties and the anthropological importance of sound.
3. Experiment with frequency and amplitude.
4. Consider designing an Adaptive AVAS.
5. Consider matching the sounds for AVAS to the physical properties of the vehicle.
6. Implement a take-off sound.

Guidelines for designing a virtual environment for testing AVAS

1. Use common and intuitive controls.
2. Spend some time optimizing the movement of vehicles and other moving objects.
3. Record and include environmental noise to your simulation.
4. Implement and adjust sound related settings, especially attenuation.
5. Add NPCs and other vehicles to your scenarios.
6. Use life-like characters and avoid using unrealistic skins and body-shapes.
7. Use animated assets.
8. Use the virtual environment for rapid prototyping.
9. Take advantage of well-known usability principles and frameworks.
10. Use VR if possible but be careful.

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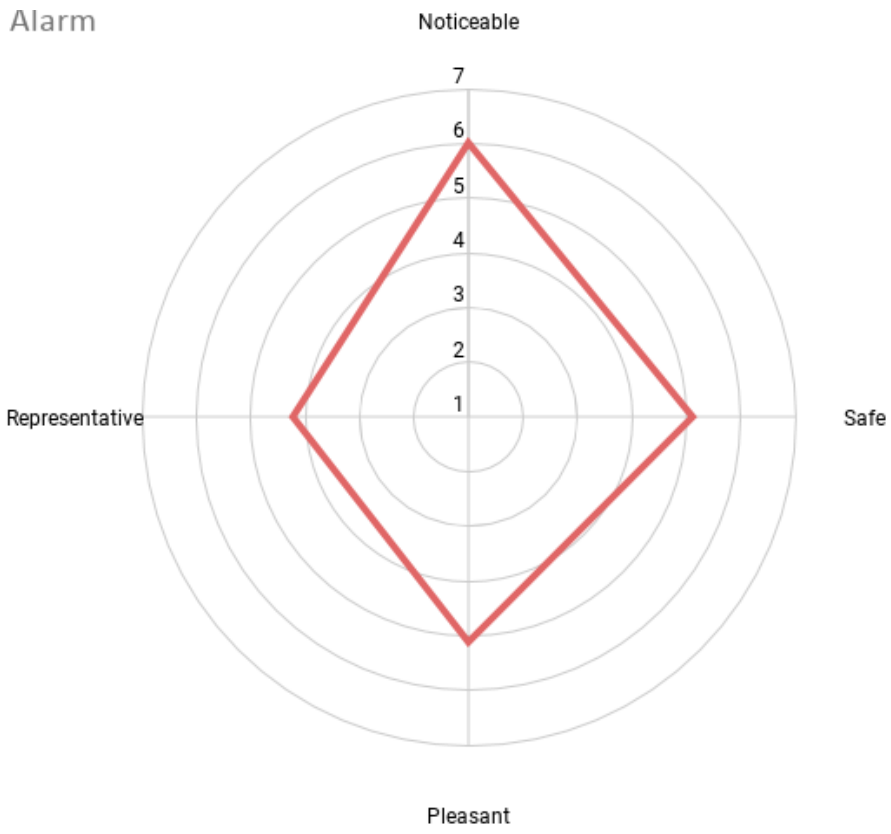
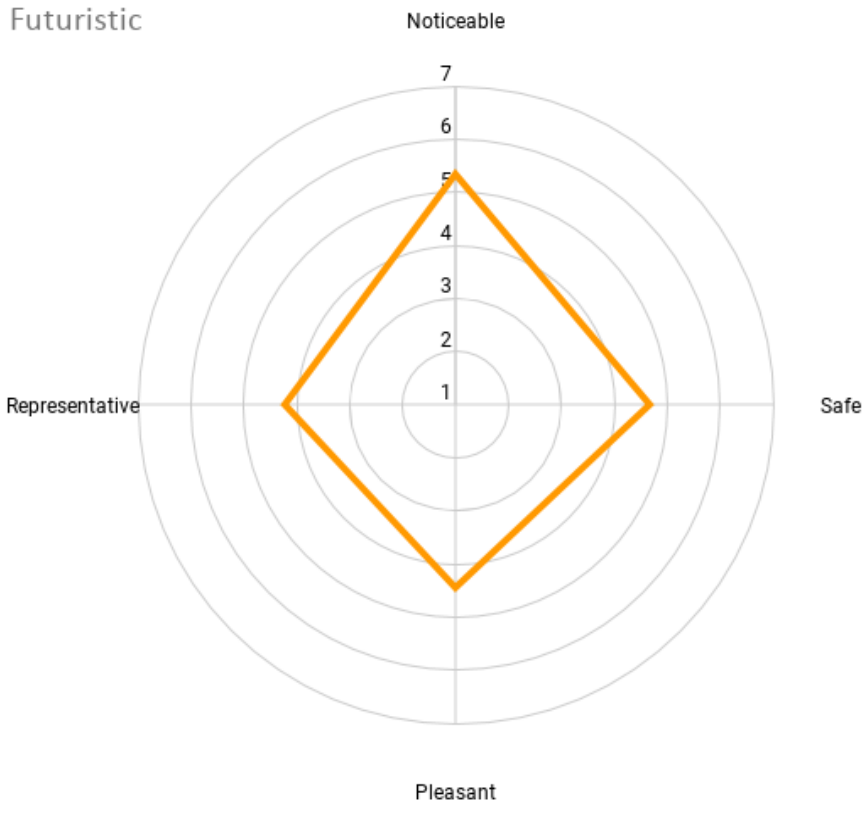
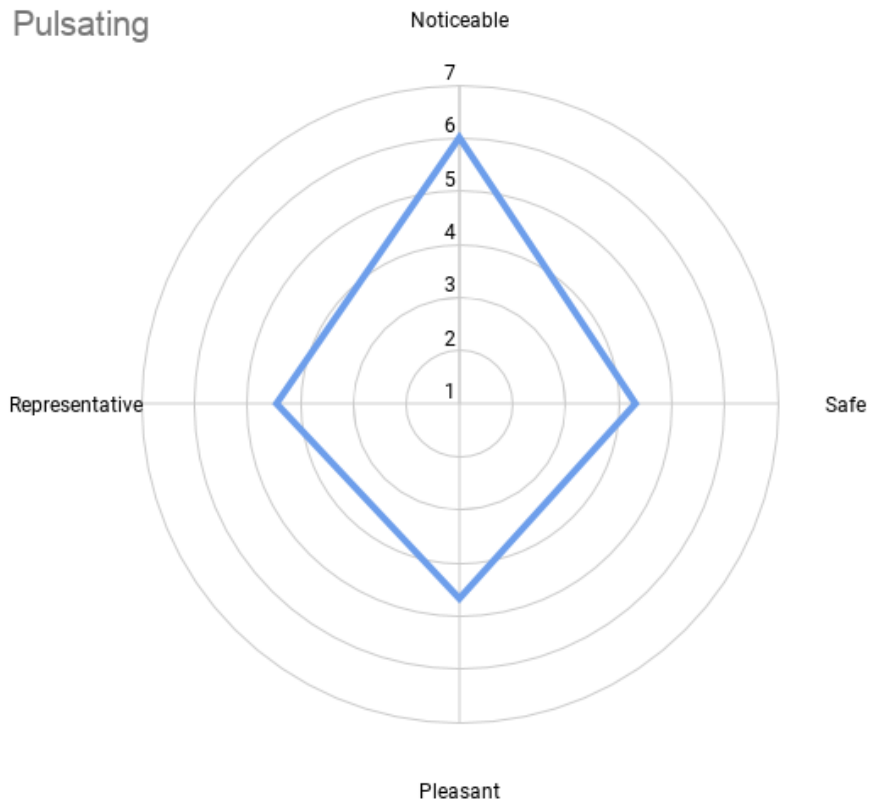
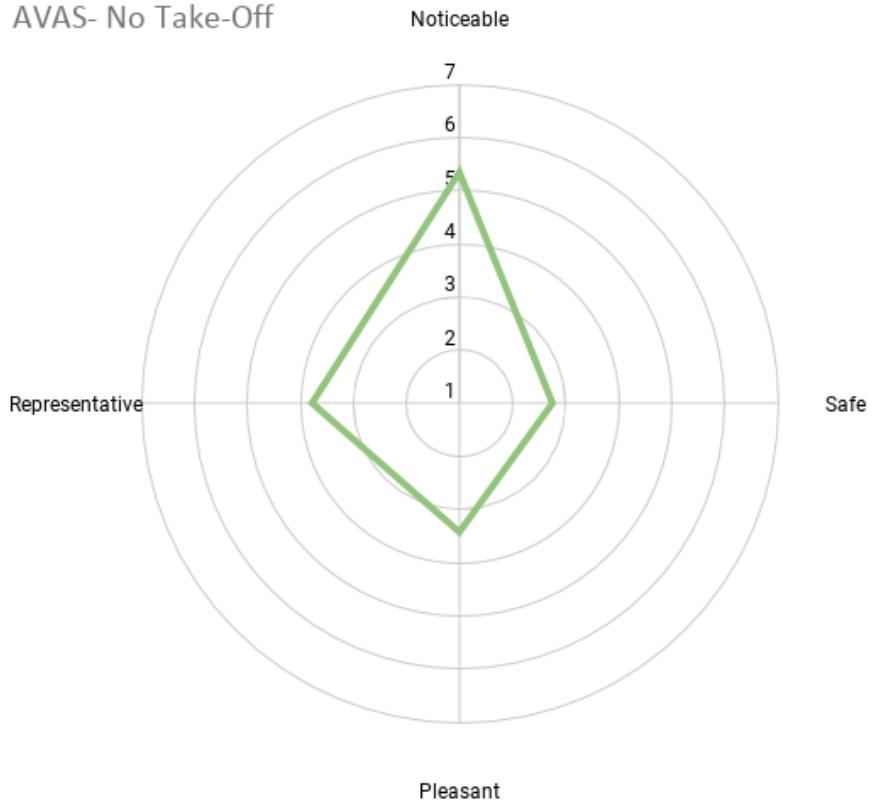
Appendices:

