



**CHALMERS**  
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# Development of an adaptive reverse warning concept

Master's thesis in Product Development

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Gothenburg, Sweden 2022

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# Abstract

Five per cent of all fatal accidents involving a Heavy Goods Vehicle (HGV) and a Vulnerable Road User (VRU) occur when the vehicle is reversing, despite the low speed of the manoeuvre. The audible reverse warning commonly used is perceived as annoying, which increases the risk of the driver deactivating the warning and, in turn, decreasing the safety of VRUs. In addition, the audible reverse warning has received criticism for contributing to societal noise pollution, which is a human health issue. Furthermore, a new UN regulation concerning the audible reverse warning will be implemented shortly, which must be considered. Because of the stated reasons, Volvo Group Trucks Technology initiated this master thesis that aims to deliver a developed and evaluated concept of a reverse warning that enhances the safety of VRUs, considers VRUs' behaviours, reduces noise pollution, and complies with regulations.

Literature studies were performed to gather information about, e.g., warning signal design, human behaviours, and legal requirements of reverse warnings. Several observations of VRUs' behaviour in situations with reversing trucks in city environments were completed. A sound experiment was performed in the central parts of Gothenburg, where 114 persons were observed. Nine interviews with truck drivers were conducted, and a survey with 37 respondents was sent out internally at Volvo Group. Both systematic and creative methods were used to generate concepts of a reverse warning. All generated concepts were evaluated through evaluation matrices, and the best concepts were evaluated by 20 participants in a virtual environment.

The final concept consists of additional lamps with flashing lights on the sides and rear of the truck and a projected warning triangle on the ground in the truck's rear. The warning triangle indicates the truck's intended pathway and enhances the visual attention of the reverse warning. The recommendation for the audible reverse warning is to keep the current well-known beeping sound. However, the sound should be adapted depending on the ambient noise level and status of the truck, i.e., idling or reversing. An adaptive sound would decrease unnecessary noise pollution, as it would emit a lower sound level in low noise areas and while idling. Furthermore, this thesis work has shown a possibility to replace the existing reverse sound with a sound perceived as more pleasant that still warns VRUs about a reversing truck.



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**Maja Malm & Rubija Rekanovic**

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# Chapter 1

## Introduction

This chapter introduces the thesis by presenting the background relevant to the project, along with the problem statement. In addition, the aim, objectives, and research questions that are to be answered through the work are presented. Furthermore, a description of the company and the current reverse warning solution is provided.

## 1.1 Background

Vision Zero, introduced in Sweden in 1997, is a road safety project that aims for a future where no one is being killed or seriously injured in traffic (Trafikverket, 2021). In 2014, 3863 fatalities caused by accidents involving Heavy Goods Vehicles (HGV) were reported in the EU. Of these fatalities were 32% Vulnerable Road Users, henceforward referred to as VRUs. VRUs refers to cyclists, pedestrians, motorcyclists, and moped riders (Kockum et al., 2017).

Volvo Trucks Accident Research Team (ART) releases a safety report every few years. The ART safety report from 2017 presents an overview of statistics of accidents in Europe that involve HGVs. The report shows that accidents causing fatalities and severe injuries to car and HGVs occupants have decreased between the years 2013 and year 2017. However, accidents causing fatalities and severe injuries to VRUs have increased from 15-25% to 30-35%. ART has, in their studies, analysed the most common scenarios that cause these accidents and have been able to show that most accidents occur when a VRU suddenly crosses a road in front of a truck (30%). 5% of the accidents are related to collisions with VRUs during low-speed reversing (Kockum et al., 2017). Furthermore, statistic shows that one-fourth of all fatal accidents related to work vehicles occur while the vehicle reverses (Health and Safety Executive [HSE], n.d). Vaillancourt et al. (2014) present that 6% of the fatal accidents in the construction industry are related to reversing vehicles. Workers at construction sites are highly exposed to moving HGVs and are at risk of being in blind spots of the truck driver, and the noise level in these areas is high. The main reasons for reversing accidents are limited rear visibility for the truck driver, stress, inattentiveness, the audible warning signal not working, and insufficient warning signals that do not call for the VRU's attention (Kockum et al., 2017).

Another concern that affects human safety is noise. *Noise* can be defined as an unwanted sound that causes annoyance in its surroundings (Stansfeld & Matheson, 2003). Noise pollution is a significant health problem in Europe, and the European Environment Agency reports road traffic to be the largest source of noise pollution. Noise causes stress in the human body and has a harmful impact on life quality (European Environment Agency, 2017). One of the contributors to noise pollution caused by HGVs is the reverse warning. The audible reverse warning signal commonly used today was first commercialised in the late 1960s (Brigade Electronics, 2018). The signal emits a monotonous high pure-tone beep sound which is perceived as annoying as it can be heard at distances far from its source, even from the inside of houses and apartments. Even though the audible reverse warning has received criticism for causing noise pollution, little effort has been made to reduce the reverse warning's impact on society's noise pollution.

In addition, the reverse warning emits the same sound level independent of the ambient noise. This induces the risk of the signal being masked in environments where the ambient noise is high and contributes to an unnecessary loud warning signal in surroundings where the ambient noise level is low (Burgess & McCarty, 2009; Vaillancourt et al., 2014). With the increasing sales of battery electric vehicles, electrically powered vehicles are more common in urban fleets. The absence of mechanical noise makes electrically powered vehicles quieter than vehicles powered by a combustion engine (Campello-Vicente et al., 2017). As the noise in urban areas decreases, the need to adapt the sound emitted from the reverse warning increases to fit the urban environment better.

Additionally, a proposed regulation is being processed, and if accepted, this regulation will affect the current audible reverse warning. To realise the aim of Vision Zero and comply with

the new processed regulation, there exists a need to develop a reverse warning that enhances safety in reversing situations while reducing noise pollution in society.

## 1.2 Problem statement

Even though the truck is equipped with aids to help perform reversing manoeuvres, and the trucks are designed to meet the industry standards regarding the sound and lighting of the reverse warning, reversing accidents with fatal outcomes are still reported. Today's standard visual reverse warning is a straightforward solution that consists of two white lights on the truck's rear end that do not effectively call for attention. Furthermore, no visual signals are located on the side of the truck. Due to this, some logistic companies equip their trucks with additional lamps, which indicates that the current standard reverse lights are not effective enough. Reviewing efficient ways to call for attention and redesigning the standard solution could potentially improve the safety of VRUs.

Additionally, the current solution of the audible reverse warning contributes to the high levels of noise in society. It thereby has a harmful effect on human health because of its inflexible high volume tonal sound. A flexible, adaptive audible warning designed to consider its surroundings is needed. Another factor that must be considered is the new processed regulation regarding the audible reverse warning.

The stated problems call for a revision of the current reverse warning. By further developing the reverse warning, there exists an opportunity to enhance the safety of VRUs and reduce societal noise pollution while ensuring that the regulations are followed. When developing the reverse warning, VRUs' behaviour must be considered to ensure that the solution is adapted to society's needs.

## 1.3 Research questions

The following research questions are to be answered in the thesis work:

- How do vulnerable road users perceive situations related to reversing heavy goods vehicles, and what influences their behaviour?
- How can the reverse warning be designed to meet regulations and user needs and enhance safety while minimising society's noise pollution?

## 1.4 Aim

VRUs' behaviour in the area around reversing trucks has not been widely reported, nor has the current reverse warning's safety. This thesis aims to investigate how the reverse warning should be designed to enhance the safety of VRUs. Furthermore, the aim is to decrease the noise pollution caused by the audible reverse warning by suggesting a solution for how to make the audible reverse warning adaptive while complying with the upcoming regulation. As part of achieving the aim, the VRU's behaviour will be studied to identify needs, which will be considered when generating and evaluating concepts of an improved reverse warning.

### 1.4.1 Stated objectives to fulfil the aim

The aim of this thesis is accomplished by fulfilling the following objectives:

- Identify how humans process information from warning signals and how warnings should be designed by performing literature reviews.
- Explore different types of audible and visual signals that can be used to warn humans by performing literature reviews.

- Identity for which truck market segments a developed reverse warning is needed by analysing the markets and their respective needs through market segmentation and interviews with truck drivers.
- Explore existing solutions for reverse warnings by performing benchmark analyses and patent searches.
- Discover how VRUs behave around reversing trucks by performing observations of VRUs in situations with reversing trucks and interviewing truck drivers.
- Specify requirements on a reverse warning by establishing a requirements specification.
- Generate concepts for a reverse warning by performing concept generation activities.
- Evaluate the proposed concepts' fulfilment of requirements by performing concept elimination activities.
- Evaluate how VRUs perceive concepts for a reverse warning by performing questionnaires and tests with virtual prototypes.
- Propose a solution for a reverse warning by analysing the results from the concept evaluation and selecting the most appropriate solution that complies with the regulations.

## 1.5 Scope and delimitations

The following paragraphs specify the scope and delimitations that define the topic and boundaries of this thesis work.

This thesis work focuses on exploring how VRUs should be warned about a reversing truck. The signals used to warn VRUs are not restricted to only audible and visual signals; however, all signals should be mounted on the truck. The VRUs considered in this thesis work are mainly pedestrians and bicyclists. The investigated hazardous situations are between a heavy goods vehicle and a VRU. The outcome of the thesis work will be a suggestion of a reverse warning, focusing on the function of the warning. Virtual prototypes are used to verify the concept. The participants participating in the verification tests are Volvo employees that work at the Volvo Group Truck Technology (GTT) office at Lundby. The thesis work is performed during a time frame of approximately four months.

This thesis work does not cover the development of aids that help the truck driver perform safe reversing manoeuvres, such as cameras and sensors. Specific variants of components to the provided concepts will not be specified, e.g., audible reverse warning loudspeakers and lamps. Hazardous situations between heavy goods vehicles and other vehicles will not be investigated. A commercialised product with established technical requirements will not be developed, and a physical prototype of the concept will not be built.

## 1.6 Current solution of the reverse warning

Volvo's trucks are equipped with both active and passive safety systems. Components that regard passive safety are, for example, the seat belt and airbags. Where passive safety systems increase safety when an accident occurs, active safety systems decrease the risk of an accident occurring. Active safety systems can be cameras and sensors that warn the driver of nearby objects, and the reverse warning signals warn the VRUs of an approaching reversing truck. Lately, there have been systems developed that have the power of controlling the vehicle by braking (Kockum et al., 2017).

All Volvo trucks are equipped with several components that serve the purpose of making reversing manoeuvres safer. When the driver puts the gear in reverse, an audible warning signal composed of a repetitive pure-tone beep is emitted. Besides the audible signal, visual signals consisting of white lights are activated on the rear of the truck, see Figure 1. The audible and visual signals aim is to alert people in the surrounding area of the truck that the vehicle is moving in reverse (Volvo Trucks, n.d, a).

To help the driver perform reversing manoeuvres, the trucks are often equipped with a reversing camera that automatically switches on when the driver puts the gear in reverse. The camera view can be seen on the side display of the truck interior panel (Volvo Trucks, n.d,b). It is worth noting that the reversing camera is located behind the cab, see Figure 1. When a trailer is mounted on the truck, the camera's visibility is limited and often completely unusable. The rear-view mirrors should also be used as a tool when reversing.



Figure 1. The camera and reverse lights of the current reverse warning.

Today, the audible warning signal can be adapted on some of Volvo's trucks, including the model Volvo FL. The audible warning is a two-tone signal, meaning that the signal's volume can be either high or low. When the driver engages the gear once, the high tone is emitted, and when the driver disengages the gear and then activates it within seven seconds, the low tone is emitted. The driver can choose to deactivate the audible warning completely with a button on the panel on all trucks (Volvo Trucks, n.d, a).

## 1.7 Company description

Assar Gabrielsson and Gustaf Larson founded the company of Volvo in the year 1927. The first focus for Volvo was to launch a car, but the first Volvo truck was released shortly after in the year 1928, and it became a great success. Today Volvo Trucks is one of the brands within the Volvo Group concern; Figure 2 shows four current brand models. Besides Volvo Trucks, the company's truck brand portfolio also consists of Renault Trucks and Mack Trucks. Within Volvo Group, trucks are accountable for 61% of the sold products; the remaining products are mostly construction equipment. This extensive brand portfolio enables Volvo Trucks to offer trucks to large customer segments all over the globe. Volvo Group's heavy-duty trucks hold a market share of 25% in Europe, 16,3% in North America, 22,2% in Brazil, and 18,9% in Japan (Volvo Group, 2020).

In 2020, roughly 166 000 trucks were sold within the Volvo Group concern; slightly over 93 000 were under the Volvo Truck brand. The net sales of trucks in 2020 were 208 billion SEK, which was 25% less than the year before. Volvo group's ambition is to be 100% safe, 100% fossil-free, and 100% more productive (Volvo Group, 2020).



Figure 2. Four models of Volvo trucks.

## 1.8 Project process

The general product development process described by Ulrich et al. (2020) consists of six phases, see Figure 3. This thesis project aims to deliver a developed and evaluated concept that can be taken further into the product development process, which indicates that the relevant process phases for this project are the two initial phases, “Planning” and “Concept development”. The planning phase sets the project’s base, e.g., the overall aim is specified, and opportunities, market segments, constraints, and existing technologies are analysed. In the following phase, customer needs are identified, and product concepts are generated and later evaluated. Evaluated concepts should be tested and developed before one or more can be selected to proceed into the next stage of the product development process.

The product development structure in this thesis work has been inspired by the Waterfall model and the model of the development funnel. The Waterfall model divides the product development process into phases dependent on the results from the previous phase (Stober & Hansmann, 2010). The number of phases varies in the literature, but the generic approach is the same. L. Trygg (personal communication, September 16, 2020) presents the model with six phases, which are: “Idea”, “Analysis”, “Design”, “Development”, “Test”, and “Final product”. This model refers to the whole product development process but was believed to be relevant to the concept development process in this project. The characteristics of the waterfall model are, reflecting on its name, that the process follows the stream of the phases and could be seen as a quite inflexible approach. However, in this project, the model was used as a more flexible method where returning to a previous phase was possible. The more structured way of planning and execution of the project was deemed a good approach because of the limited time frame.

The development funnel is a model that describes how an idea works its way from its initial start with the aim to be realised eventually. The funnel describes the overall development process with its parts of generation, analysis of alternatives, and decision making. As the name infuses, the idea of the model is to mimic a funnel, where many concept ideas enter the initial phase, and during the process, the funnel gets narrower and the concepts fewer. A

screening process of the concepts is performed before entering the next phase, and some concepts are eliminated. The process follows this structure until a concept is selected and developed into a final product (Wheelwright & Clark, 1992).



Figure 3. The general product development process presented by Ulrich et al. (2020).

Figure 4 illustrates an overview of the project process used in the thesis work to answer the two research questions and fulfil the stated objectives. Investigating behaviours of VRUs in situations with reversing trucks was done by interviewing truck drivers and performing observations in the city environment. The findings were used as inputs to the user needs specification and the creation of personas that later served as input to the concept generation. Several methods and activities were performed to develop and deliver a final concept. Some activities in the project process are recurrent throughout the project; thus, the work was utilised for iterations. A Gantt chart was used as a time plan for the project, where activities and estimated time were specified. The Gantt chart was revised and updated throughout the project to cope with changes and to maintain the proper focus at the right time. The work was performed on-site at Volvo Group Trucks Technology in Gothenburg.

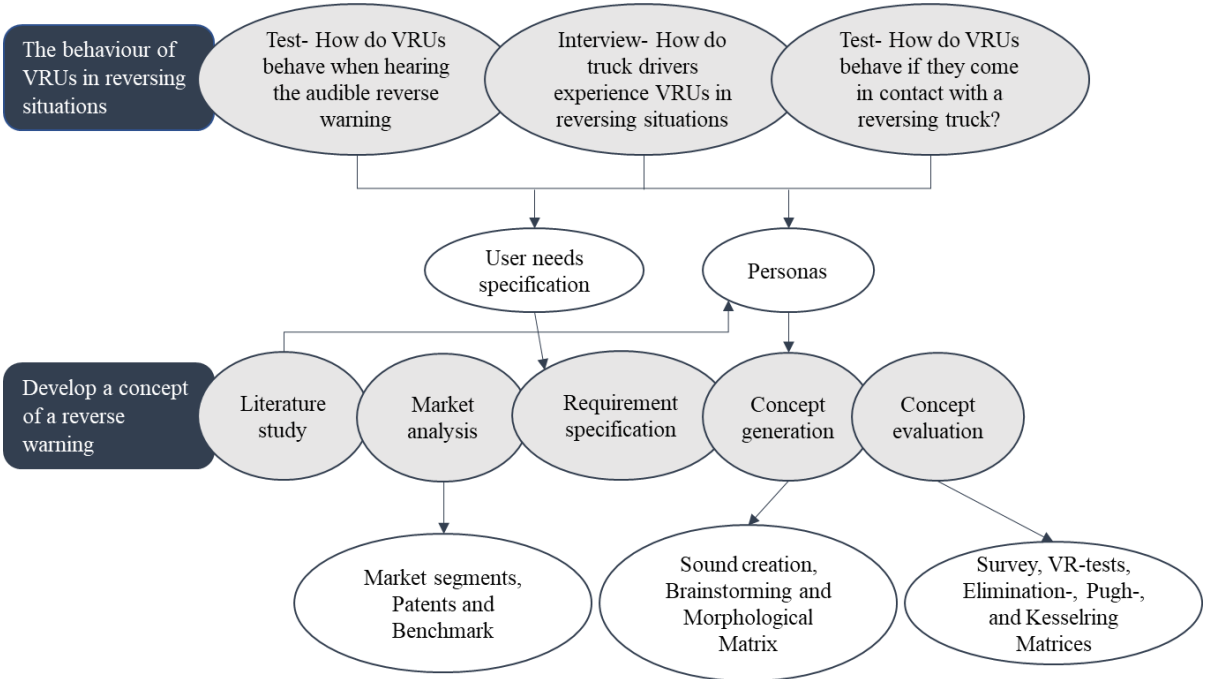


Figure 4. The project process for this thesis to be able to answer the stated research questions.



# Chapter 2

## Theoretical frameworks

This chapter presents the theoretical frameworks relevant to the project. Human interpretation of warnings and factors that influence the design of a warning system is presented.

In addition, audible and visual warning signals used to warn humans are presented. Furthermore, commonly used audible reverse warnings are compared. In conclusion, the legal requirements that influence the design of an audible reverse warning are summarized.

## 2.1 Methodology for literature studies

Before developing a reverse warning, theories and models already been developed were explored through literature studies to gain relevant information needed to design the reverse warning. The information was mainly gathered from literature and articles found in different databases, e.g., Chalmers Library, Google Scholar and Research Gate. Several keywords were used during the literature search, e.g., warning signal, human behaviour, and reverse warning. Reference lists in the read literature were also used to find other valuable sources. In addition, an expert in sounds was consulted that provided recommendations of relevant articles. Much literature was skimmed through by reading the abstract and conclusion. The literature that was deemed to be relevant was shortly summarised and saved in a shared folder of the project group to enable easy access later in the project. The findings from the performed literature studies are presented in the following sub-chapters.

## 2.2 Human information processing

To understand VRUs' behaviour in reversing situations, it is necessary first to understand how humans process information from the reverse warning. Multiple models of human information processing have been developed over the years, and a recent model is described by Wickens et al. (2022), see Figure 5. According to the model, events in the environment are first processed by the human senses and temporarily held in the short-term sensory store (STSS) for up to a second. For example, when approaching a pedestrian crossing, traffic lights are seen, and conversations from pedestrians passing by are heard. However, only a small amount of the sensory information is perceived, for example, that a specific traffic light has shifted to red. A human's attention acts as a filter that selects some elements for further processing while blocking others, such as conversations of pedestrians. Perceiving means determining the meaning of the sensory signals by using previous experiences stored in the long-term memory. Perceiving a situation often triggers an immediate response, which is chosen from a selection of possible responses. A person might decide to stop and wait for the light to turn green before passing the crossing or choose to hurry over. The decision is based on multiple factors, but it needs to be made quickly. Following the response selection, the response is executed. However, perception does not always trigger an immediate response. Humans can use their working memory to search for additional information before deciding which action to take, for example, if other pedestrians are at the crossing or if cars are starting to accelerate. When the response has been executed, the environment is somehow changed, and new information must be sensed, which is illustrated by the feedback loop at the bottom of the model (Wickens et al., 2022).

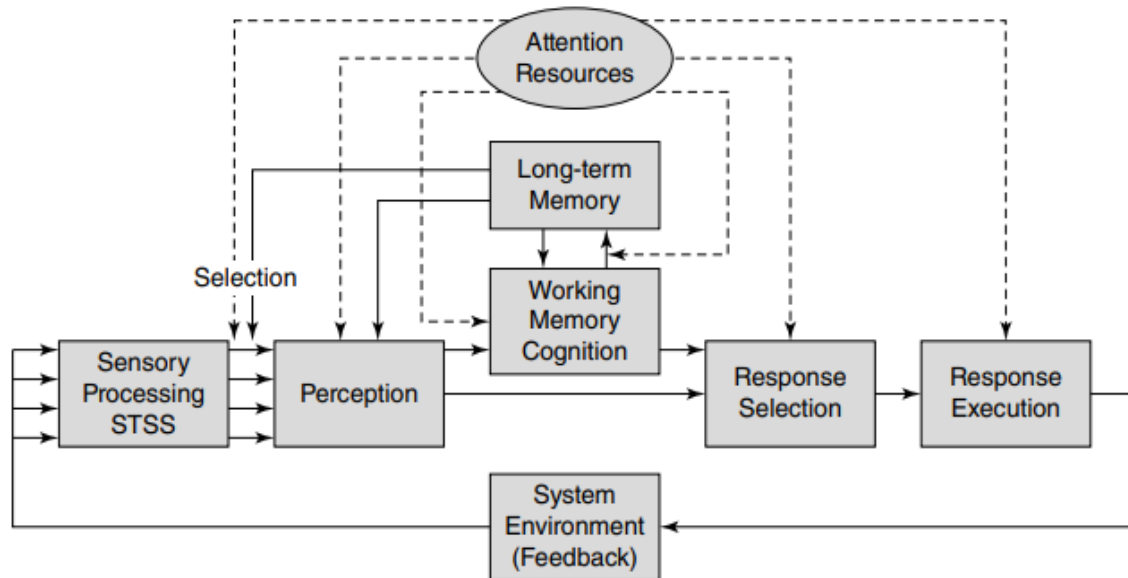


Figure 5. A model of human information processing stages (Wickens et al., 2022).

## 2.3 The human senses in relation to detecting danger

Humans have five senses: hearing, sight, smell, touch, and taste. The purpose of these five senses is to register and interpret the surroundings and are vital for detecting danger.

### 2.3.1 Hearing

*Sound* is an acoustic wave captured by the outer ear and transmitted by the vestibulocochlear nerve to the brain that registers the sound (Brydolf, 2019a).

Detecting danger through hearing is something humans have relied on since the beginning of mankind. In today's modern society, hearing is often not used to detect threats, e.g., an approaching dangerous animal that lurks around the campsite. More commonly is to hear warning signals that have been designed to alert and warn subjects in the surrounding, e.g., the reverse warning signal on a truck or a fire alarm (Haas & Edworthy, 2006).

### 2.3.2 Sight

The pupil lets light into the eye, and there it is transformed into signals by the visual cells and optic nerve. These signals are later transported to the brain's visual centra, which translates the signal into a picture that can be interpreted (Brydolf, 2019b).

The vision is of high importance to be able to detect danger. In society today, visual warning signals can be seen everywhere in various forms, e.g., warning information on consumer products, warning signs, and warning lights on reversing vehicles (Haas & Edworthy, 2006).

### 2.3.3 Smell

The human sense detects smell through gases that consist of small particles that contact the olfactory cells. Further, the olfactory nerve transport signals to the brain that register the signal and the smell can be perceived. A smell can be an alert of danger, e.g., it can indicate if something is eatable or has gone bad and can also alert of fire (Brydolf, 2019c).

### 2.3.4 Taste

Several thousand taste buds can be found on the tongue and in the oral cavity, which transports information through taste cells and nerve signals to enable the brain to interpret the taste (Brydolf, 2019c).

The sense of taste can also detect danger by signalling if something put inside the mouth tastes bad. Poisonous substances tend to have a bitter taste, which the sense of taste is sensitive to (Brydolf, 2019c). Taste can also enhance the sense of smell and more easily detect airborne dangers, which can be helpful in, e.g., underground environments and heavy industry (MineARC, 2020).

### 2.3.5 Touch

Touch receptors under our skin can detect touch, pressure, heat, and cold. The touch receptors send a signal through the sensory nerves to the part of the brain named the thalamus. The most sensitive areas of the human body are the lips and fingertips. Pain is detected by particular neurons, nociceptors, designed to react to tissue damage signals to the brain (Wnuk et al., 2018). The feeling of pain works as a protection and signals that the body is being harmed. When the brain receives information about pain stimuli, several reactions are triggered, e.g., reflexes make the body move a body part from the pain source (Brydolf, 2019d).

## 2.4 Different types of sounds

There are mainly two definitions of sound, the perspectives of physiology and physics. Physiology defines *sound* as dependent on the reception of an individual, while the definition from the standpoint of physics means that sound is independent of an individual's reception. Sound is generated by vibrations that cause movements in the surrounding molecules which causes a chain reaction, i.e., sound waves. Sound waves are dependent on a medium to travel through, meaning that sound cannot be created in a vacuum. Frequency, measured in Hertz (Hz), describes a sound and is determined by the number of vibrations per second the sound consists of. The human ear can process sounds of 20 - 20 000 Hz. Sound level is measured in decibels (dB). Commonly, the stated dB is written as dB (A), where the A stands for A-weighted, which indicates that the measured dB has been adjusted to encounter the differentiating sensitivity concerning frequencies that the human ear can comprehend. The human ear does not hear all frequencies the same, e.g., sound levels in the low and high-frequency range are perceived as lower than the same dB value in the centre of the spectrum. When the dB is A-weighted, sound levels in the lower and higher end of the frequency range are given a reduced dB value to better correspond to the volume that is perceived (PASCO, n.d; Science World, n.d; Ulfvengren, 2003). The following sub-chapters present a selection of different sounds.

### 2.4.1 Tonal sound

The audible reverse warning currently being used consists of a repetitive pure-tone beep. The most common auditory warnings consist of beeps, for example, the sound of an alarm clock or a fire alarm. Pure tonal sounds consist of waves that travel in the medium with the same phase, i.e., frequency (NE, n.d, a). However, most tones used to create music or sound consist of tones that have several sinus tones, called fundamental tones and overtones. The fundamental tone is the lowest and has the lowest frequency; this tone sets the pitch. The overtone is resonant with the fundamental tone and has a higher frequency. The overtone sets

the tone's timbre, giving the same tone different characteristics. The tone's timbre is why the same tone on a guitar and a piano sound differently (Westergren, 2009).

#### 2.4.2 The colour of noise

There are different characteristics of noise that all have unique properties, but to the human ear, all sounds like a "pssh" sound. White noise combines all frequencies audible to humans (20 Hz-20 000 Hz) with the same amplitude in the sinus curve (Neal, 2016). Some existing reverse alarms use this sound since it is easier to localise and is less likely to be masked by other noise than the traditional tonal reversing alarm (Vaillancourt et al., 2014). Different types of noise are, e.g., pink-, brown-, and blue noise. Pink noise has, unlike white noise, not a consistent amplitude over the frequency spectrum. The amplitude is reduced by half when the frequency is doubled (Neal, 2016).

#### 2.4.2 Auditory icons

Auditory icons are messages that consist of sounds present in everyday life. Compared with most common auditory warnings, auditory icons consist of complex sounds that provide information about the situation. Early on, auditory icons were used in personal computer interfaces to enhance the visual display with an auditory dimension. For example, switching between tasks is represented by a "paper flipping" sound, and deleting files from a trashcan is represented by a "paper-crunching" sound. However, over the past thirty years, auditory icons have been used in an increasing number of fields (Cabral & Remijn, 2019).

The main advantages of auditory icons, according to the literature, are the following. The auditory icons associated with the reference can reduce the reaction time and improve response accuracy. For non-experienced users, it is also easier to learn the auditory icons as they provide information about the situation. Furthermore, physical features in the sounds can be used to convey the perceived location, distance, and possibly size of the reference. Lastly, it is mentioned that the auditory icons have a good user acceptance by listeners. The disadvantages of auditory icons are that they can easily be misinterpreted. Further, it is difficult to express complex referents as auditory icons, which may impact learnability negatively. The auditory icons are also sensitive to masking by other environmental sounds (Cabral & Remijn, 2019).

#### 2.4.3 Earcons

Earcons are "abstract, synthetic tones that can be used in structured combinations to create auditory messages" (Brewster, 1994). Small building blocks called motives are used to construct earcons by modifying the parameters of the motives, which are rhythm, pitch, timbre, register, and dynamics. The five parameters allow for producing complex non-verbal auditory messages. Compared with auditory icons, earcons do not have to be associated with a particular object. For objects with no clear auditory representation, earcons can be used to yield sonification (Bhat & Lai, 2013). Earcons are, for example, used in menus to help the user stay aware of where in the tree the user is located (Dingler et al., 2008).

## 2.5 Warning signals

Laughery (2006) defines a warning signal's purpose accordingly:

Warnings have an important role in safety. Their purpose can be viewed from a few different perspectives. At a general level, warnings are intended to reduce or prevent accidents, injuries, health problems, and property damage. At a different level, warnings can be regarded as a method for communicating safety-related information to a target audience who can then make better informed decisions regarding safety issues. (p. xiii)

Humans rely on several warning signals, e.g., safety instructions on products, safety information on consumer products, traffic lights, sirens on emergency vehicles, and fire alarms. The most used warning signals are auditory and visual, each with benefits and drawbacks. Visual signals can be more informative than auditory signals, depending on the design of the warning, for example, figures and text. Auditory signals are not dependent on the receiver's attention, meaning an auditory warning signal can warn a subject without its specific attention. In contrast, a visual warning signal must be seen to be able to warn (Haas and Edworthy, 2006).

A warning signal must fulfil some critical requirements to work effectively as a warning. Two of the essential requirements for all warning signals are that they must be perceptible and understood. It is also important to understand how different signals are perceived by the listeners, i.e., representation, and if there are any associations to the designed warning signal (Haas & Edworthy, 2006).

The ideal warning signal is, according to Norman (1993), a signal that is:

- Clear and capture the important information that needs to be presented.
- Appropriate for the receiving person so that the signal is interpreted right.
- Appropriate for the specific task that the warning signal is aimed to warn for.

### 2.5.1 Auditory warning signals

There are two categories of auditory warning signals presented by Haas and Edworthy (2006), intentional and incidental. Intentional refers to warning signals designed to warn, e.g., fire alarm. Incidental warning signals arise in conjunction with a dangerous situation, e.g., screaming tires from a vehicle that brakes violently.

The intentional auditory warning signal can be divided into, speech signals and non-verbal signals. Speech signals are verbal signals where a human voice is recorded. This type of signal is beneficial in situations and environments where the percipient does not know the meaning of the signal, and it must be specified to be able to warn adequately. Another case where a speech signal is appropriate is in a countdown, where a non-verbal signal could cause miscounts. The non-verbal signal refers to signals that consist of, e.g., tones, mechanical buzzers, or bells. The simplest non-verbal signal is the short single-tone signal, which could be repeated over a period or sound once. The benefit of a single-tone signal is that it is easy to learn (Haas & Edworthy, 2006).

Studies have shown that auditory warnings are effective and suitable as a supplement to visual warnings. Warning signals that emit sounds are beneficial since the warning is more easily perceived than visual signals since visual signals must be seen to be able to warn. The

crucial functions of an audible warning signal are that it is loud enough to be heard and that the meaning of the signal is understood. The level of required loudness depends on the noise in the surrounding environment that the warning signal must be heard above. It is also essential to understand how the listeners perceive different signals and if there are any associations to the sound when a warning signal is designed (Haas & Edworthy, 2006). Vaillancourt et al. (2014) state that a warning should convey information about the danger, regarding where the danger is, and when it is a danger. Furthermore, Vaillancourt et al. list several factors that contribute to the effectiveness of reverse alarms, including masking by ambient noise, signal recognition, reaction times, perceived urgency, ability to localize the alarm, and hearing status of VRUs.

Animals also use different warning signals to communicate danger between other flock members. Many species have developed sounds that aim to warn about predators; some even have specific warning sounds for specific dangers. Some animals have learned to understand other species' warning signals, called eavesdropping, to enhance the chances of detecting an approaching predator (Templeton, 2018).

#### 2.5.1.1 Acoustic Vehicle Alerting Systems

Electrically powered vehicles are more silent than vehicles powered by combustion engines, which reduces noise pollution. However, the risk is that they are not detected by VRUs when moving at lower speed ranges. To improve the safety of VRUs, Acoustic Vehicle Alerting Systems (AVAS) have been developed for quiet road transport vehicles. UNECE has initiated the development of guidelines for the design of AVAS sounds that specify what characteristics the implemented sounds in the system should have. Among the recommendations, it is stated that "The emitted sound from the vehicle should indicate the vehicle's driving condition and provide further information regarding the vehicle's approach, presence and departure" (Fortino et al., 2016, p.997). Designing the sound to signalize the truck's departure could enhance the safety of VRUs as they would know when the truck is standing still and when it is reversing. Berge and Haukland (2019) state that visually impaired persons rely on their hearing abilities when determining whether crossing an intersection with approaching vehicles is safe. Conveying information about the vehicle's approach, presence, and departure promotes a better universal design of the truck, meaning that it enables all citizens to move around safely in traffic environments independent of any physical disabilities (Berge & Haukland, 2019).

#### 2.5.2 Visual warning signals

Visual warning signals depend on the attention of the human sight to be able to warn. There are several visual warnings, e.g., symbols, signs, and light. As briefly touched upon, all warning signals have some requirements to fulfil. Visual warning signals must, according to Laughery (2006), fulfil these three requirements:

- Call for attention - a well-designed signal can draw attention to itself and be prominent in relation to other stimuli in the nearby environment.
- Be legible - a signal that for some reason is not legible, cannot warn. Legibility can depend on, e.g., colours, forms, environmental conditions, and lighting.
- Be understandable - the receiver's comprehension of the signal is important. The intended meaning of the signal might not be the same as the person's understanding of the meaning.

Research has shown that visual signals are more dominant regarding perceptual judgment than auditory signals. Noted during experiments is also that when emitting a visual and auditory signal simultaneously, the test subject generally responds first to the visual signal. In some cases, the subject is even unaware of the auditory signal (Posner et al., 1976).

If the visual warning signal is a light source, the colour of the light impacts how the warning is interpreted. White light provides the highest intensity of all colours and can be seen from the longest distance. Red is the colour that is most associated with danger; hence red light is often appropriate for a warning signal. Furthermore, red is more visible against a blue sky than other colours during the daytime. Red is visible through the haze better than other colours with equal intensity during fog or smog. Blue light is beneficial in low light conditions as it is easier detected by the eye than red. However, twice the amount of blue light energy is required to be perceived equally to red light during the daytime. The interpretation of visual warning signals is not only based on colour, other factors, such as flash intensity and flash rate, are also important (Anderson and Plecas, 2010).

#### 2.5.2.1 Visual reverse warning used on trucks

The history of the automatic reverse light signal began in the early 1920s and was an innovation by Ford. The new system allowed illuminating the area behind the vehicle at nighttime for better visualisation for the driver and alerted the surroundings of the intentioned reversing manoeuvre. The automatic reversing light was turned on when the gear was changed to reverse and turned off when the gear was disengaged. Volvo followed Ford and implemented the reversing lights on their cars some years later (Kingston, 2018).

#### 2.5.3 Extrinsic factors that could affect the effectiveness of a warning

Research has shown that several factors affect the effectiveness of a warning, such as personality, social influence, environmental noise, and visibility. These factors are independent of how good the warning is designed. Still, it would be of importance to recognise that these factors affect the warning and thereby be able to design a warning that maximises its effectiveness. In an article, Vredenburg and Helmick-Rich (2006) have compiled several other researchers' work on the subject.

The first factor presented is the cost of compliance, meaning that all people are more or less compliant to follow warning instructions depending on the cost and benefits (Magar et al., 2008; Vredenburg & Helmick-Rich, 2006). Godfrey et al. (1985) performed a study on this behaviour. They put up a warning sign that informed people that the door was broken; if the sign referred people to take the adjacent exit, almost all followed the instruction, but if referred to a door that was placed further away, nearly all went through the door with a warning sign. Similar behaviour has been seen regarding wearing protective equipment, e.g., seatbelts and bicycle helmets, where people tend not to use the equipment if they perceive discomfort. Research has also shown that people are keener to follow the warning instructions if the possible consequence is a high risk, e.g., injuries (Vredenburg & Helmick-Rich, 2006).

Social influence is shown to be affecting how people behave regarding warnings; if the people in the surrounding does not follow the instruction, others tend to follow, and vice versa. People's personality influences how they behave in different situations, e.g., cautious and risk-taking personalities. People with a risk-taking personality are more likely to behave less safe and not follow warning instructions, e.g., not following the speed limit in traffic (Schultz Larsen, 2013; Vredenburg & Helmick-Rich, 2006). Magar et al. (2008) present that people with difficulties planning forward, weighing in all aspects of a situation, and limited

behaviour patterns are more likely to take risks. Behaviours can be influenced by personal experiences or knowledge that someone close has experienced a specific situation, e.g., a car accident, thereby being more conscious of some situations. Vredenburg and Helmick-Rich (2006) indicate that this is related to the fact that people with some related experience see the hazardous event as more frequent than someone who has no experience of the situation.

Kockum et al. (2017) report that 17% of pedestrians use their smartphones when crossing roads, which makes them less attentive to the traffic situation. A study performed by Jiang et al. (2018) shows how distractions from a mobile phone (texting, having a phone conversation or listening to music) affect pedestrians' behaviours in traffic. The performed experiment focuses on behaviours when crossing a road, but the result would be valid for other traffic situations. The study showed that walking and texting affected a pedestrian's visual attention the most. A person who walks and writes a text simultaneously was shown to walk slower and scan the environment fewer times and at a shorter time than a person who is non-distracted. Furthermore, the study showed that talking on the phone and listening to music was less distracting than texting. However, similar unsafe behaviours were observed in these cases as well. Listening to music affects the auditory attention of a person, and therefore the study concludes that pedestrians with decreased ability to detect auditory signals depend more on visual signals.

Environmental noise can be of both visual and auditory characteristics. Noise affects the effectiveness of a warning since it influences the likelihood of detection and thereby hinders people to comply with warnings. Visual noise could be different weather conditions that reduce the visibility. Audible noise is sounds that are not wanted and can be disturbing and even affect the health of humans. Environmental noise pollution is often caused by sounds generated from, e.g., crowded spaces, constructions, or vehicles (European Commission, n.d.; Vredenburg & Helmick-Rich, 2006). Masking is a term used to describe the situation where emitted noise in the surrounding disturbs or cancels out the wanted sound. Masking occurs when the noise has the same frequency or a frequency very close to the wanted sound. Depending on the frequency bandwidth of the noise and the wanted sound, masking can be partial or complete (Ulfvengren, 2003). As mentioned in Sub-chapter 2.4 *Different types of sounds*, sound is measured on a logarithmic scale in the unit dB. The scale starts at 0 dB, which is the "threshold of audibility", meaning that it is the point where the human ear can begin to detect sounds. The "threshold of pain" occurs at around 130 dB and can be compared with the sound of a jackhammer. The audible reversing alarms have a sound level of 82-107 dB and are comparatively louder than the sounds of a busy street that is around 65dB (Brigade electronics, n.d.). A recommendation presented by Vaillancourt et al. (2014) and Zheng et al. (2007) is that the auditory warning signal should be 12-25 dB above the ambient noise to ensure that the warning can call for attention.

#### 2.5.4 Parameters that influence perceived urgency of warning signals

A well-designed warning signal should have an appropriate level of urgency to warn and inform the recipient of the level of dangerousness (Vaillancourt et al., 2014). The perceived urgency could influence the reaction and response time of the recipient (Ulfvengren, 2003).

Several factors have been proven to influence the perceived urgency of an auditory warning signal. The dominant frequency is believed to influence urgency, whereas high frequencies are deemed to increase the perceived urgency. The on/off interval, how fast the sound is repeated, regular rhythm, sound pressure level, and perceived familiarity with the sound are

presented to increase the level of perceived urgency (Edworthy, 1994; Haas & Casali, (1995); Ulfvengren, 2003; Vaillancourt et al., 2014).

Like the auditory warning signal, a visual warning signal can also be perceived with different levels of urgency. An emergency warning light should have a short flash rate, as a shorter flash rate is perceived as urgent. Non-emergency warning light should be on longer than off, as it is perceived as less urgent. A visual signal designed with a red light is also deemed to be perceived as more urgent since the colour red is associated with danger (Anderson & Plecas, 2010).

### 2.5.5 Summarised findings regarding the traditional tonal reverse alarm and the broadband reverse alarm

The audible reversing alarm was invented by Ed Peterson, who sold the first warning system in 1967 (Ravo, 1999). The device warns VRUs when a vehicle is moving in reverse by emitting a sound. Most common is the tonal alarm that produces a pulsing single frequency sound, described as a “beep”. The sound can either have a fixed sound level or be automatically or manually adjusted according to the sound level of the surrounding noise. The sound is unique to the surrounding, loud enough to be heard in various situations, and easily understood as a warning. Despite this, the tonal alarm has been criticised for causing noise pollution. The tonal sound can often be heard at distances far from the actual danger zone, creating false alarms. The sound is also described as hard to localise, mainly when emitted from multiple sources (Holzman, 2011; Popoff-Asotoff et al., 2012).

Another type of audible reverse alarm is the broadband alarm that uses a white sound that could be described as a “pssh” sound. The main advantage of the broadband alarm is that its audibility is concentrated in the dangerous zone behind the vehicle. The sound is masked by the surrounding noise outside the dangerous zone, resulting in less irritation among people and less noise pollution. In addition, the white sound uses broadband frequencies that give greater directional information than the traditional tonal sound. This implies that the sounds are easier to localise and cause less confusion, implying a safer solution (Holzman, 2011).