Appendix A - Radar Charts






Pulsating
Noticeable
7
6
5
4
3
2
1
Representative
Safe
Pleasant


AVAS- No Take-Off
Noticeable
7
6
5
4
3
2
1
Representative
Safe
Pleasant

Appendix B - Online Questionnaire

Collisions with heavy goods vehicles (trucks) and vulnerable road users (pedestrians, cyclists etc) in urban areas.

Please find some time to fill in this 10 minute questionnaire.

We are two Master students in Interaction Design & Technologies from Chalmers University. We are doing our research related to collisions between Heavy Goods Vehicles (trucks) and Vulnerable Road Users (Pedestrians, cyclists etc) and would like your input.

We would like to know which situations in your opinion are the most dangerous in everyday commuting in urban areas. For this we have prepared some scenarios for you to rank based on how high the danger of collisions is for the pedestrian/cyclist.

Meaning of Danger:
"the possibility of something unwelcome or unpleasant happening."

Similar to possibility, risk, chance, probability, likelihood.

The questionnaire is anonymous.

If you have any questions feel free to contact us :
rngelep@student.chalmers.se

Thank you.
* Required

1. Please select the following (public transport not taken into account) *

Mark only one oval.

- ◯ I work as a truck driver
- ◯ I mainly commute by car
- ◯ I mainly commute by foot
- ◯ I mainly commute by cycling

2. Please specify your country of residence.

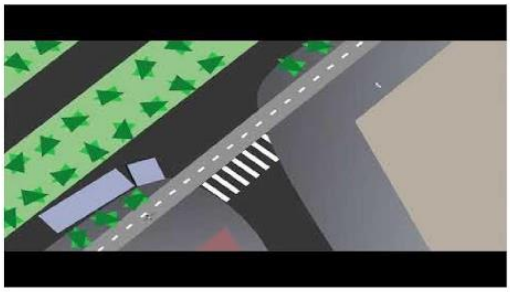
_____

3. Please specify your age group

Mark only one oval.

- ◯ Under 18
- ◯ 18-25
- ◯ 25-35
- ◯ 35-45
- ◯ 45-55
- ◯ 55-65
- ◯ 65+

Please watch the Scenarios below before continuing.



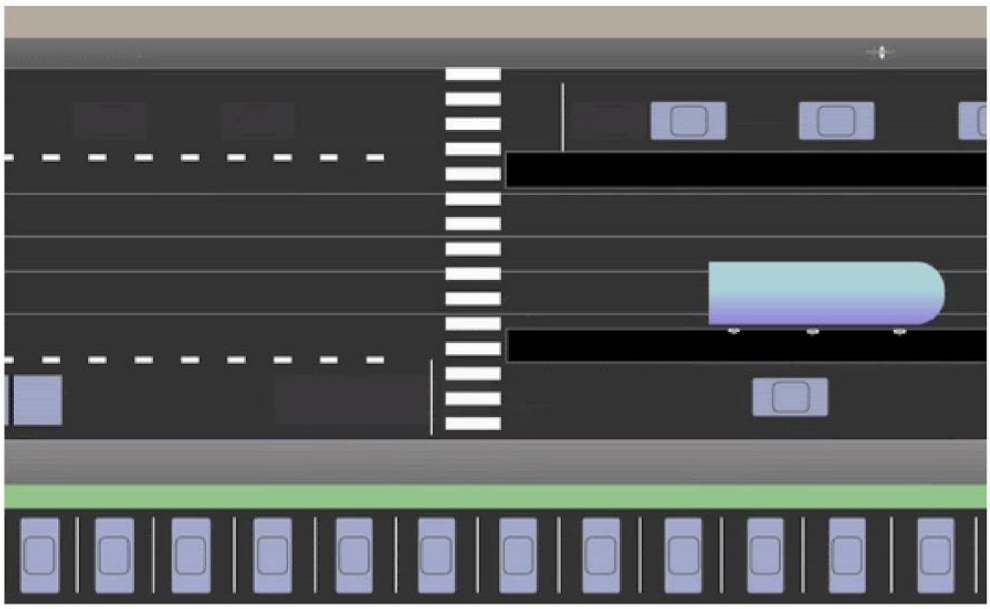
http://youtube.com/watch?v=SZf-YKzkUpk

Please rank the scenarios based on how high the danger of collision is for the pedestrian/cyclist

1 represents not dangerous at all and 6 represents very dangerous.

4. Please rank the danger of the following scenario - Truck taking off from a stand still. *

Scenario: Risk of collision between a truck and a pedestrian/cyclist during take-off/starting at crossroads or pedestrian crossings. Impact with front of truck.