The traditional tonal alarm can, as mentioned, be difficult to localise, which is also something many people experience when localising emergency vehicle sirens. Some frequency ranges are more prominent for the human ear when it comes to localisation. Frequencies below 1500 Hz and higher than 3000 Hz are important to include in a sound that must be easy to localise. The dominant frequency in a traditional reversing alarm is between 1000 Hz and 4000 Hz, which is a range where the majority of the available localisation frequencies are not available. With its white sound, the broadband alarm covers a broader frequency spectrum and is, in theory, more easily detectable (Vaillancourt et al., 2014). A consistent pattern of sound pressure levels (dB) is also shown to be beneficial when it comes to easy sound localisation. A study presented by Vaillancourt et al. (2014) showed that the traditional tonal alarm has an uneven sound pressure pattern. The study showed that the sound pressure level could go up 15 dB when moved just a few centimetres from the starting point, and then the sound pressure level could go down again, followed by a rising dB and so forth. The broadband alarm has shown to be better performing, considering an even sound pressure level. Catchpole et al. (2004) conducted a study comparing different frequency broadband alarms, a tonal alarm, and a combination of both. The result showed that the combined alarm performed better considering rapid and accurate localisation.

According to Vaillancourt et al. (2014), the tonal alarm is perceived as more urgent than the broadband alarm. However, it was shown that the familiarisation of the tonal sound impacted the results. This has also been detected in other studies concerning reverse warning alarms.

In some places, broadband alarms and adaptive tonal alarms are included in regulations and recommendations to reduce noise pollution from construction sites. Regulations to reduce construction site noise pollution in New York City demand trucks be equipped with either a broadband alarm or an adaptive tonal alarm. The tonal alarm should be adapted to emit lower sound levels after standard working hours or when the truck is present around locations where the noise pollution must be low, e.g., hospitals and schools (Vaillancourt et al., 2014). The Environment Protection Authority in Victoria in Australia (2021) recommends that a broadband alarm, flashing lights and adaptive alarms should be used to reduce noise from construction sites.

## 2.6 Summarised findings regarding legal requirements gathered from the processed UN regulations regarding the audible reverse warning

Today, there are no regulations regarding audible reverse warnings on trucks. However, one regulation is being processed and will likely be approved as a UN Regulation. If approved, the regulation will become valid in the year 2023. The regulation consists of two parts. The first part is more relevant for the audible reverse warning unit producer. The second part is more relevant for the producer of vehicles where the audible reverse warning unit would be mounted. However, it would be necessary for a vehicle producer, in this case, Volvo Group, to understand both parts of the regulation. Part I regulates how the audible reverse warning unit must sound and be tested to be approved, e.g., specified frequency ranges and measured sound pressure levels at a distance of one meter. Part II regulates how the audible reverse warning unit must be mounted and tested and how it sounds when mounted on the vehicle. In Part II, the specified sound pressure level is referred to as levels measured at a distance of seven meters and mounted on a truck. The regulations will not regulate whether an audible reverse warning should exist on the truck, so it is optional to equip a truck with an audible reverse alarm.

A summary of the markings described in the proposed UN regulation by the Task Force on Reverse Warning Sound (TF RWS, 2022) that is believed to be within the scope and deemed relevant for this thesis work will be presented in the following sub-chapters.

### 2.6.1 General specifications of the audible reverse warning

The audible reverse warning component must emit an acoustic signal consisting of at least one silent part. The pattern of the acoustic signal must be repeated at least 24 times per minute and at the most 120 times per minute. The measured frequency range of the reverse warning unit must be within the range of 1000 Hz to 3500 Hz.

### 2.6.2 Non-self-adjusting audible reverse warning system

A non-self-adjusting system is an audible warning that cannot automatically adjust the emitted sound's volume, implying that the audible reverse warning must be adjusted manually. The regulation presents three different volume levels for this type of adjusting system, "Low level", "Normal level", and "High level". These volume levels are specified with a dB (A) interval that must be complied with, see Table 1. The offset between the measured volume levels in the final design for a device with the "Low level" and "Normal level" must be at least 5 dB. The sound must reach the minimum sound level (62 dB(A))

within two cycle times of the pattern of the sound to comply with the requirements. It is assigned a classification based on how many volume levels the audible reverse warning complies with, see Table 2. Note that the classifications L and H are only allowed if the vehicle is equipped with another device that includes the "Normal level" classification.

Table 1. The specified required dB (A) that must be complied with depending on different levels.

	Volume interval dB (A) Part I	Volume interval dB (A) Part II
Low level	$62 \leq V < 77$	$45 \leq V < 60$
Normal Level	$77 \leq V < 92$	$60 \leq V < 75$
High Level	$97 \leq V < 112$	$80 \leq V < 95$

Table 2. Specified class types.

Class type	Available volume levels
Class L	"Low level"
Class N	"Normal level"
Class H	"High level"
Class I	"Low level" & "Normal level"
Class II	"Normal level" & "High level"
Class III	"Low level", "Normal level" & "High level"

### 2.6.3 Self-adjusting audible reverse warning system

A Self-adjusting audible reverse warning device is a device that automatically can adjust its volume. The device measures the surrounding noise level and adjusts the volume of the emitted sound to maintain a sound level higher than the ambient noise and thereby minimise the risk that the warning signal could be masked. The regulation has set a required interval that the emitted volume must be within, depending on the ambient noise. The sound pressure level interval specified in Part II is referring to a measure performed at a distance of seven meters from the audio source with a tolerance of  $\pm 4$ . Including tolerances, the sound pressure level cannot be lower than 45 dB (A) or higher than 95 dB (A). Within this interval, the emitted sound must be at least 5 dB (A) louder than the ambient noise, but not more than 8 dB (A) louder.

### 2.6.4 Stepwise self-adjusting audible reverse warning system

A Stepwise self-adjusting audible reverse warning device is a device that automatically can adjust the volume depending on the ambient noise level. Unlike the self-adjusting audible reverse warning device presented in the sub-chapter above, the stepwise device has three volume levels: "Low level", "Normal level", and "High level". The specified dB (A) for each level is the same as the levels presented in Table 1. Table 3 presents the allowed volume level at a specified ambient noise interval.

Table 3. The table presents the specified volume level that is required to be emitted at a specified ambient noise level for stepwise self-adjusting audible reverse warning systems.

Ambient noise dB(A)	Allowed volume level
$A \leq 50$	<i>Low level</i>
$50 < A \leq 55$	<i>Low level or Normal level</i>
$55 < A \leq 65$	<i>Normal level</i>
$65 < A \leq 70$	<i>Normal level or High level</i>
$70 < A$	<i>High level</i>

**2.6.5 Pause function of the audible reverse warning**

It is allowed to include a pause function to the audible reverse warning, meaning that the warning can be turned off if desired. However, some requirements of its function need to be fulfilled if this type of function is installed. The deactivation function must be located at a distance from the driver so that it is reachable for the driver at a normal seating position. If the audible reverse warning is deactivated, this must be indicated clearly to the driver. If the audible reverse warning is turned off, it must automatically be activated when the vehicle is turned off and restarted.



# Chapter 3

## Market analysis

This chapter presents the methodology and results of the activities performed in the market analysis. The market is analysed through a market segmentation that provides the identified needs for the different truck segments. In addition, benchmark analysis and patent analysis present information about existing solutions for reverse warnings.

### 3.1 Market segmentation

Market segmentation is usually performed in the early product development process to identify customers that share common needs. This way, the company can deliver more targeted products to the different identified groups. Besides common needs, the market can be segmented based on demographic, geographic, or psychographic aspects. The competitors and company's products are mapped onto the different segments, from which opportunities can be identified for each segment (McDonald & Dunbar, 2012).

Volvo Trucks have segmented its market into four segments, long haul, regional distribution, city distribution, and construction. From these segments, Volvo Trucks has developed a product portfolio consisting of products with different attributes and requirements to meet the needs of different customer segments. Analysing the different segments will be of use to better understand in which segment a revised reverse warning is needed and if the specific needs differ depending on the segment.

First, the environment and work tasks for each of the four market segments were formulated. These characteristics were based on observations from each segment's typical environments. Later, the VRUs' presence in each surrounding and the likelihood of VRUs encountering a reversing truck were formulated.

#### 3.1.1 Long-haul

Long haul transportation is Volvo's largest segment, where the truck models FH and FH16 are the leading products; see Figure 6 for a picture of the FH16 model. Long-haul vehicles are suited for long-distance and heavy transport. The truck is most often equipped with a larger cab where there is a place for the driver to sleep and even some kitchen necessities. The long-haul transports usually move in areas where the surrounding is adapted to enable easy manoeuvring with large vehicles and where reversing is intended not to be needed. The long-haul trucks often collect their transportation goods at an industry site, a harbour, or logistic centres, places which are often restricted areas for unauthorized people. The freight is often delivered to the same type of area. Along most heavily trafficked roads, there are rest stops intended for trucks, which are often designed so that the driver can drive in at the rest stop, park and drive out without reversing, see Figure 7. Generally, long-haul trucks do not encounter many VRUs, and the reversing situations during a typical shift are few.



Figure 6. Volvo Truck's model FH16.



Figure 7. Example of a rest stop for trucks.

### 3.1.2 Regional distribution

Volvo Trucks offer several models suited for regional distribution, i.e., FH, FH16, FM, FL, and FE. Which model to choose depends on the weight of the freight to be transported. Loading and unloading that could require reversing occur several times a day, but most often in areas where unauthorized people are not present, e.g., loading docks; see Figure 8 for an example. As for long-haul distribution, regional distribution mainly operates in areas designed for large trucks to ease the manoeuvrings. However, urban areas can be a part of the route where interactions with VRUs might occur.



Figure 8. Volvo truck's model FM at a warehouse.

### 3.1.3 City distribution

The Volvo Truck models FE and FM are dedicated to city distribution. The trucks are designed to manage a lot of starts and stops during the day and can be manoeuvred in confined spaces. Many other road users are also present where a city distribution truck operates, such as VRUs and cars, making it more challenging to manoeuvre the truck. Figure 9 shows different situations where a truck is present in a city environment. City areas are often not designed and adapted for large vehicles, leading to situations where reversing is necessary. City distribution often includes reversing in high-traffic areas, and the trucks must be driven on small streets and alleyways to get close to the stores and restaurants where the goods are delivered. Since trucks operate in areas where others do not always foresee them, the warning signals on the truck must work adequately to warn VRUs of its presence and intended manoeuvre. The environment in city areas is often stressed, with many people on the

move. The delivery driver often works on tight schedules, making it even more critical to have well-working warning signals and safety tools to avoid accidents. However, while the warning signals must be clear, the city areas have significant problems with high noise pollution.



Figure 9. Different city environments where trucks are present.

### 3.1.4 Construction

Volvo Truck's FM, FMX and FL models are suited for construction work. The environment can be hectic at a construction site due to the many vehicles and people moving around. Besides this, paths for the vehicles and workers to move on are often not marked, which could lead to hazards if the workers move in the truck's blind spots. However, the driver receiving help from a "spotter" is possible at a construction site. The present VRUs in these areas are most often workers on the site who are used to being around heavy vehicles. See Figure 10 for examples of how a construction site can look.

Construction sites are often loud, resulting in high noise pollution, which can interfere with the warning signals of a reversing truck. At a construction site, workers often wear hearing protection to block out noise, which could reduce the effect of an audible warning signal. There can also be an issue if more than one truck reverses simultaneously since the warning signal from a tonal alarm is more challenging to locate when heard from several directions (Holzman, 2011).



Figure 10. Different construction sites.

### 3.2 Benchmark analysis

Before developing a product, it is essential to research the market to understand competing products. *Benchmarking* is a tool used for comparing competitors' products with the company's products on the market. Besides understanding competitors' products and technologies, benchmarking also helps a company assess its relative position in the market by providing a point of reference to measure product attributes. The first step to performing a benchmark analysis is to form a list of relevant product properties. Then competing products are identified by searching for information. After collecting the product information, the information should be systematised and analysed. When analysing the benchmark, it is possible to determine, for example, what product is best in class per property and to predict industry trends (Otto & Wood, 2000).

For this project, a first benchmark analysis was performed to gain insights into what audible reverse warnings competitors to Volvo offers. In addition, aids that help the drivers perform reversing manoeuvres and systems that enhance the safety of VRUs were investigated. Later, a second benchmark analysis was performed to understand what audible reverse warning suppliers offer.

The following properties were considered essential to compare in the first benchmark analysis:

- Type of segment
- Type of audible reverse warning
- Adaptability of the reverse warning
- Aids for helping the driver perform reversing manoeuvres
- Aids for enhancing the safety of VRUs

The analysed competitors were Mercedes Benz, Scania, DAF, Isuzu, MAN, and IVECO. Data was gathered from Volvo's website and the competitors' websites, and relevant information

was collected and systematised in a table that can be seen in Table 4. By analysing the result, it can be seen that all brands use an audible reverse warning with a tonal sound. The sound of the audible reverse warning can be adapted manually from high to low sound on two of the competitors' trucks and one of Volvo's trucks. However, the sound cannot be adjusted automatically on any truck. All trucks that were analysed have rear cameras except for Volvo FL. Further, Mercedes Benz offers mirror cameras that replace the side mirrors and enhance the rear-view. Isuzu and IVECO are the competitors that offer the fewest aids for improving the safety of VRUs, as they only provide the Advanced Emergency Brake. Mercedes Benz and Scania offer more aids, consisting of different ADAS functions and cameras that offer enhanced views.

Table 4. Benchmark on different competitors regarding their aids concerning reverse warnings.

Property	Product							
	Volvo FH	Volvo FL	M. Benz Actros	Scania P-series	DAF LF	Isuzu Class 4	MAN TGX	Iveco S-way
Segment	City distribution, light construction, waste, recycling	City distribution	Long-haul	Urban and regional transport	Urban and regional transport	Distribution	Long-haul	Long-haul
Audible reverse warning	Tonal	Tonal	Tonal	Tonal	Tonal	Tonal	Tonal	Tonal
Adaptive audible reverse warning	-	Manual (high, low)	Manual (high, low)	Manual (high, low)	-	-	-	-
Aids for reversing	Rear camera	-	Rear camera, mirror-camera	Rear camera, rear sensors	Rear camera	Rear camera	Rear camera, bird view	Rear camera, rear sensors
Aids for enhancing safety of VRUs	Passenger corner camera, advanced emergency braking	Kerb view window, advanced emergency systems	Active side guard assist, active brake assist, cameras	Side detection, city safe window, advanced emergency braking, 360°cam	Kerb view window, advanced emergency braking	Advanced emergency braking	Turn assist, emergency brake assist, side cameras	Advanced emergency braking

In the second benchmark analysis, the parameters used were use environment, output sound, sound level, and adaptability of the reverse alarm. Four suppliers were analysed, whereas Rubbolite is the supplier of the reverse warning unit that Volvo uses today. Data was gathered from the suppliers' websites and systematised in a table that can be seen in Table 5. By

analysing the results, it can be seen that the suppliers offer three types of reverse alarms other than the tonal sound alarm. White sound alarms, multifrequency alarms and bespoke message alarms are common among the suppliers. The multifrequency alarm emits sound at multiple frequencies, and similarly to the white sound alarm, it sounds "pssh". Furthermore, three of the benchmarked products automatically adapt the sound of the reverse alarm depending on the ambient noise level. The sound level of the investigated products varies between 87 dB and 107 dB, where the reverse alarms with higher sound levels are often marketed for use in construction environments, and the others are marketed as all-around reverse alarms.

Table 5. Benchmark on different audible reverse warning devices.

Property	Product							
	BBS-107	BBS-TEK	SA-BBS-97	BC-01	AVR95	M700	EA9724	EA5200
Brand	Brigade electronics	Brigade electronics	Brigade electronics	Brigade electronics	Amber Valley	Rubbolite	ECCO	ECCO
Use environment	Construction	All-round	All-round	All-round	All-round	All-round	Construction	Construction
Output sound	White sound	White sound	White sound	Bespoken message	Bespoken message	Tonal sound	Multi-frequency	Multi-frequency
Sound level [dB]	87-107	82, 87, 92 or 97	77-97	90	85	97	77-97	97
Adaptive	Adjusts to 5-10 dB above the ambient noise level	No	Adjusts to 5-10 dB above the ambient noise level	No	No	No	Adjusts to 5 dB above the ambient noise level	No

### 3.3 Patent search

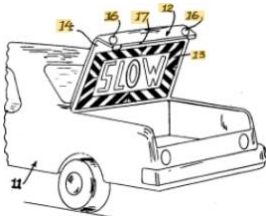
To gain further knowledge about solutions on the market, a patent search was conducted. The databases used for the search were Espacenet and Google Patents, and the keywords used for the search were combinations of "reverse", "backup", "alarm", "warning", "vehicle", "sign" and "symbol". To narrow down the number of results and extract the most relevant patents, some requirements were applied during the search. For example, requiring that the keywords are included in the title and abstract, and requiring that the exact phrase is searched for by using quotation marks. The result from the patent search can be seen in the following sub-chapter.

#### 3.3.1 Relevant patents found during the patent search

The patent search resulted in some relevant patents which can be viewed in the following sub-chapters. The found patents yielded some inspiration for the upcoming concept generation phase. For instance, the patent "Warning device on the lid" shows that it is possible to utilize existing space on the vehicle for another purpose. The foldable and extendable warning signs are examples of how to make the solution space-efficient and only visible when needed. The

patent “Generated symbols on the ground” shows that warning symbols can be projected on the ground instead of mounted on the vehicle. Patent “Prevention of collision with radio signals” shows that the VRUs existing mobile phones can be used to inform the VRUs about an approaching vehicle.

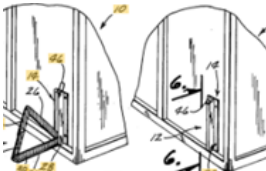
3.3.1.1 Warning device on the lid



A symbol or warning message is mounted on the inner surface of the trunk lid of the vehicle. An illuminating means is mounted on the vehicle that illuminates the sign when the lid is open by projecting light against the sign (Mosch, 1977). A picture of the patent can be seen in Figure 11.

Figure 11. Picture of the patent “Warning device on the lid” (Mosch, 1977).

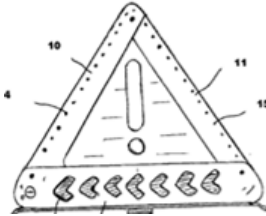
3.3.1.2 Foldable warning sign



A foldable warning sign is mounted on the side of a vehicle. The sign consists of elongated segments with light reflective material that can be moved from the housing to an operative warning position (Kitrell, 1982). A picture of the patent can be seen in Figure 12.

Figure 12. Picture of the patent “Foldable warning sign” (Kitrell, 1982).

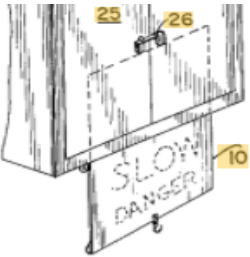
3.3.1.3 Warning triangle



A warning triangle device for use in motor vehicles has light-emitting diodes that form arrow symbols (Malakouti, 2006). A picture of the patent can be seen in Figure 13.

Figure 13. Picture of the patent “Warning triangle” (Malakouti, 2006).

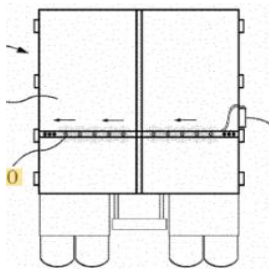
3.3.1.4 Extendable warning sign



A sign mounted beneath the rear of a truck takes up minimum space when not in use and can be extended when needed. The headlights of approaching vehicles illuminate the sign during the night (Von Kreidner & Taylor, 1966). A picture of the patent can be seen in Figure 14.

Figure 14. Picture of the patent “Extendable warning sign” (Von Kreidner & Taylor, 1966).

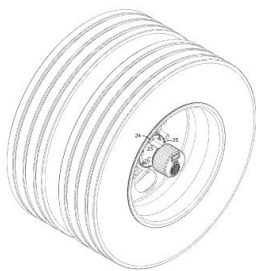
### 3.3.1.5 Emergency lighting system



A strip with LED lights is placed on the rear of the truck (Moinicken, 2019). A picture of the patent can be seen in Figure 15.

Figure 15. Picture of patent “Emergency lightning system” (Moinicken, 2019).

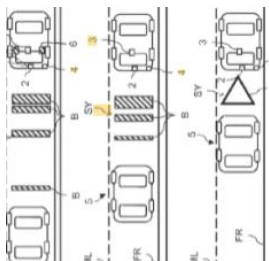
### 3.3.1.6 Hub-mountable wheel-rotation detector



A detector mounted on the wheel detects that the vehicle is moving in reverse and emits a reversing alarm from the rear of the truck (Aldape & Stewart, 2018). A picture of the patent can be seen in Figure 16.

Figure 16. Picture of patent “Hub-mountable wheel-rotation detector” (Aldape & Stewart, 2018).

### 3.3.1.7 Generated symbol on the ground



A lightning module generates a warning symbol on the ground automatically with input from a sensor that determines when the distance between the vehicle and the other road user falls below a specified distance (Hanafi et al., 2020). A picture of the patent can be seen in Figure 17.

Figure 17. Picture of patent “Generated symbol on the ground” (Hanafi et al., 2020).

### 3.3.1.8 Prevention of collision with radio signals



A collision between a vehicle and road user is prevented with radio signals that through the antenna on the vehicle and the mobile phone of the road user transmit and receive signals of the road user’s location. The vehicle and the road user receive an alarm signal about the other’s approach when the distance falls below a specified distance (Veniaminovich, 2021). A picture of the patent can be seen in Figure 18.

Figure 18. Picture of patent “Prevention of collision with radio signals” (Veniaminovich, 2021).



# Chapter 4

## Behaviour of VRUs in reversing situations

This chapter presents the methodology and results of the activities performed to understand how VRUs behave in situations with reversing trucks. Personas are created, interviews with truck drivers are performed, and observations of VRUs are made. The results of the activities complement the earlier findings on how VRUs behave and serve to answer the first research question.

## 4.1 Personas

*Personas* are a tool that can be used to easily visualise identified customer/user segments by creating fictional persons with specific attributes and needs (L. Almfelt, personal communication, December 8, 2020). In this project, personas have been used in an early stage to help with visualisation and initial understanding of different VRU behaviours and needs in traffic situations where a truck is reversing nearby. To start creating a persona, personal assumptions of general personalities and physical attributes that are more exposed to dangerous traffic situations were discussed. In combination with general beliefs about human behaviours, the findings from the literature review, see sub-chapter 2.5.3 *Extrinsic factors that could affect the effectiveness of a warning*, served as input to the created personas. The discussion resulted in six persons for whom personas were created: a child, an elderly pedestrian, an adult pedestrian, an adult cyclist, a youth on an electric scooter, and a construction worker. Each persona was given a name and an age to make the fictional person more realistic. Then a background was formulated for each persona, with a short description of their surroundings. Specific attributes were stated to strengthen the personality of each persona and served as input for formulating each persona's needs. As a result of the created personas, the project group understood the different needs of VRUs, which gave inspiration for the forthcoming concept generation. The created personas can be seen below.



Göran, 87 years old

*“I enjoy being outdoors”*

Göran is a retired man who lives in a smaller city within walking distance to all necessities. When he does his errands, he passes trafficked roads and intersections on the way. Göran usually runs errands in the forenoon, which is the time of the day when many delivery trucks are in circulations on the small streets of the city centra. When vehicles move on pedestrian streets, trucks can appear in places where they are unforeseen.

**Attributes:** Reduced hearing and vision, slow moveability.

**Needs:** Clear audible and visible signals, time to move away from the vehicle.



Sara, 35 years old

*“My work is my passion”*

Sara works as a business consultant in the big city. During the day, she moves around from one meeting to another while often highly occupied with checking her emails or taking business calls. Sara describes herself as the ultimate multitasker. Others would say that she is inattentive to her surroundings when walking on the streets.

**Attributes:** Ambitious, stressed.

**Needs:** Warning signals that call for her attention.



Kevin, 19 years old

*“I enjoy the wind in my hair when I’m sliding down the street”*

Kevin is a student that enjoys listening to music and playing video games. He often stays up late playing games and snoozes the alarm too many times in the morning. As he often oversleeps, he is in a constant rush. Luckily, he has an E-scooter that he travels with to school when he doesn’t make it to the bus.

**Attributes:** Optimistic, irresponsible.

**Needs:** Clear signals that can be spotted from distance, relies on the driver’s attention.

Lucas, 8 years old

*“I like running and playing ball with my friends”*

Lucas lives in a suburb close to his school and friends. He moves around freely in the area without supervision from his parents and passes medium to small roads daily. He likes to play football and compete with his friends about who runs faster. The play does not stop where a road starts.

**Attributes:** Imaginative, playful.

**Needs:** To not have responsibility, clear warning signals.



Reza, 28 years old

*“When I’m not coding, I’m exploring the world”*

Reza works as a web developer, lives a bit outside of the city and travels by bike to work. He is an adventurous person, and when he is not travelling the world, he is dreaming about it. Riding a bike makes him feel free, as he avoids getting stuck in traffic by swooshing past obstacles.

**Attributes:** Adventurous, daydreamer, risk-taker.

**Needs:** Clear signals that can be spotted from distance.



Felicia, 35 years

*“I’m always surrounded by people and machines”*

Felicia works at a construction site. There are no proper roads, so trucks and construction vehicles move around and reverse freely. The environment is noisy and ear protection is required. With so many things going on at the same time, she needs to stay alert all the time.

**Attributes:** Attentive, leader.

**Needs:** Visual warning signals and audible warning signals that are adapted for protection aids.



## 4.2 Interviews with truck drivers

To learn how VRUs behave around reversing trucks, the project group consulted truck drivers to obtain their experience on the subject. For gathering qualitative data, interviews are recommended as the primary data collection method by Ulrich et al. (2020), with the motivation that interviews are less costly than focus groups and that they allow one to gain experience of the use environment of the product. The interviews aim to discover how the truck drivers perceive that VRUs react to the current reverse warning and if the warning is sufficient for the VRUs to move out of the way of the truck. Further, the aim is to gather needs that the new concept is expected to fulfil and understand in which environments an improved reverse warning is needed. By interviewing truck drivers from different segments, for example, long-haul distribution and city distribution, the experience of each use environment can be gained along with the needs of each segment. The structure of the interviews is semi-structured, meaning that questions are formulated to guarantee that specific topics are included. However, the formulation and order may vary. Before the interview, a guide is designed that covers the questions and topics that should be addressed during the interview (P. Wallgren, personal communication, November 17, 2020).

### 4.2.1 Planning and conducting the interviews

The interview guide was produced during a brainstorming session, where the goal was to find topics of interest to discuss with the truck drivers. Five topics were identified during the brainstorming session: background, the current reverse warnings effect, behaviour of VRUs, reversing accidents, and suggestions for improvements. The driver's background is discussed at the beginning of the interview to understand the driver's experience, driving environment, and how frequently the driver needs to reverse the truck. After this, the current reverse warning is discussed to know whether they are considered enough to alert VRUs about the trucks' intention to reverse. Further on, the driver is asked how users behave around the truck and if differences in behaviour have been observed depending on the VRUs' age or if the VRU is a pedestrian or bicyclist. Then, the drivers are asked about their accident history related to reversing and how frequently near-accidents occur, to understand how often an experienced truck driver is involved, or near to be, in an accident. By retrieving this information, the problem definition for this project could be further strengthened. Lastly, suggestions for improvements are collected by asking the driver to reflect upon the ideal way of warning a VRU about a reversing truck and what needs to be improved on the current warnings.

Drivers for the interviews were found by contacting various haulage contractors in the region through telephone and email. Some haulage contractors were able to provide interested truck drivers for further interviews in person and over the phone. Before performing the interviews, the project group contacted the General Data Protection Regulation (GDPR) department at Volvo to ensure that the GDPR was followed. Volvo's GDPR state that all interviews with external people must fill out a form to approve their participation. Unfortunately, this form only exists in a physical form, which complicates the process of performing interviews remotely. Due to this, only interviews that could be completed in person were conducted, resulting in fewer interviews. Nevertheless, nine interviews were scheduled with truck drivers working in different environments. The interviews were performed on-site at the drivers' current workplace, notes were taken, and the interview was recorded on audiotape, if approved by the interviewee, to avoid missing any information. The recorded interviews were later summarised to ease the analysis.

#### 4.2.2 Analysis of gathered data and results from the performed interviews

The KJ method is a suitable method for analysing qualitative data. The KJ method is performed by writing statements collected through the interviews on small pieces of paper and sticking them on a board. When all statements have been visualised on the board, statements that share a common theme can be grouped. When all statements have been categorised, the different themes can be analysed, and similarities between themes can be identified. For example, similar customer needs can be grouped as one theme and relate to the different customers (P. Wallgren, personal communication, November 17, 2020). The KJ method was used to analyse the interviews and performed by writing statements from the interviews on a whiteboard and later grouping the statements. Figure 19 represents a summary of the board for three of the topics. The statements about VRUs' behaviour and suggestions for improvements are presented as quotes; see Figures 20 and 21. The result of the analysis is described in the following sub-chapters.

##### 4.2.2.1 The interviewed truck drivers' background

Six of the interviewed drivers work at a test facility, two work with city distribution, and one picks up garbage containers in city environments. The drivers presently working at the test facility have previous experience in city distribution, long-haul distribution, deliveries to construction sites, or bus driving. The interviewed drivers have between 15 and 42 years of experience, except one driver at the test facility who has one year of truck driving experience and 17 years of experience in bus driving. The drivers working in city environments state that they need to reverse their trucks at almost every delivery/pick-up spot, often due to the narrow streets in the city. Furthermore, the drivers state that reversing can be a demanding task as many VRUs occupy the streets and can appear unforeseen. The drivers working at the test facility reverse their trucks approximately 3-6 times during a shift, and the reversing is mainly performed at parking spots where few VRUs are present. The drivers working at the test facility with previous experience in city distribution recall reversing their trucks several times during the shift. Those who have experience with long-haul deliveries recall reversing most often at parking spots.

##### 4.2.2.2 The effectiveness of the current reverse warning

The drivers that work with city distribution do not consider the current reverse warning as an efficient tool to hinder VRUs from approaching the truck when it is reversing. The drivers recall that people often hurry behind the truck, even when it reverses against a building. In addition, one driver mentions that the signals are apparent; however, people tend to ignore the signals. Furthermore, another driver mentions that the signals are insufficient as they do not hinder people from approaching the truck.

The drivers working at the test facility recall the current reverse warning being usually sufficient with loud and clear signals. The drivers mention that people often show respect and wait for the truck to reverse. Furthermore, one driver mentions that the truck gains attention by itself and that there is no need for an improved reverse warning. By comparing the answers from the two groups of drivers, it can be seen that the environment and the presence of VRUs significantly affect the effectiveness of the reverse warning.

##### 4.2.2.3 Behaviour of VRUs in situations with reversing trucks

When asked about the behaviour of VRUs, all drivers mentioned that they could observe differences in behaviour depending on if the VRU is a pedestrian or bicyclist. Bicyclists were described similarly by all drivers, namely, as less attentive than pedestrians. Many drivers mentioned that bicyclists often come at high speed, making them less receptive to the

warning signals. In addition, some drivers described bicyclists as being more prone to taking risks. One driver stated that bicyclists' minds work in a particular way; if bicyclists believe they can make it past the truck, they will proceed even though they hear and see that the truck is reversing.

The answers varied when the drivers were asked if any differences could be observed depending on the VRUs age. Some drivers described adults as the most observant VRU, stating that adults are more rational than children and older people. Others experienced adults as inattentive, stating that adults are often stressed and walk around looking at their phones.

Some drivers described the elderly as the most observant group, as they have time to wait for the truck to reverse. One driver described the elderly as a fascinated group that often stops and watches the driver reverse the truck. On the other hand, older people were described as confused and having slow reactions by some drivers.

Teenagers were described as inattentive by most drivers, and the majority of the drivers stated that teenagers are often occupied by their phones which steal their attention. Furthermore, some drivers recall teenagers moving in groups and influencing each other with risk-taking behaviour. Children were described as not observant and often not understanding possible dangers by most drivers. Several drivers described children as being caught up in another world; however, since adults usually supervise children, the drivers did not perceive children as causing difficulties.

In addition to the performed interviews, the project group found a previous thesis work about visual communication between truck drivers and their surroundings. In the thesis, interviews with truck drivers were performed similarly. According to the interviews, the truck drivers described cyclists as not showing consideration for other road users, lacking knowledge of traffic rules, and thinking that they have priority in traffic. Some truck drivers even described cyclists as driving like crazy and thinking they were immortal. Pedestrians were described as behaving well except for when being in crowded areas. However, pedestrians wearing headphones or looking at their phones were described as caught up in another world. Hence, the truck drivers felt they needed to be extra careful with pedestrians with headphones and phones, as it is difficult to predict their next move (Styf, 2018).

#### 4.2.2.4 Accidents related to reversing

Most of the interviewed drivers had only been in minor reversing accidents where materials had been damaged. One of the drivers working with city distribution had been in a reversing accident with another vehicle, where no one got hurt. Another driver working with city distribution had witnessed a fatal accident with a pedestrian in a working situation.

#### 4.2.2.5 Suggestions for improvements of the reverse warning

When asked how the reverse warning could be improved, most drivers answered that the visual signals should be improved. Many mentioned that lights could be added to gain attention from the VRUs. Two drivers mentioned that the signals should be improved for people with reduced hearing. Some drivers proposed ways to improve the audible reverse warning. Their suggestions were to emit an “angrier” sound or the current sound from multiple sources on the truck, for example, behind the cab. Several drivers mentioned that signals, visual and audible, should be added to the side of the truck.

### 4.2.3 Takeaways from the interview results

Through the interviews, the project group understood how VRUs behave around reversing trucks and could use the gained knowledge to verify the previously made personas. Furthermore, the project group gained insight into which segments need an improved reverse warning. Like the market segmentation, the interview results indicated that trucks moving in city environments yield the most significant need for an improved solution. Therefore, the project group decided to proceed with developing a reverse warning solution specifically for the city environment. Furthermore, the interview results discovered needs and suggestions that would serve as input in the upcoming concept generation phase.



Figure 19. Summary of the KJ method visualised on a board.

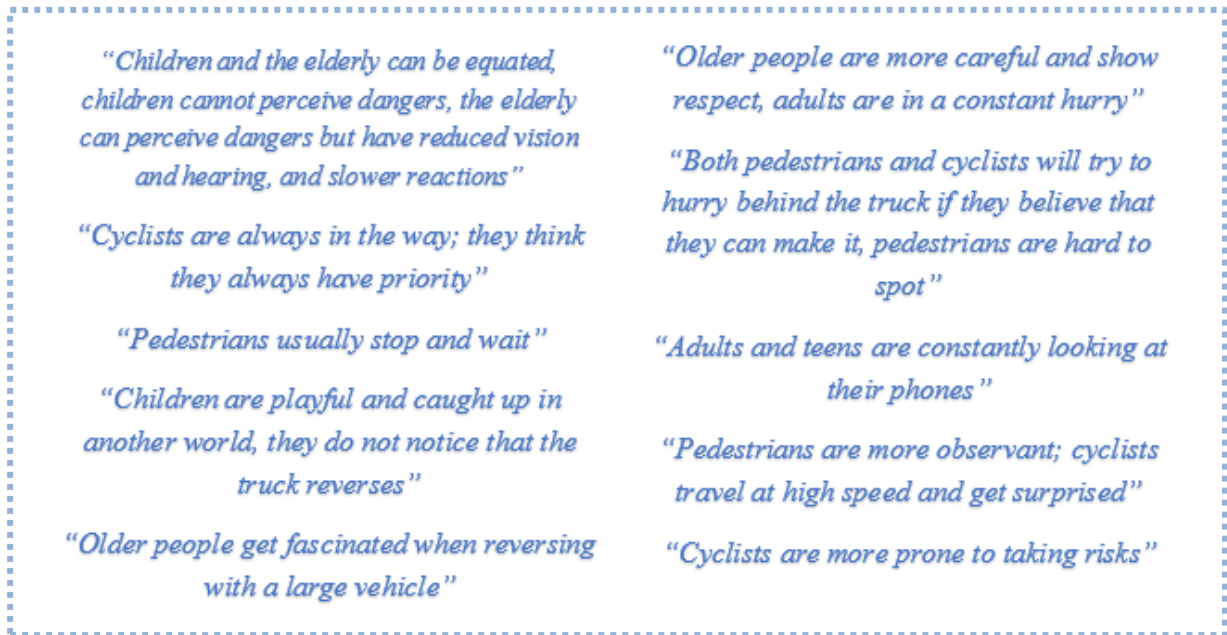


Figure 20. Quotes on how truck drivers perceive VRUs.

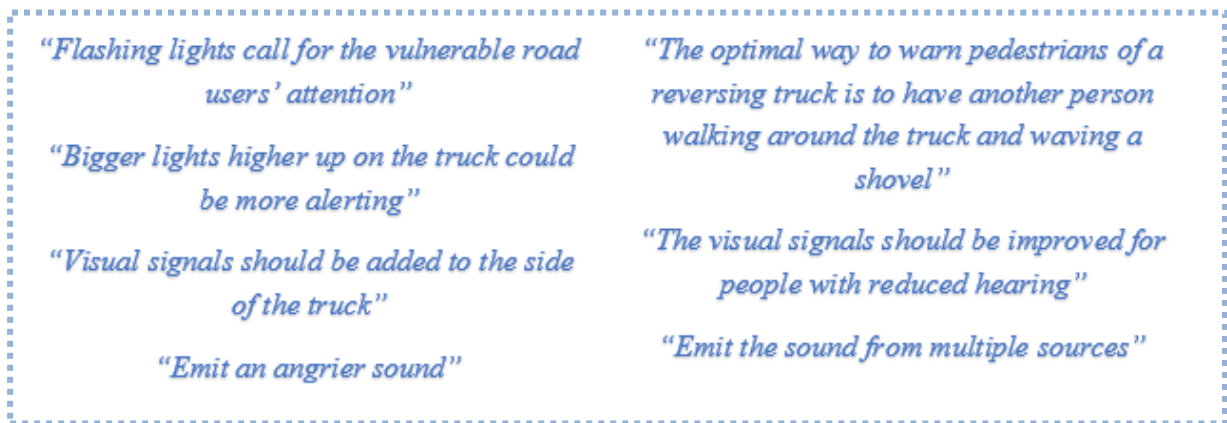


Figure 21. Quotes on suggestions about how the reverse warning could be improved.

## 4.3 Observations in the city environment

In this sub-chapter the methodology and results of the performed observations are presented.

### 4.3.1 Identification of critical reversing spots

To learn how trucks move around and reverse in the city environment and identify critical reversing spots, observations were performed in the city centre of Gothenburg on several occasions. The observations were performed by walking around the city centre and observing trucks that perform reversing manoeuvres. The locations where reversing manoeuvres occurred were documented by film and notes. Because the observed situations would be videotaped, which could be viewed as odd by bypassing people, the project group decided to wear a keychain with a Chalmers logo and the Volvo pass cards to signal that a project was being performed. However, the chosen equipment was discreet enough to not interfere with the results.

Several critical reversing spots could be identified through the observations; see Figure 22. Spot 1 on the map in Figure 22 shows an intersection between vehicles (blue) and VRUs (red). Trucks that deliver goods to the stores in the mall, the hotel, and nearby restaurants stop at spot 1. Since the passage is small, the trucks are forced to reverse in or reverse out of the passage. Since VRUs pass the intersection, the spot is critical for performing reversing manoeuvres. Figure 23 shows a street view of the spot. Spot 2 in Figure 22 is similar to spot 1 as the VRUs are put at risk when trucks reverse in or out of the passage. Spot 2 is therefore also considered to be a critical spot for reversing.

Spot 3, see Figure 22, is located along the street marked with red dashes that branch into smaller streets. Trucks deliver goods to stores located on the smaller streets and if the streets are clear from other vehicles, the trucks can pass without reversing. However, other vehicles often occupy the small streets during the daytime, making it impossible for trucks to pass without reversing. The VRUs moving along the streets are then put at risk, as the driver's rearview is often limited on such small streets.



Figure 22. Map of Gothenburg city centre where the identified critical reversing spots are marked.



Figure 23. An identified critical spot where trucks commonly reverse in the city centre of Gothenburg.

#### 4.3.2 VRUs' behaviour in situations with reversing trucks

Besides learning how trucks perform reversing manoeuvres in the city environment and identifying critical reversing spots, the observations were also an opportunity to identify how VRUs behave around reversing trucks. Several reversing situations could be spotted with pedestrians of varying ages and bicyclists during the observations, and some were recorded on video. The project group could observe that bicyclists often pass behind the reversing truck instead of stopping to wait for it to reverse. Figure 24 illustrates a recorded situation where a bicyclist passes closely behind a reversing truck with the reverse warning activated. The bicyclist cannot see what hides around the reversing truck yet passes behind it at high speed. The bicyclist exposes himself to a dangerous situation which indicates risk-taking behaviour. When the truck driver notices the bicyclist, the driver is forced to brake emergently. The observations confirm the previously made personas of how a bicyclist act on the road, as well as the input given from the interviewed truck drivers.



Figure 24. An observed bicyclist passes closely behind a reversing truck.