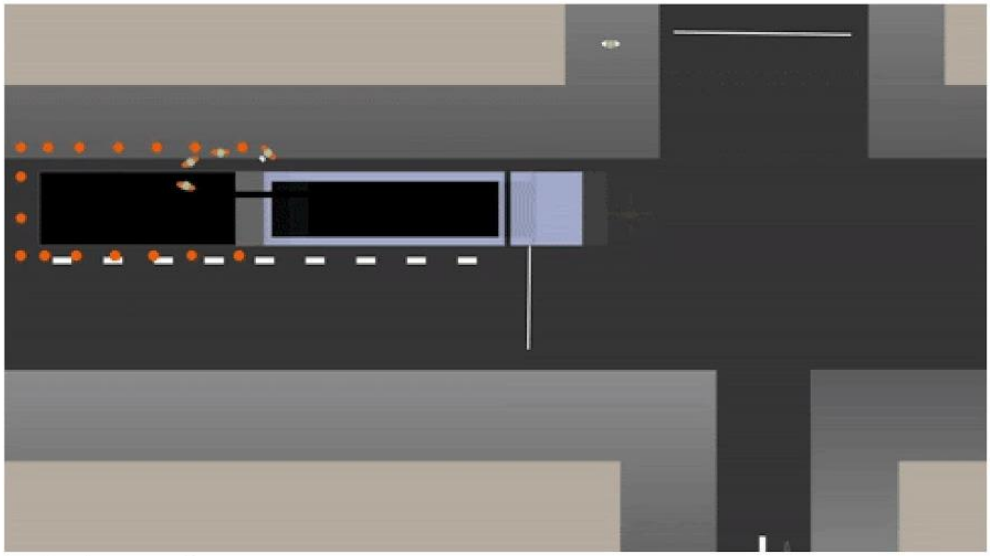
Mark only one oval per row.

	1- Not dangerous at all	2	3	4	5	6- Very dangerous
Truck taking off from a stand still.	⬭	⬭	⬭	⬭	⬭	⬭

5. Describe your thoughts about the scenario. You can also describe a similar scenario that is more dangerous.

6. Please rank the danger of the following scenario - Construction site *

Scenario: Risk of collision between a truck and a pedestrian/cyclist at a construction area in a city (e.g. Road works, building renovation). Cyclist/pedestrian passes through the safe work area where a truck is remotely controlled to take-off and drive forward.



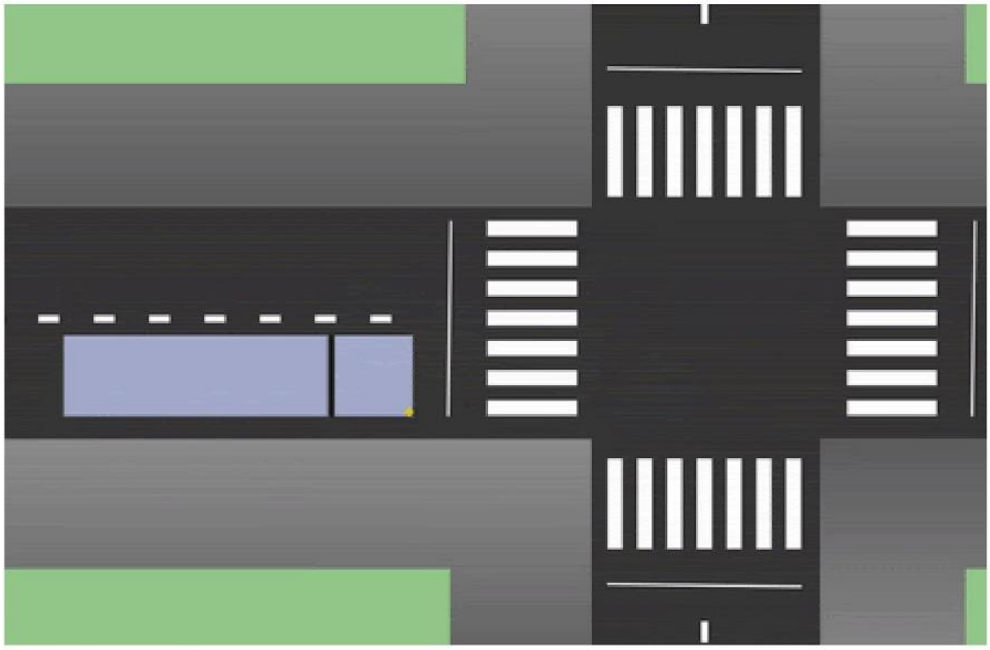
Mark only one oval per row.