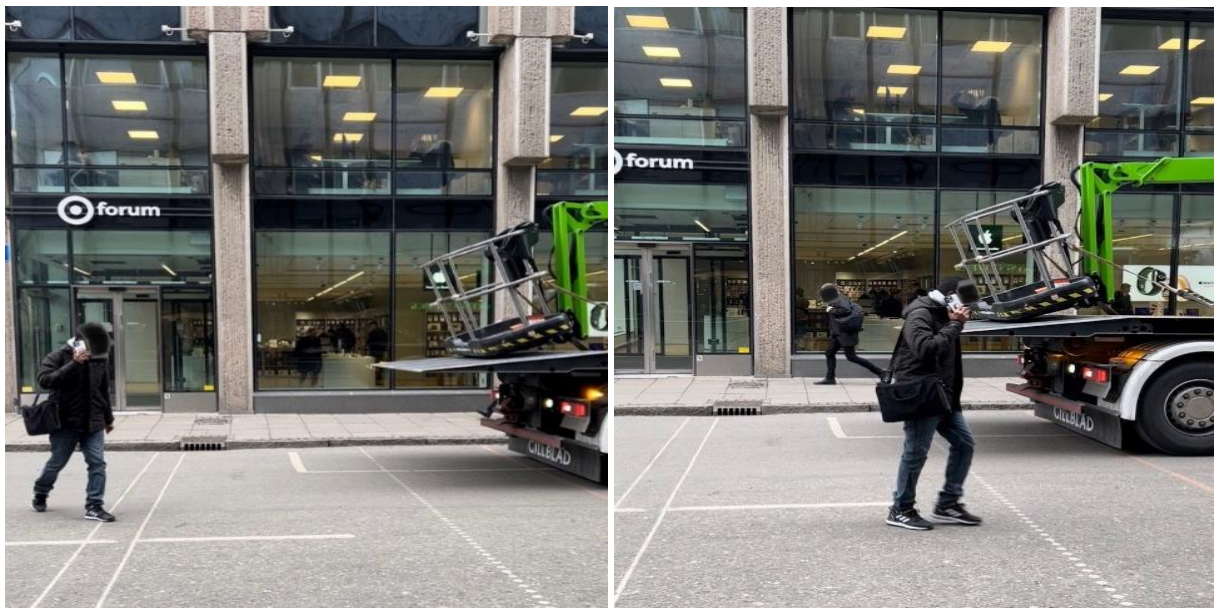


Figure 25. A pedestrian talking on the phone passes closely behind a reversing truck.

The observed adults acted differently in the situations that were spotted. Some adults illustrated risk-taking behaviour. Figure 25 demonstrates an adult who passes close to a reversing truck with the reverse warning activated while talking on the phone. The adult does not reflect upon the reversing truck, so the truck driver needs to take control of the situation by stopping. During the same reversing manoeuvre, the truck approaches a pedestrian crossing that must be crossed so that the truck driver can complete the manoeuvre. Many people crossed the specific pedestrian crossing in both directions during the reversing manoeuvre, and the truck driver needed to stop and wait until the people had passed. When idling at a near distance from the crossing, waiting for a safe moment to finish the reverse manoeuvre, the reverse warning signals were activated. This led to some people stopping just before the crossing and waiting, and some people walked across the pedestrian crossing, resulting in a confusing situation for all involved.

Figure 26 illustrates another situation, where the adult marked in red passes behind the truck that is reversing with the reverse warning activated meanwhile the adult marked in green stops to wait. The observations confirm that adults are observant. However, they are often stressed, and in combination with being occupied with their phones, they act unobservant to their surroundings. Further, the observations confirm the previously made personas and input from the truck drivers about how adults act on the road.



Figure 26. The adult marked in red passes behind the truck and the adult marked in green stops to wait.

In the examples shown in Figures 24-26, the trucks were reversing with the reverse warning activated. However, the project group witnessed some trucks reversing without the audible reverse warning activated, even though the trucks were moving in city environments during the daytime when VRUs could be present. The reverse warnings were probably deactivated because the truck driver perceives the sound as annoying or because the truck driver has received complaints of being annoying. The observations confirm that the noise from the trucks reversing does not only cause pollution but can also decrease safety if turned off.

Another interesting observed situation was not related to a reversing truck, instead, this truck was about to drive out from one of the earlier mentioned alleys. A person talking on the phone walks out in front of the truck without making sure that the truck driver has noticed her, see Figure 27. The truck driver luckily sees the pedestrian in time and stops. The truck was appearing from behind a building, so it would most probably have appeared as a surprise to the pedestrian. However, no indication was shown that the pedestrian took action to ensure that it was safe to pass.



Figure 27. An observed pedestrian walks in front of a truck which has started its departure out of the alley.

#### 4.3.2.1 Plan for conducting a structured observation test

The results of the unstructured observations in the city environment concluded that the collected data was of good value but that the method was time-consuming. An idea arose that the observations could be controlled and, thereby, more efficient by setting up the situation with a borrowed truck from Volvo. By doing this, several reverse situations would be performed and observed at the same location during a short period. However, it was concluded by the project group that there was an imminent risk of accidents if the test had been performed, and thereby it was decided that the more structured test would not be performed.

#### 4.3.2 The audible reverse warnings influence VRUs' behaviour

One of the research questions for the project is how VRUs behave in reversing situations with trucks. Since the reverse warning is being developed, it is necessary to investigate how VRUs perceive the current audible reverse warning to develop an improved solution. By observing VRUs' reactions to the audible reverse warning, it would be possible to conduct answers to the following questions:

- Does the warning signal induce a reaction?
- How urgent is the warning signal perceived?

Before planning the observation, literature studies were conducted to see if similar observations have been performed and to find appropriate methods that can be used to observe VRUs. One particular study was found through the literature review conducted in Albuquerque, USA. The study's objective was to determine how preschool children respond to audible reversing alarms. The children were asked to walk behind a stationary vehicle twice, where the vehicle emitted a warning sound the second time. The children's responses were recorded, and the location and distance to where the response occurred were noted (Sapien et al., 2003).

#### 4.3.2.1 Planning of the test

With inspiration from the reviewed study, an observation session was planned. Since only the reactions to the sound were being investigated, it was deemed, by the group, not necessary to use a real truck for the experiment. Instead, the plan was to use speakers that *Observer 1*, 1 in Figure 28, manages from behind the corner of the main street. When a VRU approaches a marked spot 7 meters away from the corner, *Observer 2*, 2 in Figure 28, standing in front of the VRU, gives *Observer 1* a sign to turn on the warning sound. The hypothesis is that the VRU will pursue one of the following actions when approaching the corner:

- Turn head around to localise the sound
- Slow down before the intersection
- Stop before the intersection
- Do nothing

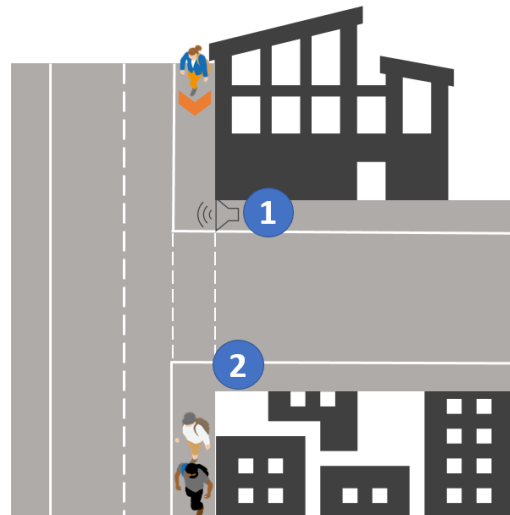


Figure 28. Planned setup of the test.

Observer 2 records the VRU on video, and the test is then repeated with another approaching VRU.

#### 4.3.2.2 Conduction of the test

The test was performed in a crossing of Torggatan and Postgatan in the central parts of Gothenburg, see Figure 29. In Figure 30, the set-up of the test can be seen. The green dot indicates the speaker's position that played the reverse alarm and *Observer 1*. The red dot indicates the position of *Observer 2*, that were to observe the reactions of the analysed VRU and give a signal to *Observer 1* to start the alarm when the VRU passed the marked blue dot. Only the VRUs that were moving in the direction of the yellow arrow were observed in this test. *Observer 2* recorded the analysed VRU with a mobile phone to enable a later and more accurate analysis of the behaviour. The sound was turned off when the VRU had passed the crossing. The observations were performed on both single VRUs and pedestrians that walked in a group or closely behind each other. The time duration of the test was 20 minutes to avoid too many disturbances for the people located in the buildings close by. The test was performed two times on two different days since most of the persons observed during the first test were teenagers and the project group wanted to complement the results with more data.

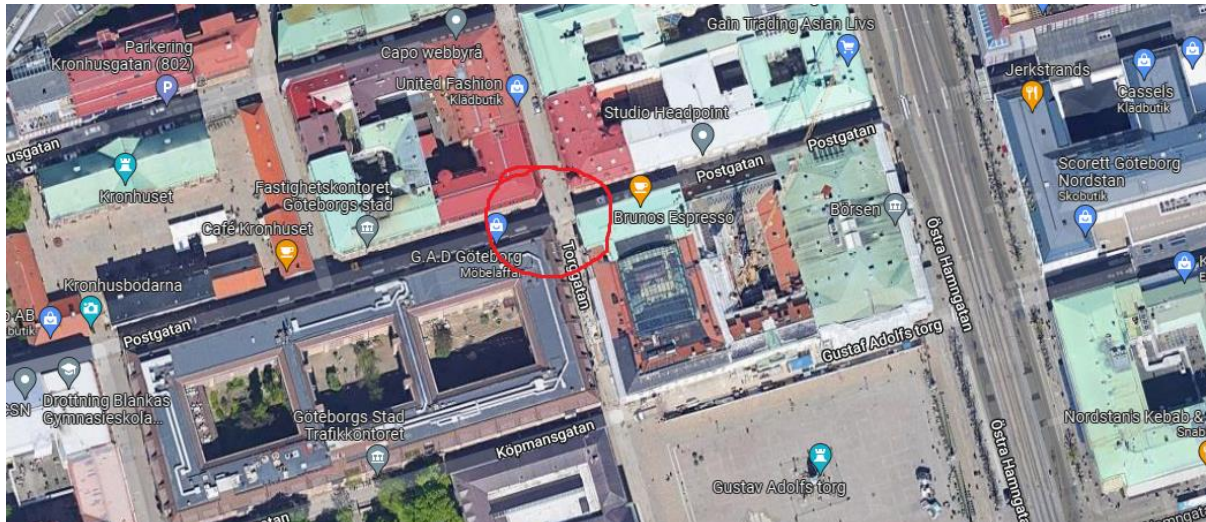


Figure 29. Map of Gothenburg city centre where the test was performed.



Figure 30. Test set-up.

#### 4.3.2.3 Result and analysis of the first test

During the tests, 114 VRUs were spotted and analysed. To evaluate if different VRUs behave differently depending on age, the stated personas were used, i.e., child, teenager, adult, and senior. Bicyclists were also chosen to be a separate category. An analysis of the spotted VRU's behaviour could be done from the video recordings taken at the test site. The VRU's behaviour was evaluated in terms of four different actions that the VRU could make when the sound was turned on, as earlier mentioned. These actions were, no response, look, slow down, or stop. Table 6 shows the result of the analysed behaviour of each category. Most spotted VRUs were to be categorised as teenagers. The majority of the VRUs, i.e., 51% looked before passing the corner, 45% did not induce any reaction and walked straight out in the crossing. The results indicate that the warning signal is not perceived as very urgent, based on the actions taken by the VRUs.

Table 6. Results from test of audible reverse warning.

Persona	Quantity	Action			
		No response	Looks	Slows down	Stops
Child	1		1		
Teenager	65	34	31		
Adult	42	17	22	3	
Senior	4		3		1
Bicyclist	2		1	1	
Total	114	51	58	4	1
Total (%)		45	51	4	1

#### 4.3.2.4 Planning of the second test with a real truck

As mentioned, a test with a real truck was planned to evaluate VRUs' behaviours when present around a reversing truck, but the test was never performed because of safety aspects. However, a test where a truck borrowed from Volvo, standing still with the reverse warning activated, was believed to be a safe option to test VRUs' behaviours when approaching a vehicle that indicates to reverse. This was deemed a more realistic set-up than the test presented above. However, an issue arose when planning the test. An area where the truck could stand still without blocking traffic, where many people pass and where they need to walk behind the vehicle was required to be found. In addition, the audible reverse warning signal would need to be emitted for an extended period without disrupting other people too much. Some suitable areas were found, but it was then realised that a special permit was needed or trucks were restricted from the area. Because of this, the test was not performed.



# Chapter 5

## Concept generation

“A product concept is an approximate description of the technology, working principles, and form of the product.” (Ulrich et al., 2020, p.122). This chapter presents the methodology and results from the activities performed to generate concepts. To begin with, a target requirements specification is developed. Then, concepts are generated using both systematic and creative methods.

## 5.1 Concept generation approach

An overview of the taken approach can be seen in Figure 31 where the dark blue boxes refer to the concept generation approach and the grey boxes refer to the later concept evaluation approach and the final approach which is presented in Chapter 6 *Concept evaluation*, Chapter 7 *Adaptive reverse warning* and Chapter 8 *Final concept*. A further description of the concept generation process will be given in the forthcoming sub-chapter.

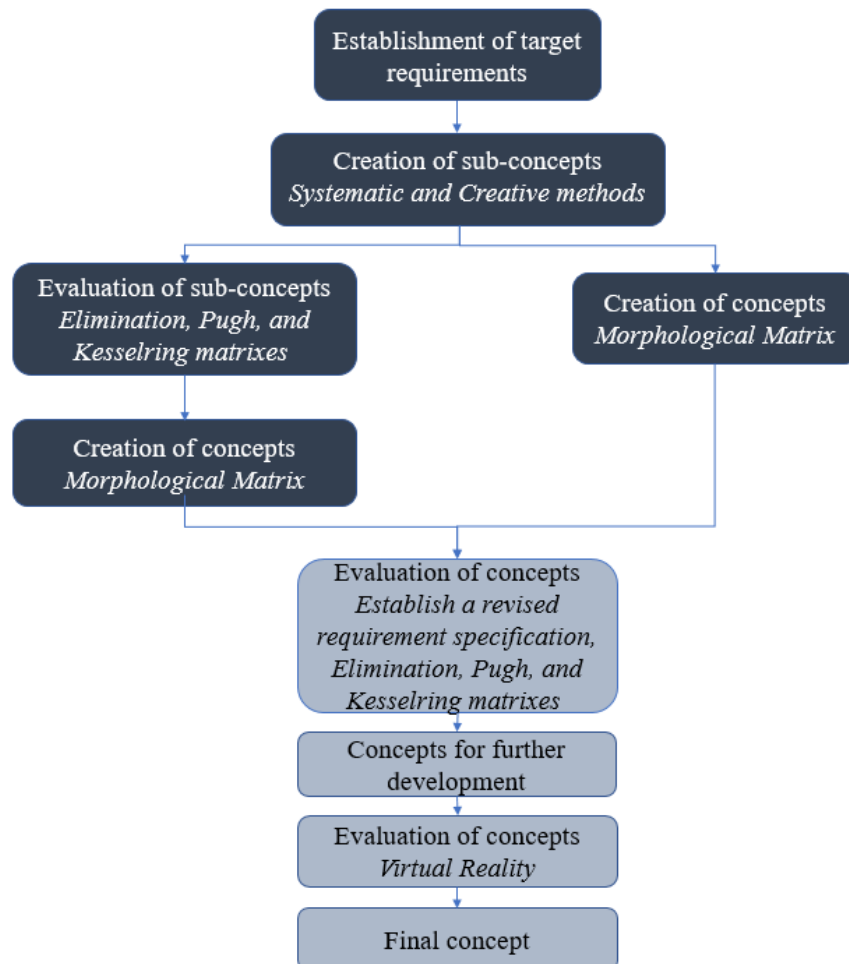


Figure 31. An overview of the concept generation and evaluation approach.

## 5.2 Establishing a target requirements specification

Before entering the concept development phase, the suggestion is to establish a requirements specification. The specification gives direction in the concept generation process and provides information for the later concept evaluation (Roozenburg & Eekels, 1995). When establishing a requirements specification, the problem formulation can be used as a starting point when generating requirements. Experience, information, and needs from customers and other stakeholders are collected to gather requirements from the various stakeholders, such as internal requirements, customer needs, and legal requirements (L. Almefelt, personal communication, January 20, 2021). Ulrich et al. (2020) recommend establishing target requirements early in the development process that should later be revised in iterations as new information and knowledge are gained. Finally, the final specifications can be set, and the product can be verified.

Furthermore, Ulrich et al. (2020) state that the requirements should not explain how to design the product but express what the product must fulfil. The goal is to describe each requirement

with at least one metric, even though assigning a quantifiable metric for all requirements might not be possible. Each requirement with related metrics is rated on its importance on a scale from one to five to ease the prioritisation and ensure the realisation of the most critical requirements. According to L. Almefelt (personal communication, January 20, 2021), a verification method should be assigned to all requirements to evaluate the fulfilment of the requirements and a stated justification.

This thesis work will follow a combination of the recommendations presented above. The target requirements are presented in this chapter, and the revised final targets are presented in the following chapter.

### 5.2.1 Target requirements specification

When establishing the initial requirements specification, the problem formulation of the project was used as a starting point. The problem formulation states that a reverse warning that improves the safety of VRUs and decreases noise pollution should be developed. The requirements derived from the problem formulation are presented in the target specification, see Table 7. In addition, further requirements were identified internally by the project group. Each requirement was assigned a metric that the project group considered suitable. The purpose of developing a target specification was to use the target requirements when performing the first concept elimination activities presented in this chapter. The specification was later revised when new data had been collected through, e.g., interviews and extended literature research.

Table 7. Target requirement specification. *D* stands for demand and *W* stands for wish.

Requirement	Metric	Importance	D/W	Justification	Verification
1. The warning signal should be interpreted as a warning.	>80% of participants interpret the signal as a warning	5	D	Problem formulation	Survey, VR-test
2. The warning signal should be interpreted as emitted from a vehicle.	>50% of participants interpret the signal as emitted from a vehicle.	5	D	Problem formulation	Survey, VR-test
3. The warning signal should be interpreted as emitted from a reversing vehicle.	>30% of participants interpret the signal as emitted from a reversing vehicle.	3	D	Problem formulation	Survey, VR-test
4. The warning signal does not disrupt another road user's view.	Yes/No	5	D	Internal	Binary
5. The warning signal does not emit materials during use.	Yes/No	2	D	Internal	Binary
6. The sound should be environmentally acceptable.	Participants perceive the warning signal as not irritating.	4	W	Problem formulation	Survey

## 5.3 Systematic concept generation

When generating concepts, there must be a general understanding of the problem. Here the identified customer needs and set target specifications are helpful to be able to generate product concepts (Ulrich et al., 2020). When the problem is defined, and in some cases, even divided into smaller sub-problems, Ulrich et al. (2020) recommend searching for a solution both internally and externally. The external search aims to find existing solutions, which is often the most resource-efficient approach. The external research relates to the systematic methods that L. Almefelt (personal communication, January 18, 2021) also presents: literature and patent research, interviewing users and experts, and benchmarking existing similar products.

The approach to generating concepts for this thesis work was to start with a combination of systematic concept generation methods. The purpose of the systematic concept generation was to collect external and internal information that would serve as an input to the creative concept generation methods and directly serve the project with possible solutions on the market.

### 5.3.1 Concepts generated through Benchmark

The first activity in the systematic approach was to perform benchmark analyses, see Sub-chapter 3.2 *Benchmark*, which yielded insight into what solutions of reverse warnings exist on the market. For instance, the bespoke message alarm was found through the benchmark analysis, which inspired the generation of the speaking alarm concepts in the later concept generation process.

### 5.3.2 Concepts generated through patent search

Patents were also reviewed, see Sub-chapter 3.3 *Patents*, to evaluate the intellectual property rights needed to be considered in the project. The patent search was also inspired to take further into the creative concept generation process. The patent “Prevention of collision with radio signals” (see Sub-chapter 3.3.1.8 *Prevention of collision with radio signals* for patent description) was further processed as a concept to evaluate.

### 5.3.3 Further literature research

The performed literature study presented in Chapter 2 *Theoretical framework* was valuable input to the concept generation. YouTube has also been a useful tool to listen and gather inspiration from different types of sounds that could be used as a warning signal.

## 5.4 Creative concept generation

After the systematic concept generation, concept generation activities with more creative characteristics were performed. The output from the earlier concept generation was used as an input. Further the creative approach will be presented.

### 5.4.1 Creative concept generation through Brainstorming

The internal search presented by Ulrich et al. (2020) relates to the creative methods suggested by (L. Almefelt, personal communication, January 18, 2021), where brainstorming is one of the most common methods. Brainstorming serves to generate many creative concept ideas, where the goal is to welcome “crazy” proposals and not be limited by feasibility. The output from the systematic concept generation and outputs from observations, personas, and market segmentation were used as inputs to the creative concept generation process. The initial

creative concept generation approach was to perform five brainstorming sessions where the focus was to generate concepts of different warnings that call for the attention of each human sense, i.e., hearing, vision, touch, smell, and taste. However, the sense of taste was eliminated before the brainstorming session since it was considered not to be reasonable, and therefore only four sessions were performed.

The first brainstorming session aimed to generate concepts that intend to warn VRUs of a reversing truck visually. The participants had access to A3 papers, papers with a picture of a truck, and pens. A timer was set to 10 minutes. During this time, the participants sketched and wrote as many ideas as possible without talking. When the 10 minutes were over, each participant presented their concept ideas. Then another 10 minutes of sketching was performed, where the participants could continue with the idea that earlier was presented or add new concept ideas. This brainstorming session resulted in many sub-concepts, some of which can be seen in Figure 32. The same approach was used to generate concepts that warn through touch and smell. When generating sub-concepts related to sound, ideas could be written on paper or visualised with the help of YouTube. The four brainstorming sessions resulted in many sub-concepts. However, the idea of calling for the attention of the VRUs with the help of smell might be, in theory, a possible complement to other warning signals. However, all the concepts involving an emitted smell were eliminated. There were several reasons for this. The concept would require a refill on the smell, which the truck driver would need to maintain. To ease this work for the driver, some type of indication on the dashboard must exist to signal the need for a refill. There is also a risk that the emitted smell would linger in the area where the truck has been, even after the reversing situation is performed, leading to a false alarm. Some smells, like fire or petrol, might be too alerting and associated with situations of more severe danger than a reversing truck, making it difficult for the VRU to differentiate what the smell is signalling. The remaining generated concepts for sound, visual and touch were taken further as an input to the Morphological matrix that will be presented in the upcoming sub-chapter.

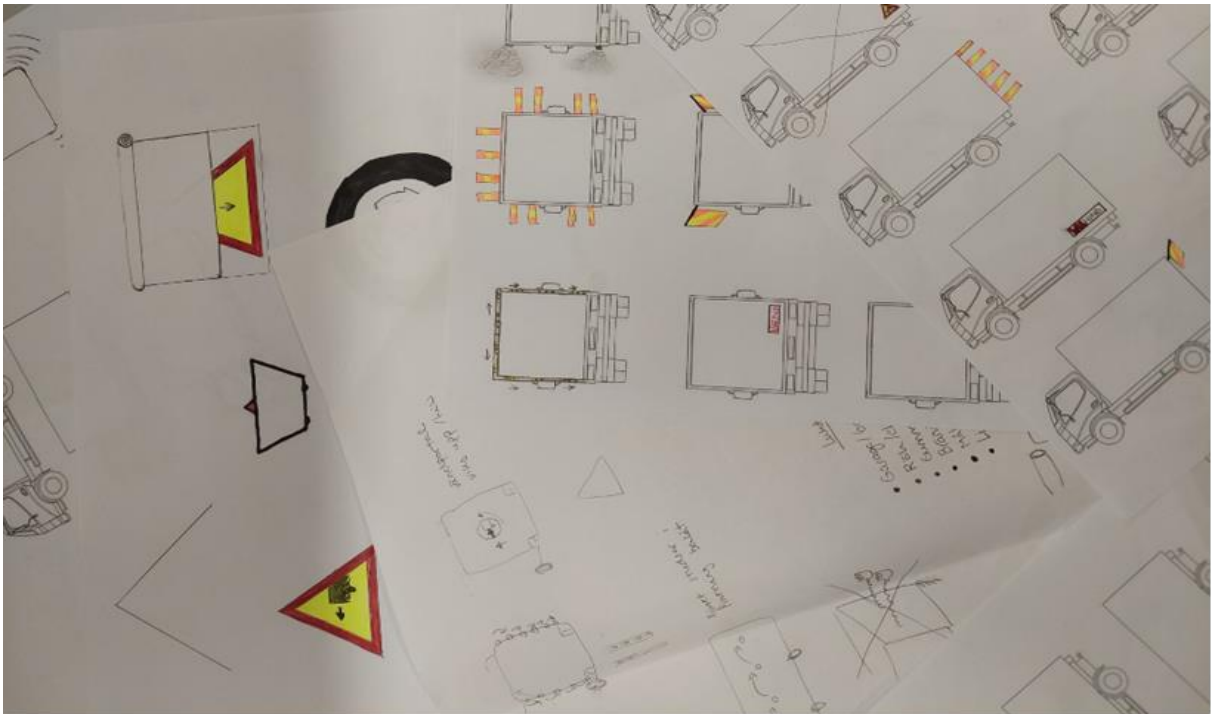


Figure 32. Some of the sketched brainstormed ideas.

## 5.5 The theme-based Morphological matrix

The generated concepts for each sense were initially viewed as sub-concepts that could be combined using a Morphological matrix. A Morphological matrix can be a helpful tool when generating concepts for complex products with several sub-functions. Sub-functions are specified, and through, for example, brainstorming, several solutions for each sub-function can be generated. After that, a matrix is created where the solutions for the different sub-functions can be combined, resulting in multiple possible concepts (L. Almfelt, personal communication, January 18, 2021).

The subfunctions created for the Morphological matrix correlate with the themes from the brainstorming session, i.e., warn through hearing, vision, touch, and smell. The four sub-functions specified were to *warn visually from the rear*, *warn visually from the side*, *warn audibly*, and *warn through touch*. The generated sub-concepts were then inserted under the corresponding sub-function. Figure 33 presents the generated solutions for warning visually on the rear of the truck, Figure 34 presents the generated solutions for warning visually on the sides of the truck, Figure 35 presents the generated concepts for warn audibly, and Figure 36 presents the generated solutions for warning by touch.

Combining all sub-concept in the matrix would result in 12 960 possible concepts, which would be an overwhelming and non-realistic number of concepts to evaluate and systematically eliminate. Additionally, the project group saw the possibility of combining sub-concepts within the same sub-function, which would result in even more possible concepts. To find a proper way of massively reducing the number of possible concepts, the Chalmers supervisor for this thesis work, Lars Almfelt, was consulted. The initial plan for reducing the number of possible matrix combinations was to perform severe eliminations of the generated sub-concepts using an Elimination matrix before proceeding with the Morphological matrix. However, this approach might risk that some concepts are eliminated too fast because there might exist sub-concepts that would be of reason to eliminate; however, in combination with another sub-concept, it would prosper and benefit from synergy. L. Almfelt (personal communication, Mars 3, 2022) suggested that concepts could be reduced in two ways, following the more structured initial plan of extensive elimination of sub-concepts or stating different themes where sub-concepts from the Morphological matrix would be chosen and combined. The optimal approach would be to perform both activities and later evaluate all the generated concepts, which was the chosen method for this project. First, the theme-based approach was performed, using the generated sub-concepts from the earlier brainstorming sessions.

Lamps with flashing light	Lamps with travelling light	LED strips with pulsating light	Warning triangle that illuminates when reversing	Foldable warning triangle	Slidable sign with reversing truck
Rotating sign with reversing truck	Sign on blind	Scrolling text "WARNING REVERSING"	Projection on ground	Laser on ground	Visual notification from phone/watch
Spotlights on top	Sign changes color to red when reversing	Flags	Serpentines	Jack in the box	Smoke

Figure 33. Solutions for how to warn visually on the rear of the truck.

Lamps with flashing light	Lamps with travelling light	LED strips with pulsating light	Warning triangle that illuminates when reversing	Foldable warning triangle	Slidable sign with reversing truck
Rotating sign with reversing truck	Sign on blind	Scrolling text "WARNING REVERSING"	Projection on ground	Laser on ground	Visual notification from phone/watch
White reversing light on the side	Arrows that show the wheel direction	Arrows that light up			

Figure 34. Solutions for how to warn visually on the sides of the truck.

Tonal sound	Broadband sound	One-third octave band sound	Auditory icon	Earcon	Speaking: recorded warning message
Speaking: driver interacts	Audible notification from phone/watch				

Figure 35. Solutions for how to warn audibly.






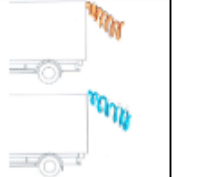
Pressure waves	Vibrating alarm from phone/watch	Truck creates vibrations in ground	Soft stick that unfolds and hits the VRU	Water that sprays	Warm/Cold air
					

Figure 36. Solutions for how to warn by touch

### 5.5.1 Concepts generated by theme approach

The chosen themes used to generate concepts through the created Morphological matrix were based on the stated personas, technical level, level of clarity, and hearing and visual impairment. Sub-concepts that, by the project group, were believed to be best suited for each specific theme were chosen and combined with other sub-concepts solutions of the specified functions. Some theme-generated concepts were structured to consist of one or more sub-concepts from each sub-function. The generated concepts are presented below.

#### 5.5.1.1 Clarity

The concept "Clarity" is a concept that uses clear signals to indicate that the truck is reversing. The visual signals consist of an illuminating warning triangle on the rear of the truck and illuminating arrows that point in the direction of the truck's intended pathway on the sides of the truck. A spoken alarm is chosen as the audible signal as it is considered clearer to hear a verbal message that describes an action than to hear a non-verbal sound. However, this presumes that the announced message is in a language the receiver understands. Otherwise, the clarity is greatly reduced. The soft stick that unfolds from the truck and hits the VRU was chosen to be the clearest warning signal that warns by touch. Figure 37 shows a sketch of the concept.

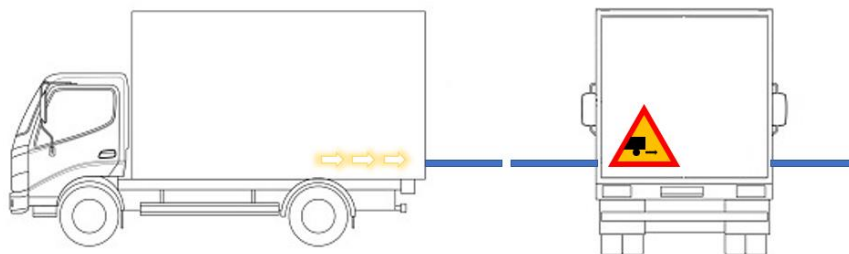


Figure 37. Concept Clarity.

### 5.5.1.2 Abstract

The concept "Abstract" uses abstract signals to indicate that the truck reverses. The visual signals consist of lamps where the lights follow a specific pattern. On the truck's rear, the light travels from the top to the bottom, and on the sides of the truck, the light travels from the front to the back. The travelling lights show the truck's intended pathway. A broadband alarm is selected as an audible warning signal, and vibrations in the ground are selected to warn the VRUs by touch. Figure 38 shows a sketch of the concept.

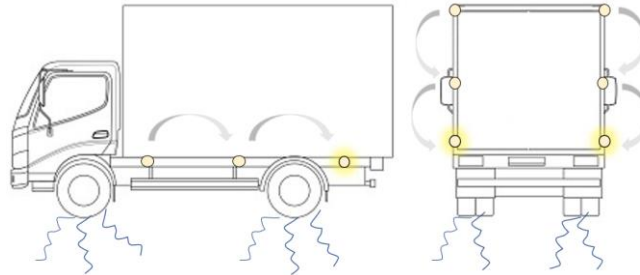


Figure 38. Concept Abstract

### 5.5.1.3 High-tech

"High-tech" is a concept that consists of sub-solutions that require a high level of technicality. The visual signals consist of projections on the ground, both on the rear and sides of the truck. In addition, a visual signal is sent to the VRU's phone. The VRU is notified audibly by an audible signal sent to the VRUs phone and a speaking alarm emitted from the truck. A vibrating phone alarm and vibrations in the ground are selected to warn the VRUs by touch. Figure 39 shows a sketch of the concept.

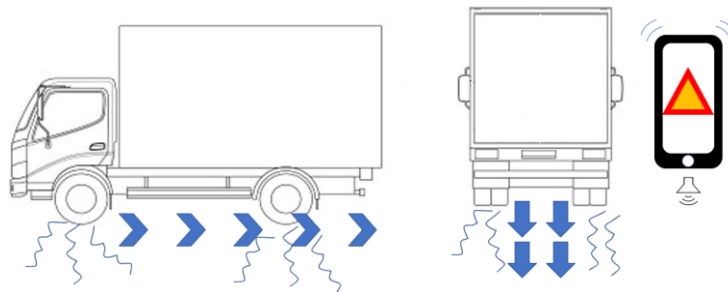


Figure 39. Concept High-tech

### 5.5.1.4 Low-tech

"Low-tech" is a concept that consists of sub-solutions that require a low level of technicality, as opposed to the "High-tech" concept. The visual signals consist of lamps with flashing lights on the truck's rear and lamps with continuous lights on the sides of the truck. A tonal alarm is chosen to warn audibly, and warm or cold air is chosen to warn the VRUs by touch. Figure 40 shows a sketch of the concept.

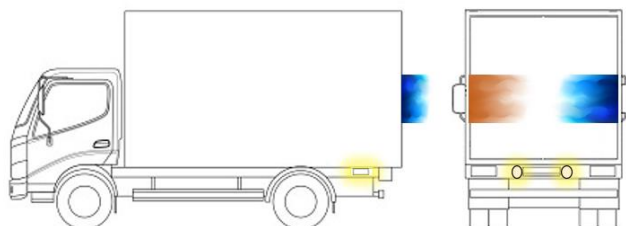


Figure 40. Concept Low-tech

### 5.5.1.5 Child

The concept "Child" consists of warning signals selected to warn children. Children are taught to stop at red traffic lights and only pass green traffic lights. With inspiration from the traffic lights, a sign that changes colour from green to red is selected on the truck's rear. On the side of the truck, lamps with light that travels from the front to the back are chosen to signalize the truck's intended pathway. The speaking alarm is selected as an audible signal, and soft sticks that unfold are selected to warn by touch. Figure 41 shows a sketch of the concept.

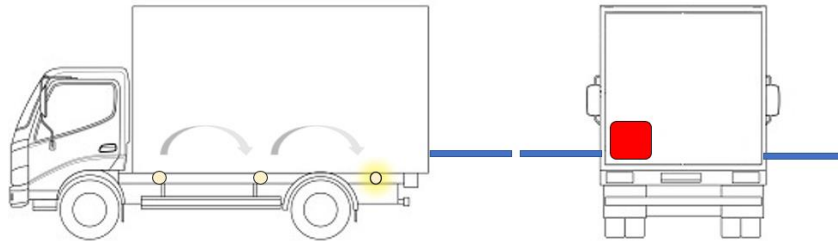


Figure 41. Concept Child.

### 5.5.1.6 Senior

Older people generally have reduced vision and hearing. Therefore, sub-concepts with clear warning signals are selected for the concept "Senior". Pulsating serpentine flags on the rear of the truck and illuminating arrows on the truck's sides are selected as visual signals. The one-third octave band sound is selected as an audible signal since it allows the sound to be emitted in several frequencies simultaneously. Further, pressure waves are selected to warn by touch. Figure 42 shows a sketch of the concept.

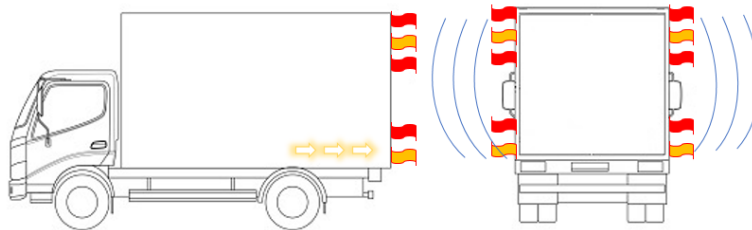


Figure 42. Concept Senior.

### 5.5.1.7 Adult

The concept "Adult" was believed not to need to be as clear as the concepts for children and seniors. Lamps, with light travelling from the top to the bottom on the truck's rear and from the front to the back on the truck's sides, are chosen as visual signals. The broadband alarm is chosen as an audible signal. The selected sub-concepts are combined with signalling VRUs nearby the truck with a visual, audible, and vibrating alarm in the VRUs phone. Figure 43 shows a sketch of the concept.

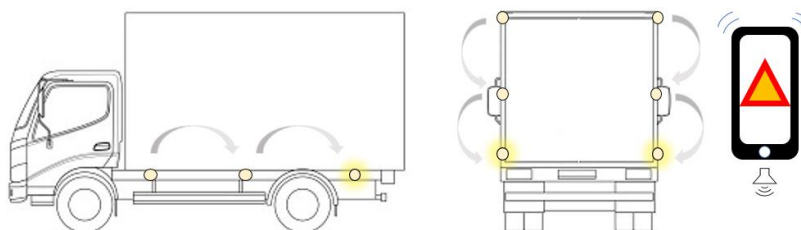


Figure 43. Concept Adult.

### 5.5.1.8 Teenager

The teenager theme was chosen to be quite like the adult theme, but with some increase in perceived alertness. The visual signals are the same as the adult theme concept, i.e., travelling light and signals sent to the phone. A tonal alarm is selected to warn audibly, and pressure waves are selected to warn the VRUs by touch. Audible and vibrating signals are also sent to VRU's phone. Figure 44 shows a sketch of the concept.

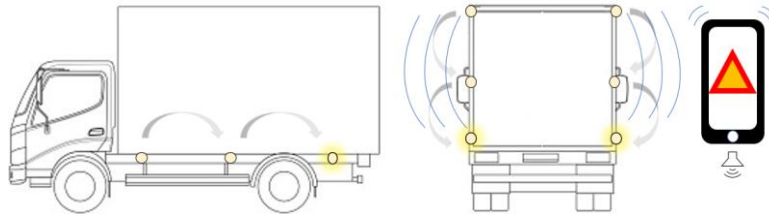


Figure 44. Concept Teenager.

### 5.5.1.9 Bicyclist

The initial perception is that bicyclists move faster than pedestrians and require warning signals that can be spotted from a distance. Therefore, LED strips with pulsating light emitted from top to bottom on the truck's rear and from front to back on the truck's sides are selected as visual signals. In addition, a warning triangle that illuminates when reversing is added to the rear of the truck. A tonal alarm is selected to warn audibly, and pressure waves are selected to warn by touch. Figure 45 shows a sketch of the concept.

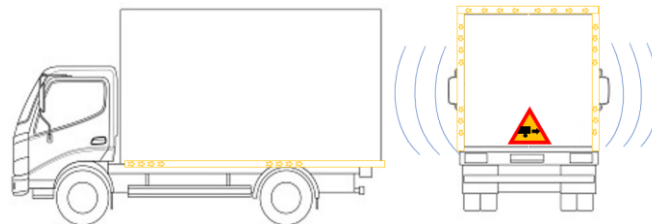


Figure 45. Concept Bicyclist.

### 5.5.1.10 Hearing loss

The concept "Hearing loss" focuses on people with hearing losses that depend more on visual impressions, so multiple visual signals are selected for this concept. On the truck's rear, a warning triangle is projected on the ground, and lamps with flashing lights are mounted. The visual signals on the truck's sides consist of a foldable warning triangle and lamps with travelling lights. The one-third octave band sound is chosen as an audible signal, and a vibrating signal is sent to the VRU's phone, indicating the presence of the reversing truck. Figure 46 shows a sketch of the concept.

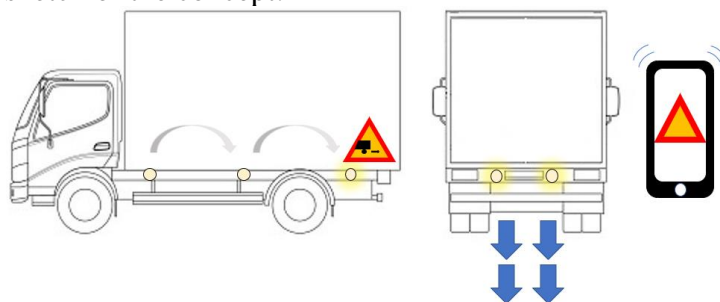


Figure 46. Concept Hearing loss.

#### 5.5.1.11 Visual impairment

The concept “Visual impairment” focuses on warning signals that can warn VRUs with visual impairment, so the visual signals selected are exaggerated. Pulsating serpentines and flashing lights are selected as visual signals on the rear and sides of the truck. A combination of a broadband alarm and a speaking alarm is selected to warn audibly, and vibrations in the ground and emission of warm or cold air are selected to warn by touch. Figure 47 shows a sketch of the concept.

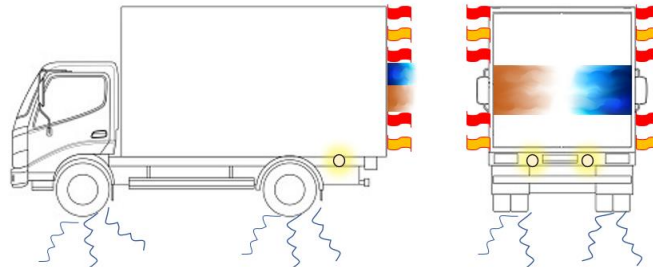


Figure 47. Concept Visual impairment

#### 5.5.1.12 Construction

Construction workers are often exposed to hectic environments with high noise levels. Attentive visual signals consisting of lamps with travelling lights and spotlights are selected on the truck’s rear, and LED strips with pulsating lights are selected on the truck’s sides. A broadband alarm is selected to warn audibly, and pressure waves are selected to warn by touch. Figure 48 shows a sketch of the concept.

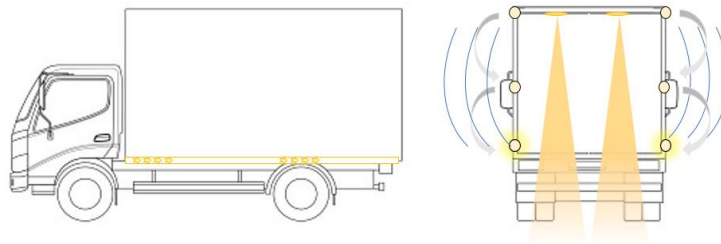


Figure 48. Concept Construction

### 5.6 The elimination-based Morphological matrix

The elimination-based Morphological matrix effectively reduces the number of sub-concepts before proceeding further with the Morphological matrix, thereby reducing the number of possible combinations. This approach aimed at eliminating the number of sub-concepts to the point where the method of the Morphological matrix would be possible to perform, i.e., all sub-concepts should be combined, and all the generated concepts should be evaluated (Ulrich et al, 2020). Methods of evaluating concepts with matrices are beneficial since the decision process is documented, the decisions taken will be based on the requirements and criteria that are set for the product, and the matrices often give a good overview of the results (L. Almfelt, personal communication, January 18, 2021).