	1- Not dangerous at all	2	3	4	5	6- Very dangerous
Construction site	⬭	⬭	⬭	⬭	⬭	⬭

7. Describe your thoughts about the scenario. You can also describe a similar scenario that is more dangerous.

8. Please rank the danger of the following scenario - Truck driving parallel to a VRU (Pedestrian, Cyclist etc) on the same road. *

Scenario: Risk of a collision between a truck and a pedestrian/cyclist in the same lane - side of truck hits VRU (Pedestrian, Cyclist). For example lane changing, merging or cutting-in and narrow roads with on coming traffic.



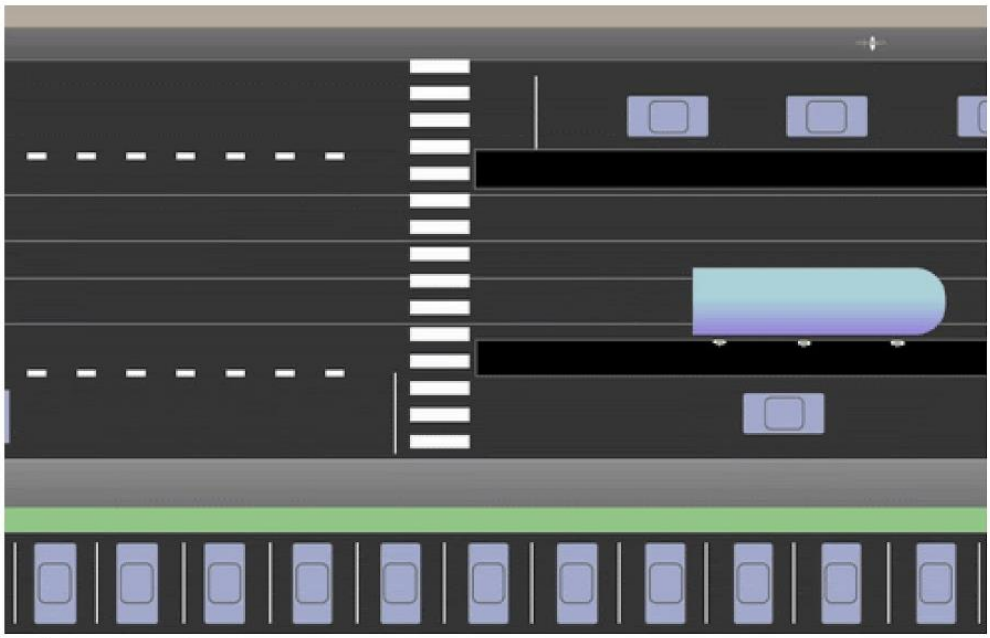
Mark only one oval per row.

	1 - Not dangerous at all	2	3	4	5	6- Very dangerous
Truck driving parallel to a cyclist or pedestrian on the same road	◯	◯	◯	◯	◯	◯

9. Describe your thoughts about the scenario. You can also describe a similar scenario that is more dangerous.

12. Please rank the danger of the following scenario - Truck driving in constant speed forward. *

Scenario: Risk of collision between a truck and a pedestrian/cyclist at intersection. Cyclist/pedestrian suddenly crosses road in front of truck, for example at crossroads.



Mark only one oval per row.

	1- Not dangerous at all	2	3	4	5	6- Very dangerous
Truck driving in constant low-speed forward	◯	◯	◯	◯	◯	◯

13. Describe your thoughts about the scenario. You can also describe a similar scenario that is more dangerous.

14. Please rank the danger of the following scenario - Truck Reversing. *

Scenario: Risk of collision between a truck and a pedestrian/cyclist during reversing by trucks.

Mark only one oval per row.

	1 - Not dangerous at all	2	3	4	5	6 - Very dangerous
Truck reversing /	◯	◯	◯	◯	◯	◯

15. Describe your thoughts about the scenario. You can also describe a similar scenario that is more dangerous.

16. Do you believe that we missed some dangerous scenarios that are not listed in this Questionnaire? Please describe your scenario.

17. Have you personally seen or experienced a situation that resulted in or was close to a Truck-Pedestrian/ Cyclist accident? If yes, what happened?

18. Do you have any additional information you would like to give?

Appendix C - Experiment Questionnaire

Code:

QUESTIONNAIRE

SCENARIO 1

How well did you hear the vehicle?

Not at all Very Clearly

1 2 3 4 5 6 7

How well did the audio show the intentions of the vehicle?

Very poorly Very well

1 2 3 4 5 6 7

What is your general impression of the audio as an indication of the intentions of the truck?

Very Irritating Pleasant and fitting

1 2 3 4 5 6 7

How appropriate was the signal in indicating the physical properties of the vehicle?

Very inappropriate Very appropriate

1 2 3 4 5 6 7

Appendix D - Interview Questions

INTERVIEW

After having gone through the experiment, you will be asked to take part in a short interview about your experience and ideas.

1. Do you have any general comments about the simulations and the controls?
2. How realistic was the simulation in general?
3. How realistic was the movement in the simulation?
4. How realistic was the audio in the simulation?
5. How well did the simulation capture the idea of a take-off sound in your opinion?
6. Was there a certain take-off sound that caught your attention? If so, why?
7. Did any of the sounds make you confused about the intentions of the truck? (if a certain sound fits another function e.g. reversing, turning, etc.)
8. Do you think a take-off sound would make the streets safer? If so, and a real truck was to have one of the sounds (pulsating, alarm, futuristic or NO AVAS), which one would you prefer to have warn you of a take-off? Any other fitting sounds you'd like to hear instead?
9. If it was magic, how would you like to have an electric truck warn you about its intentions?

Thank you for participating in the study!

Appendix E - Instructions

INSTRUCTIONS

In this experiment we are interested in your impression of different Acoustic Vehicle Alerting Systems. These systems are safety systems that warn other road users of the presence of a hybrid/electric vehicle. In this experiment, you are asked to follow the instructions below and pay extra attention to the sounds of the vehicle.

There will be a total of four instances in this experiment. After each test, you will be presented with a few questions about your experience. After having gone through the experiment, you will be asked to take part in a short interview about your experience and ideas.

Instructions:

1. Close the instructions on the top left corner.
2. Walk up to the closest cross road and stop.
3. Look for vehicles, make sure they have stopped to let you cross.
4. Cross the street when safe

Appendix F - Interview with Electric bus drivers

INTERVIEW WITH ELECTRIC BUS DRIVERS

We are currently working on AVAS, it is a Acoustic Vehicle Alerting System for electric vehicles, specifically trucks. We would like to know your concerns regarding everyday commuting in urban areas as an experienced driver with electric buses. We are focusing on vulnerable road users.

1. What is the most stressful part of your work?
2. Which scenarios are the most dangerous in your opinion?
3. What are the scenarios where extra attention should be paid to HGVs and their interaction with buses? Please explain.
4. What are the biggest differences between an electric bus and a combustion engine bus?
5. How would you improve the road safety?

Appendix G - Interview with VRUs

INTERVIEW WITH VRUS

We are currently working on AVAS, it is a Acoustic Vehicle Alerting System for electric vehicles, specifically trucks. We would like to know your concerns regarding everyday commuting in urban areas as an Vulnerable Road Users. We are focusing on truck and pedestrian communication.

1. What is your most common way of commuting when not using public transport?
2. Have you noticed any electric trucks in your commuting?
3. Which scenarios involving trucks are the most dangerous for you in your opinion?
4. Do you know where the blind spots of a truck are? If so, are you actively aware of them when commuting?
5. Do you know of any other parts/features of the truck that are dangerous from your perspective?
6. Have you had any dangerous situations/accidents with trucks?
7. How would you improve the road safety? What are the scenarios where extra attention should be paid to interaction between trucks & VRUs?
8. You are walking towards the store – you see a truck approaching at the intersection; what are your though