The chosen evaluation matrices in this project are the Elimination matrix, Pugh matrix and Kesselring matrix, which are recommended by L. Almfelt (personal communication, January 18, 2021) to ensure a concept evaluation with different perspectives. Further, the process of evaluating and eliminating sub-concepts is presented, where all generated sub-concepts within visual warning signals and warning signals through touch will be evaluated. Since the generated sub-concepts of sound were only brainstormed ideas of different types of sounds, e.g., an auditory icon, and not a specified sound, the project group deemed it challenging to

perform the different evaluation matrices. It was also believed to be more challenging to evaluate sounds in general by performing matrices. Therefore, a decision was made not to evaluate the sub-concepts regarding sound ideas in this stage. As a result, the generated concepts through the elimination-based Morphological matrix would not consist of sounds until specific sound concepts had been developed and evaluated by external reviews, which will be presented in Sub-chapters 5.7 *Creation of sound concepts* and 5.8 *Creation of survey to collect external opinions of the created sound concepts*.

### 5.6.1 Elimination matrix

The first step in the concept evaluation and decision-making phase is eliminating inferior concepts that do not fulfil all needs and requirements. In an Elimination matrix, the set criteria and concepts are listed. The listed criteria could be: the concept solves the main problem, fulfils all demands, is compatible, is safe, fits the portfolio, and can be realised at a reasonable cost. Each concept is checked against the criteria and assigned a plus (+) if fulfilled, a minus (-) if not fulfilled, and a question mark (?) if more information is needed. If a concept does not fulfil one or more criteria, the concept will be eliminated (L. Almefelt, personal communication, January 18, 2021). The method would be a very strong filter, which would be beneficial in this project to reduce the generated sub-concepts extensively.

The created Elimination matrix assessed all sub-concepts regarding visual and touch warning signals. The chosen criteria where the concept solves the main problem, i.e., interpreted as a warning signal, fulfils all demands, i.e., the specified requirements, is compatible, is safe, fits Volvo's product portfolio, and can be realised at a reasonable cost.

#### 5.6.1.1 Elimination matrix on the created visual signals

Twenty-two concepts of visual warning signals were inserted into the Elimination matrix, and nine concepts were deemed valid for further development. Concepts such as the *Foldable Warning Triangle* and the other warning-triangle concepts were eliminated due to not fitting the product portfolio. Concept *Smoke* was eliminated due to the risk of endangering road users because of deteriorated vision conditions and being too attentive. The Elimination matrix can be seen in Appendix A where a comment on the reason behind each eliminated concept can be found.

Lamps with travelling lights, LED strips with travelling lights, lamps with flashing lights, flags, projections on the ground, spotlights, a sign that changes colour, and continuous lights, were the concepts that successfully made it through the matrix and were taken on further in the evaluation process.

#### 5.6.1.2 Elimination matrix on the created touch signals

Seven concepts of warning signals that warn by touch were inserted into the matrix. However, none of the concepts was taken for further development. All concepts were deemed not to fulfil one or several of the criteria. The fulfilment of demands refers to the initial requirement specification presented in Table 7. The matrix can be seen in Table 8.

Table 8. Elimination matrix of the concepts regarding touch.

Solution alternative	Criteria						Criteria fulfilment: (+) Yes (-) No (?) More info needed (!) Check with specification	Decision: (+) Continue (-) Remove (?) More info needed (!) Check with the specs
	Solves the main problem	Fulfils all demands	Compatible/Realizable	Reasonable cost	Safe	Fits portfolio		
	Pressure waves	+	+	-	-	+	+	Not realisable
Phone vibration	+	+	-	-	-	+	Not realisable, irritating	-
Vibrations in ground	+	?	-	-	?	?	Expensive or not reasonable size on the solution to create vibrations.	-
Soft stick	+	+	+	+	-	-	Even though the stick will be in a soft material, it could hurt someone if it hits wrong	-
Spraying water	+	-	-	?	-	-	People will not enjoy being sprayed with water, space-consuming, and emits material (water) during use.	-
Spraying water on specific VRU	+	-	-	-	-	-	People will not enjoy being sprayed with water, space-consuming, and emits material (water) during use.	-
Warm/cold air	+	?	-	-	+	-	Expensive, space-consuming and not sustainable (high energy use)	-

### 5.6.2 Development loop of the generated concepts

After the performed Elimination matrix, the remaining visual concepts were reviewed in a concept development loop. A discussion was held if there were concept ideas that could be developed before proceeding further. Regarding the visual warning signals, a decision was made to develop the pulsating LED strips. The idea was to add two more functions, continuous light and flashing light, to the sub-concept. Another idea that arose was developing all concepts consisting of physical warning triangles that were eliminated due to not fitting the portfolio. The idea was to merge the eliminated concepts with the *Projection on the ground* concept. The initial plan for the *Projection on the ground* concept was that the projections would be arrows, which would indicate the direction of the truck. However, it was believed that a projected warning triangle would be even more informative and maybe call for more attention to the VRU. The reviewed and developed sub-concepts are visualized in Figure 49 and taken further into the concept screening.

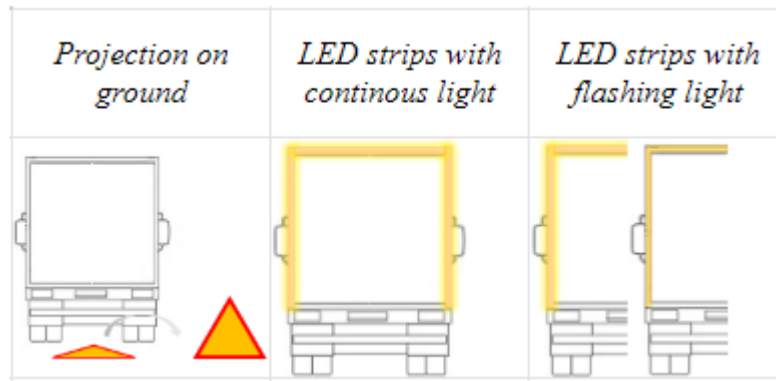


Figure 49. Concepts generated through development loop.

### 5.6.3 Concept screening using the Pugh concepts selection method

The Pugh concept selection method, also called the Pugh matrix, serves the purpose of screening concepts quickly and enables visual comparison of the screened concepts. The first step in the screening stage is to prepare the Pugh matrix by listing the concepts and selection criteria. The next step is to select one of the concepts as the reference concept. The concepts are then evaluated by comparing the concepts' fulfilment of criteria to the reference concept's fulfilment of criteria. The concept is assigned a plus (+) if being better than the reference, zero (0) if same as the reference, and minus (-) if worse than the reference. After the rating, the pluses, minuses, and zeros should be summarised, and a net score for each concept should be calculated. The last step is to rank the concepts, and the concepts that are ranked high should be taken for further investigation and development. However, it is not enough to only evaluate with the Pugh matrix once; the recommendation is to perform an evaluation with several different reference concepts and then compare the results before deciding. Attributes from other concepts could also be combined to develop new concepts that should be included in the further evaluations with the Pugh matrix (Pugh, 1990; Ulrich et al., 2020).

#### 5.6.3.1 Pugh matrix on the created visual warning signals

In the first iteration of the Pugh Matrix, an ordinary reversing light was chosen as the reference concept to indicate how the concepts perform compared to the current solution. In this case, the current solution was ranked number one due to its simplicity and low cost. The signal is also well-known and strongly associated with a reversing vehicle. However, several concepts were rated better than the current solution concerning interpretation as a warning signal, which shows that combining the current solution and an additional visual warning would be beneficial.

Travelling lights were chosen as the reference concept in the second iteration. The sub-concept of *Continuous light* was ranked higher because it is believed to be less annoying than a flashing light.

In the third iteration, a LED strip with continuous light was chosen as the reference concept and was ranked as the third-best concept. Continuous light by separate lamps, travelling light and headlights were ranked higher than the reference. Install separate lamps is argued by the project group to be more easily installed since fewer attachment points would be needed. Maintenance is also deemed to be easier since only one component will have to be changed and not the whole strip, this also affects the reliability of the solution.

The sub-concepts *Flags* and *Projection* were in all three iterations rated low, which would indicate that these would not be valid to develop further.

#### 5.6.4 Concept scoring with the Kesselring matrix

Concept scoring with the Kesselring matrix was the last step in the concept evaluation. During an evaluation with the Kesselring matrix, the relative importance of the selection criteria is weighted, and the concepts are rated against each criterion. The first step is to prepare the Kesselring matrix by listing the concepts and the selection criteria in the matrix, and weighing the criteria, usually on a scale from one to five. The next step is to rate the concepts for how well they fulfil each criterion on a scale from one to five. When all concepts have been ranked, the rating of each criterion is multiplied by the relative importance of the criterion. The last step is to summarize the criteria scores for all concepts and rank the concepts. After internal discussions and consideration of the ranking results, selected concepts are taken further for development. After the concepts have been further developed, an evaluation with the Kesselring matrix can be performed again to narrow down the concepts further (L. Almefelt, personal communication, January 18, 2021).

##### 5.6.4.1 Kesselring Matrix on the created visual signals

The weighted criteria, ideal value, and targeted value can be seen in Table 9. The criteria *interpreted as a warning* and *visible day and night* were weighted high since these criteria must be fulfilled to ensure that the signal works as a warning signal and can be seen. The criteria *interpreted as a reverse warning* and *low space consumption* were weighted second most important. It would be beneficial if the warning were to be registered by the VRU and be understood as a reverse warning, as this would enable quicker and more accurate action. There is also limited space on the truck and many components that must fit, so the solution must take as little space as possible. *Low cost, easy installation* and *high reliability* were rated low in this matrix, not because these criteria are of low importance for the final product, but because in this project, the focus is on developing the concept with an optimal solution for warning VRUs of a reversing truck.

As a result of the performed Kesselring matrix for visual warning signals, the concept *Travelling light* was ranked as number one, *Continuous light* as number two, and *Flashing light* as number three, see Table 9. However, similar solutions with LED strips had results close to the top three ranked solutions but were decided not to be further developed. The project group decided to take concept *Projections on the ground* for further development even though the concept had been rated low in the matrix. The concept was believed to have been evaluated under unfair circumstances due to its questionable visibility in daylight. The matrix can be seen in its entirety in Appendix B.

Table 9. Parts of the Kesselring matrix performed on the created visual signals.

		Solution alternative							
		Ideal		Continuous light		Travelling light		Flashing light	
Criterion	W	V	T	V	T	V	T	V	T
Interpreted as a warning	5	5	25	3	15	4	20	5	25
Interpreted as reversing	4	5	20	4	16	4	16	3	12
Visibility in the day	5	5	25	4	20	4	20	4	20
Visibility in the night	5	5	25	5	25	5	25	5	25
Low cost of product	2	5	10	4	8	4	8	4	8
Easy installation	2	5	10	4	8	4	8	4	8
Easy maintenance	3	5	15	5	15	5	15	5	15
Low annoyance	3	5	15	5	15	4	12	4	12
High reliability	2	5	10	5	10	5	10	5	10
Low space consumption	4	5	20	4	16	4	16	4	16
<b>T=∑T<sub>j</sub></b>		175		156		158		151	
<b>T/T<sub>max</sub></b>		1		0,891428571		0,902857143		0,862857143	
<b>Ranking</b>				2		1		3	
<b>Further development</b>				Yes		Yes		Yes	

### 5.6.5 Morphological matrix on visual warning signals

After extensive evaluation and elimination, most sub-concepts were rejected. The final sub-concepts were four different visual warning signals on the side of the truck, three visual warning signals on the rear side of the truck, and three different sounds. A decision was made to not include the sound concepts in the Morphological matrix. The possible combinations would be too many, and since the project group concluded that the sound and visual signal would not be dependent on each other.

The final seven sub-concepts were all inserted in a Morphological matrix, which resulted in 12 possible concept combinations. The performed Morphological matrix can be seen in Table 10, and the generated concepts can be seen in Table 11. The 12 generated concepts were taken further into an evaluation process together with the concepts generated with the theme-based Morphological matrix.

Table 10. Morphological matrix.

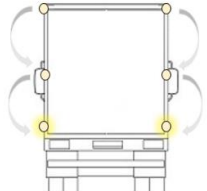
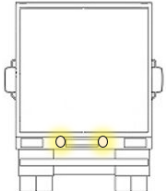
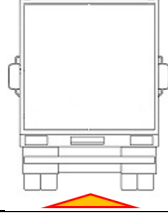




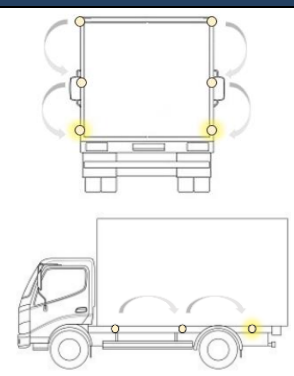
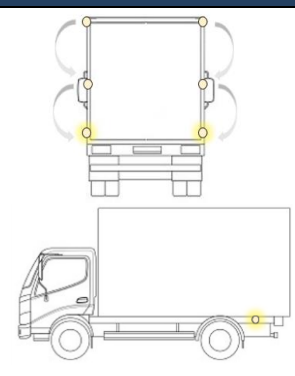
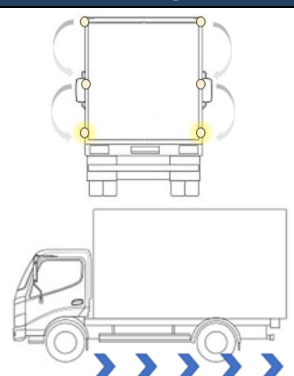
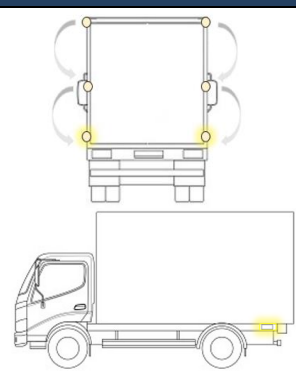
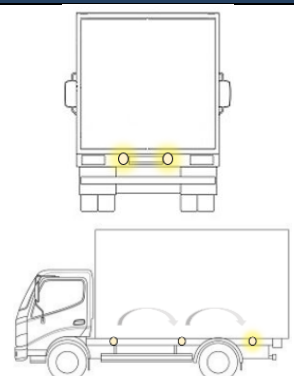
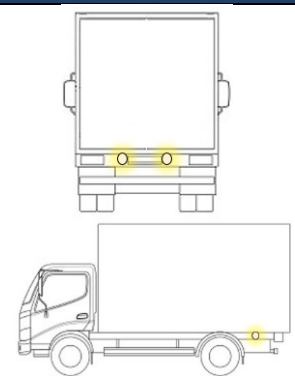
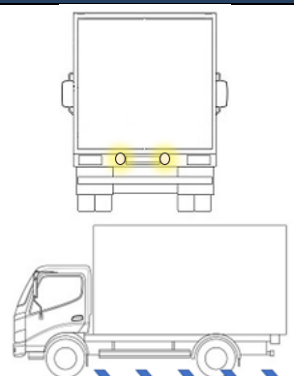
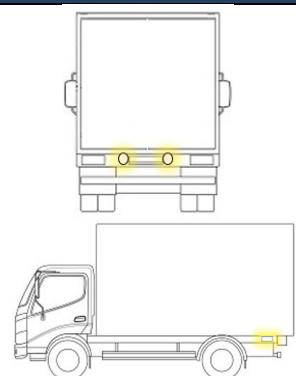
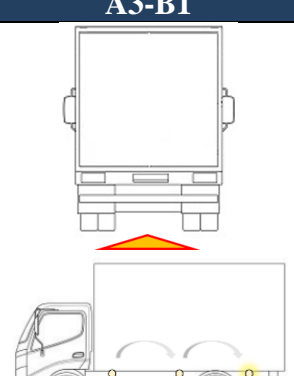
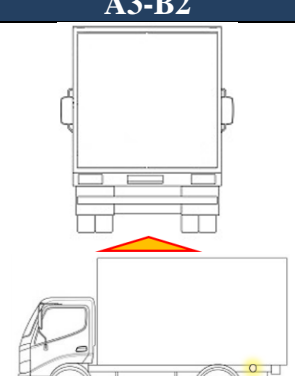
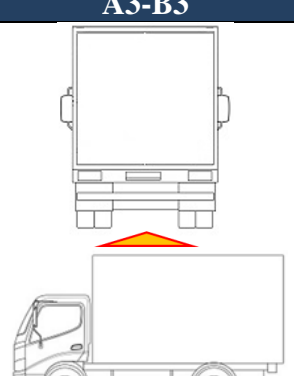
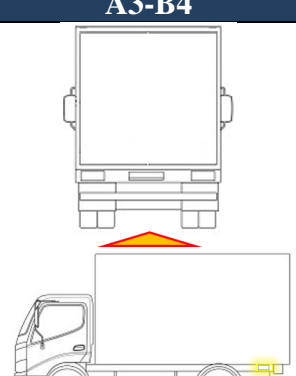
Function	Solution			
	Solution 1	Solution 2	Solution 3	Solution 4
Warn from rear (A)	Lamps where the light bounces from top to bottom	Flashing white light	Projected warning triangle on ground	
				
Warn from side (B)	Lamps where light bounces from front to rear	Flashing white light	Projected arrows on ground	White ordinary reversing light on side (continuous)
				

Table 11. The generated concepts created by the performed Morphological matrix.

A1-B1	A1-B2	A1-B3	A1-B4
			
A2-B1	A2-B2	A2-B3	A2-B4
			
A3-B1	A3-B2	A3-B3	A3-B4
			

## 5.7 Creation of sound concepts

Most of the brainstormed sound concepts were an overall description of different types of sounds, e.g., tonal alarm, white sound, and speaking alarm. These served the further development of sound concepts with focus areas to create sounds within. Since none of the project members had earlier experience with sound creation, the first step was to get familiar with suitable software. A recommendation was given to test the digital audio workstation program named REAPER. Some virtual instruments can be inserted in this program, e.g., a synth, and plugins can be downloaded and installed in the software to enable more functions and pre-set noises. The used plugin in this project was a free tool named TAL-NoiseMaker from the company TAL Software GmbH. The project group was able to create some initial test sounds but felt that there was a need to consult an expert in sound design to be further

able to develop more realistic sound concepts. A sound designer at Volvo Group was contacted, and the group met this contact on two occasions. Helpful feedback and further explanations of how tools can be used to change the appearance of the sound was given. After that, sound concepts of tonal and broadband characteristics were created. Features such as intensity, melody, tones, frequency, and delays were mixed to develop different sounds. Some of the sounds were aimed to have similarities with the existing reversing alarms, and some with more futuristic features. Sounds found on the internet were also used to create new concepts, e.g., animal sounds, screaming tires, and a rewinding record. In the end, around 20 sound concepts were created.

## 5.8 Creation of survey to collect external opinions of the created sound concepts

To gather external opinions of the created sound concepts from people that could be possible “users” of the warning signal was deemed crucial to evaluate the sounds accurately. A digitalised survey was planned to enable efficient quantitative data collection. Online surveys are also recommended by Ulrich et al. (2020) to be a helpful method when evaluating concepts. As described in Sub-chapter 2.4 *Warning signals*, there are two general requirements that a warning signal must fulfil to work as a warning signal, i.e., the warning must be noticeable, and the meaning of the warning must be understood. For the planned survey, the second requirement was deemed relevant. It was, together with the target requirements specification, see Table 7, used as the base when formulating the questions for the survey. The first question, “Do you perceive this sound as a warning?” aimed to give an indication of how well the sound was understood as a warning. The second question, “Do you perceive this sound to be urgent?” aimed to indicate which level of danger the sound express. The third and fourth questions, “Do you find this sound to be annoying?” and “What type of feelings do you experience when listening to the sound?”, aimed to analyse what experiences the listeners felt when listening to the sound. The last three questions, “Do you think of any type of object when you hear the sound?”, “Do you associate this sound with a vehicle?” and “Do you associate this sound with a vehicle moving in reverse?” aimed to answer how well the warning was understood as a warning of a reversing vehicle. The collected data from the survey aimed to validate the sounds against the stated requirements. The respondent was asked to rate the sound on a scale of one to five or write an answer when further elaboration was needed.

Out of the 20 created sounds, a selection of 13 sounds was included in the first survey draft. Each sound had the same seven questions. Most of the remaining seven sounds were just different versions of one of the chosen sounds with some changed variable, e.g., the beat per minute or frequency. The project group decided to include those sounds that differentiated the most to ensure that the respondent could distinguish the sounds.

J. Malmqvist (personal communication, November 18, 2020) strongly recommends that the draft of the survey should be revised in iterations, and a pre-test of the survey should be performed to make sure that the survey is easy to follow and that the respondent understands the questions. A test person was asked to answer the survey and give feedback. The received feedback was that the survey contained evaluations of too many sounds, making the time spent on the survey longer than expected. Furthermore, some of the sounds were perceived as similar and hard to distinguish. After the first revision, the number of sounds was reduced from 13 to eight. After that, a second test person was asked to evaluate the revised survey. The received feedback from the second person was to include an introduction sound as the

first sound to provide the respondent with a chance to get familiar with the layout of the survey and thereby minimise the risk that the first sound would be evaluated differently. An introduction sound was added where the collected answers would not be analysed. Lastly, the supervisor at Volvo was consulted, and one additional question was added to gain more elaborative answers from the respondents. The final survey consisted of nine sounds, including the introduction sound, with nine related questions each, where the questions were the same for all the sounds. The survey was sent out internally at Volvo to approximately 170 people, with the aim of receiving 50 responses. The survey was planned to be available for one week, and a reminder e-mail would be sent out after four days.

The sounds that were included in the survey can be found in a link in Appendix C.

### 5.8.1 Survey results and data analysis

The final number of responses was 37. Since the respondent was asked to rate the sounds on a scale from one to five for most questions, the sounds could be easily compared based on the gathered data. A table was created where the mean value from each question of each sound and the top two rated feelings were inserted, see Table 12. The results show that the original tonal sound, the most common reverse warning sound today, was rated with the highest score regarding warning capacity, urgency experience, vehicle association, and association regarding a reversing vehicle. This result was predicted by the project group and believed to be a good reference point to evaluate the other created sounds. However, it is essential to weigh in that the original tonal sound might get higher ratings because it is familiar and imprinted as a warning signal of a reversing truck, which has been shown in other studies (Vaillancourt et al., 2014). Meaning that the warning signal might not be the best, but since it is strongly imprinted and associated with a reversing vehicle, the ratings are high compared with new sounds that have no imprinted association. The next best-rated sound was *Bouncing Ball*, which is a tonal sound but with a bouncing characteristic. This sound is quite similar to the original tonal sound, which might explain its rating. *Bouncing Ball* was rated as less annoying compared to the original reversing alarm. The most common feeling was calm, compared to stressed and irritated, which were the most felt feelings when hearing the original sound. The white sound familiar as a reversing warning signal on construction sites was rated lowest as a warning signal and the perceived urgency, and almost the lowest regarding the vehicle and reversing association. The sound concept *Reversing Vinyl* was added as an auditory icon, meaning that the sound is associated with something related to the situation, i.e., something in reverse. Many respondents commented that they associated the sound with a reversing tape or vinyl but that it was highly annoying and had a low association with a vehicle. The results from the survey were used as input to evaluate the sounds further.

Table 12. Results from survey. Green marked boxes indicate the concept that received the best result. Blue indicates concepts with the worst result. Light grey indicates the next best ratings.

Sound	Warning	Urgency	Annoyance	Vehicle association	Reversing association	Feeling
<i>Sound 1: Introduction Bicycle bell</i>	3.26	2.83	3.46	2.49	1.86	Irritated 15 Calm 11
<i>Sound 2: Future Tonal</i>	2.62	2.49	2.14	2.38	1.95	Calm 20 Other 12
<i>Sound 3: Tonal</i>	3.38	3.27	3.05	2.27	1.81	Stressed 11 Irritated 10
<i>Sound 4: Reversing vinyl</i>	2.3	3.03	4.57	1.24	1.32	Irritated 25 Stressed 13
<i>Sound 5: White sound</i>	2.05	2.49	3.54	1.7	1.65	Confused 17 Irritated 15
<i>Sound 6: The owl</i>	3.22	2.95	2.97	2.08	2	Confused 12 Other 10
<i>Sound 7: Echo</i>	3.22	3.11	2.84	2.38	2.27	Calm 9 Confused/Other 8
<i>Sound 8: Bouncing Ball</i>	3.39	3.42	2.33	3.28	3	Calm 13 Other 12
<i>Sound 9: Tonal original</i>	4.69	4.28	3.53	4.64	4.78	Stressed 18 Irritated 12

#### 5.8.1.1 Survey results validated against the stated requirement specification

In the target requirement specification, see Table 7, four requirements are stated to be verified through the sound survey. The respondents were asked to rate the sounds on a scale from one to five. A rating of “3”, “4”, or “5” to the questions regarding requirements one, two and three, see Table 13, was viewed as a “yes” response. Sound 8 and Sound 9 fulfilled all the demanded requirements. Sound 7 was very close to receiving a score of 80%.

A rating of “1” or “2” to the question regarding sound annoyance was interpreted as the sound not being annoying. Requirement 6 was formulated as a wish, and the results show that Sound 8 was rated as the second least annoying sound.

Based on the results of the survey, the project group decided to take Sound 7 (Echo), Sound 8 (Bouncing Ball) and Sound 9 (Tonal original) further into the next development loop and further evaluation. Since the requirement specification list at this stage of the project consisted of initial targets, it was argued that Sound 7 was close enough to the target requirement of 80%.

The updated sounds are provided through a link that can be found in Appendix D.

Table 13. Verification of requirements based on the results from the survey. The yellow marked section refers to the requirement stated as a wish.

Requirements found in Table 7	Metric	Sounds								
		1	2	3	4	5	6	7	8	9
1. The warning signal should be interpreted as a warning.	>80% of participants interpret the signal as a warning	70%	51%	81%	41%	32%	70%	78%	81%	100%
2. The warning signal should be interpreted as emitted from a vehicle.	>50% of participants interpret the signal as emitted from a vehicle.	42%	38%	35%	5%	22%	35%	51%	86%	100%
3. The warning signal should be interpreted as a signal emitted from a reversing vehicle.	>30% of participants interpret the signal as emitted from a reversing vehicle.	20%	24%	24%	8%	19%	32%	42%	67%	100%
6. The sound should be environmentally acceptable.	Participants perceive the warning as not annoying.	17%	68%	24%	2%	19%	27%	38%	61%	19%



# Chapter 6

## Concept evaluation

This chapter presents the methodology and results of the activities performed to evaluate the generated concepts. The target specifications are revised, and an updated requirements specification is developed. Evaluation matrices such as the Elimination matrix, Pugh matrix, and Kesselring matrix are used to evaluate the concepts and support decision making. In conclusion, a selection of concepts is tested in Virtual Reality.

## 6.1 Revised requirement specification

The target requirements focused on general aspects of what a warning signal must fulfil. The target specification was revised as the project group gained more knowledge through literature studies and insight into customer needs. Since all sub-solutions for touch were eliminated in the previous chapter, no requirements for touch were generated. With the information gathered from the researched literature, it was possible to define more detailed requirements for designing the sound and visual signals of the reverse warning. For instance, VRUs should perceive the correct location of the warning sound, and the sound should not be masked by noise in the environment. Furthermore, the visual signal should be visible in all light and weather conditions.

Ulrich et al. (2020) suggest that it is essential to consider customer needs when developing a requirements specification. The needs of the customers should be rephrased to requirements with target metrics. Some customer needs could be identified during the previously performed interviews with the truck drivers. The drivers requested visual signals on the side of the truck to warn the VRUs that approach the truck from the side. Further, the drivers requested that the visual reverse warning should be improved for people with reduced hearing and the audible reverse warning be improved for people with visual impairments. The customer needs were rephrased into requirements and included in the requirements specification in Table 14.

Table 14. Established requirements specifications for the reverse warning. D stands for demand and W stands for wish.

Requirement	Metric	Imp. (1-5)	D/W	Justification	Verification
<b>Audible reverse warning</b>					
1. Requirements regarding improved safety for VRUs.					
1.1 The sound should be interpreted as a warning.	>80% of participants interpret the sound as a warning	5	D	Problem formulation	Survey, VR-test
1.2 The sound should be interpreted as emitted from a vehicle.	>50% of participants interpret the sound as a vehicle	5	D	Problem formulation	Survey
1.3 The sound should be interpreted as emitted from a reversing vehicle.	>30% of participants interpret the sound as a reversing vehicle	3	D	Problem formulation	Survey, VR-test
1.4 The sound should be understandable without knowledge of a specific language.	Yes/no	5	D	Internal	Binary
1.5 The sound should not be masked by the environment.	>90% of participants recognise the warning in a noisy environment.	5	D	Literature study	Sound test
1.6 The sound should be locatable.	>60% of participants can localise the source of the sound.	3	D	Literature study	User test
2. Requirements regarding decreased noise pollution.					
2.1 The sound should be environmentally acceptable.	Participants perceive the warning as not irritating.	4	W	Problem formulation	Survey
2.2 The sound should be adaptive.	Minimum of 3 sound levels.	5	D	Problem formulation	Binary
3. UN regulations regarding the audible reverse warning.					
3.1 Sound level.	$62 < \text{dB} < 112$	5	D	UN regulation	Measure sound
3.2 Number of repeated cycles.	24-120 cycles per minute	5	D	UN regulation	Count
3.3 Sound frequency.	$1000 \text{ Hz} \leq 3500$	5	D	UN regulation	Measure
<b>Visual reverse warning</b>					
1. Requirements regarding improved safety for VRUs.					
1.1 The visual signal is interpreted as a warning.	>80% of participants interpret the sound as a warning.	5	D	Problem formulation	VR-test

Requirement	Metric	Imp. (1-5)	D/W	Justification	Verification
1.2 The visual signal is interpreted as a reversing vehicle.	>30% of participants interpret the sound as a warning.	4	D	Problem formulation	VR-test
1.3 A visual signal should be seen from the rear and sides of the truck	Yes/no	5	D	Customer need	Binary
1.4 The visual signal is visible in all light conditions.	Visible from >10 m distance.	5	D	Internal	Simulation
1.5 The visual signal is visible in all weather conditions.	Visible from >10 m distance.	3	W	Internal	Simulation
1.6 The visual signal is only activated in reversing situations.	Not visible when not reversing.	5	D	Problem formulation	Functional analysis
2. Technical requirements.					
2.1 The visual signal does not interfere with other functions.	Yes/no	5	D	Internal	Functional analysis
2.2 The visual signal does not disrupt other road users' views.	Yes/no	5	D	Internal	Binary
2.3 The visual signal does not emit materials during use.	Yes/no	2	D	Internal	Binary

## 6.2 Elimination of inferior concepts

In the previous chapter, 24 concepts were generated using two different approaches. Twelve concepts were generated using a thematic approach, and twelve were developed after having evaluated the sub-concepts at first and combined them with a Morphological matrix. During the evaluation of sub-concepts, all sub-concepts for how to warn by touch were eliminated. This implies that the twelve concepts generated using the thematic approach should be eliminated as they contain sub-concepts for touch. However, instead of directly eliminating the concepts, the concepts were evaluated using an Elimination matrix, see Table 15, to determine how the complete concepts fulfilled the criteria. According to L. Almefelt (personal communication, January 20, 2021), it is possible to harmonise conflicting requirements by utilising synergies between sub-solutions. This implies that a solution that is not feasible on its own, can become feasible if combined with another solution. The evaluation with the Elimination matrix was performed following the same methodology that has previously been described in Sub-chapter 5.8.1 *Elimination matrix*. The results from the Elimination matrix show that none of the concepts fulfils all criteria in the matrix, which indicates that the sub-concepts for warning visually, audibly, and by touch lack synergies.

To evaluate whether the concepts can be realisable if the sub-concepts for touch are eliminated, another Elimination matrix was performed, see Table 16. Through the second Elimination matrix, the concepts' fulfilment of criteria is evaluated based on only visual and

audible signals. Three of the twelve concepts passed the second Elimination matrix, and the results are elaborated on in the following paragraphs.

Concept *Clear* does not fulfil all demands since the arrows on the truck are visible when the truck is not reversing, and the speaking reverse alarm cannot be understood without knowledge of a specific language. Further, the warning triangle on the truck's rear does not align with Volvo's portfolio, and therefore the concept is eliminated. If the arrows were projected on the ground instead, the arrows would only be visible when the truck reverses. Additionally, if the warning triangle were projected on the ground, it would align with Volvo's portfolio. Further, if the spoken message were changed to another sound, this concept would fulfil all demands. If these changes were made, this concept would be equal to concept A3-B3, which means that concept A3-B3 is a concept that signalises clarity.

Concept *Abstract* fulfils all criteria in the second Elimination matrix. It can be seen that the concept is equal to concept A1-B1 that was generated using the other approach.

Concept *High-Tech* uses a combination of projections on the ground and visual notifications in the VRUs smartphone. This concept is eliminated because integrating the VRUs smartphone for visual notifications would not be realisable in the near future. The concept is therefore eliminated. However, if the concept only uses projections on the ground, it would be equal to concept A3-B3. Concepts *Adult* and *Teenager* also use notifications in the VRUs smartphone, which is not realisable, and the concepts are therefore eliminated.

Concept *Low-Tech* fulfils all criteria in the second Elimination matrix. However, it can be seen that the concept is equal to concept A2-B4 that was generated using the other approach.

Concept *Child* uses a speaking reverse alarm that cannot be understood without knowledge of a specific language, which is listed as a demand in the requirements specification. Since the concept does not fulfil all demands, it is eliminated. However, if the speaking message were exchanged for another sound, the concept would pass all criteria in the Elimination matrix. Concepts *Elderly* and *Visual impairment* uses serpentine to warn visually. The serpentine are not considered realisable, as the many connection points would make it hard to realise the function of only activating the warning when reversing. The concepts are therefore eliminated.

Concepts *Bicyclist* and *Hearing loss* both use warning triangles that are considered not to fit Volvo's portfolio, hence the concepts are eliminated. Besides this, the concept *Hearing loss* uses notifications in the VRUs smartphone, which is not considered realisable.

Concept *Construction* fulfils all criteria in the Elimination matrix and is therefore taken for further evaluation.

Table 15. Elimination matrix.

Solution alternative	Criteria					Criteria fulfilment: (+) Yes (-) No (?) More info needed	Decision: (+) Continue (-) Remove (?) More info needed
	Solves the main problem	Fulfils all demands	Realisable	Safe	Fits portfolio		
						Comment	Decision
Clear	+	-	+	+	-	Arrows are visible when not reversing.	-
Abstract	+	+	+	+	+	Many issues with vibrations in the ground.	-
High tech	+	-	-	-	-	Smartphone/watch alert is not realisable today.	-
Low tech	+	+	-	+	-	Emitting warm/cold air is not sustainable and takes space.	-
Child	+	+	-	-	-	A stick that unfolds is not realisable and can hurt the child.	-
Elderly	+	-	-	+	-	Arrows are always visible.	-
Adult	+	-	-	-	-	The smartphone/watch alert is not realisable today.	-
Teenager	+	-	-	-	-	Smartphone/watch alert is not realisable today.	-
Bicyclist	+	+	-	-	-	Pressure waves are not realisable.	-
Hearing loss	+	-	-	-	-	Smartphone/watch alert is not realisable today	-
Visual impairment	+	+	-	+	-	Serpentines and warm/cold air are not realisable.	-
Construction	+	+	-	+	-	Pressure waves are not realisable.	-

Table 16. Elimination matrix without the sub-concept “warn by touch”.

Solution alternative	Criteria					Criteria fulfilment: (+) Yes (-) No (?) More info needed	Decision: (+) Continue (-) Remove (?) More info needed
	Solves the main problem	Fulfils all demands	Realisable	Safe	Fits portfolio		
	Comment						Decision
Clear	+	-	+	+	-	Arrows are visible when not reversing.	-
Abstract	+	+	+	+	+		+
High tech	+	+	-	-	-	The smartphone/watch alert is not realisable in the near future.	-
Low tech	+	+	+	+	+		+
Child	+	-	+	+	+	Speaking alarm is not understood by all.	-
Elderly	+	-	-	+	-	Arrows are visible when not reversing.	-
Adult	+	+	-	-	-	The smartphone/watch alert is not realisable in the near future.	-
Teenager	+	+	-	-	-	The smartphone/watch alert is not realisable in the near future.	-
Bicyclist	+	+	+	+	-	The warning triangle does not fit the portfolio.	-
Hearing loss	+	+	-	-	-	The warning triangle does not fit the portfolio.	-
Visual impairment	+	+	-	+	-	Serpentines are not realizable.	-
Construction	+	+	+	+	+		+

### 6.3 Concept screening with the Pugh matrix

Three of the concepts generated with the thematic approach passed the second Elimination matrix and should be taken for further evaluation. Since two of the concepts are equal to the concepts developed using the other elimination approach, only concept *Construction* proceeds to the evaluation along with the twelve concepts developed using the other approach. To evaluate which of the thirteen concepts should be further developed, Pugh matrices were used to screen the concepts. The evaluation was performed using the same methodology described in Sub-chapter 5.8.3 *Concept screening using the Pugh concepts selection method*. To ease the screening, the concepts were divided into three categories and evaluated one at a time.

The first category consists of concepts that use lamps with travelling lights on the truck’s rear, see Table 11. The reference concept for this category is concept A1-B1, which uses travelling lights both on the back and sides of the truck. The results of the Pugh matrix evaluation, see

Table 17, show that concepts A1-B1 and Construction are the best combinations. Furthermore, concepts A1-B2 and A1-B3 share a second ranking. Besides LED strips with travelling light, concept *Construction* also has a spotlight on the rear of the truck, which gives a somewhat better warning effect than concept A1-B1 during the night. However, concept *Construction* uses three types of different light sources and is therefore considered more complex than concept A1-B2, which only uses one type of light source. Therefore, it is not taken for further development. A1-B2 and A1-B3 are taken for further development., and A1-B4 is eliminated due to the low net value.

Table 17. Pugh matrix for concepts that use lamps with travelling lights on the truck's rear.

Criterion	Alternative				
	A1-B1	A1-B2	A1-B3	A1-B4	Construction
Interpreted as a warning (day)		+	-	-	0
Interpreted as a warning (night)		+	-	-	+
Interpreted as a reversing manoeuvre (day)		-	-	-	0
Interpreted as a reversing manoeuvre (night)		-	+	-	0
Annoyance		-	+	+	-
SUM +		2	2	1	1
SUM 0		0	0	0	3
SUM -		3	3	4	1
Net value	0	-1	-1	-3	0
Ranking	1	2	2	3	1
Further development	Yes	Yes	Yes	No	No

The second category consists of concepts that use lamps with flashing lights on the truck's rear, see Table 11. The reference concept uses lamps with flashing lights on both the back and side of the truck. The results of the Pugh matrix, see Table 18, show that concept A2-B1, which uses flashing lights on the rear combined with travelling lights on the sides of the truck, is the best combination. The reason for this is that the concept both signals a strong warning and shows the direction of the truck. Concept A2-B2 is second best according to the Pugh Matrix and is also taken for further development. Concepts A2-B3 and A2-B4 are eliminated.

The third category consists of concepts that use projection on the ground in the truck's rear, see Table 11. The reference concept uses projection on the ground, both on the back and sides of the truck. The results of the Pugh Matrix, see Table 18, show that projection on the ground on the rear of the truck combined with either travelling or flashing lights on the side of the truck are the best combinations and are taken for further evaluation. Since the visibility of only using projections is questionable in daylight, concept A3-B3 is not accepted for further

development. Meanwhile, concept A3-B4 which uses lights on the side of the truck, is taken for further evaluation

Table 18. Pugh matrix for concepts that use lamps with flashing lights on the truck's rear.

Criterion	Alternative			
	A2-B2	A2-B1	A2-B3	A2-B4
Interpreted as a warning (day)		-	-	-
Interpreted as a warning (night)		-	-	-
Interpreted as a reversing manoeuvre (day)		+	-	0
Interpreted as a reversing manoeuvre (night)		+	+	0
Annoyance		+	+	+
SUM +		3	2	1
SUM 0		0	0	2
SUM -		2	3	2
Net value	0	1	-1	-1
Ranking	2	1	3	3
Further development	Yes	Yes	No	No

Table 19. Pugh matrix for concepts that use lamps with a projection in the truck's rear.

Criterion	Alternative			
	A3-B3	A3-B1	A3-B2	A3-B4
Interpreted as a warning (day)		+	+	+
Interpreted as a warning (night)		+	+	-
Interpreted as a reversing manoeuvre (day)		+	+	+
Interpreted as a reversing manoeuvre (night)		-	-	-
Annoyance		-	-	0
SUM +		3	3	2
SUM 0		0	0	1
SUM -		2	2	2
Net value	0	1	1	0
Ranking	2	1	1	2
Further development	No	Yes	Yes	Yes

## 6.4 Concept scoring with the Kesselring matrix

Through the concept screening with the Pugh matrix, thirteen concepts were narrowed down to eight concepts. The concepts were scored with the Kesselring matrix to decide which of the eight concepts should be further developed. The previously developed criteria for the Pugh matrices are used in the Kesselring matrix and are listed vertically in the matrix, and the solution alternatives are listed horizontally, see Table 20. The evaluation with the Kesselring matrix was performed using the same methodology as described earlier in Sub-chapter 5.8.4 *Concept scoring with the Kesselring matrix*.

The results from the Kesselring matrix show that concept A1-B2 is the highest scoring concept. A1-B2 is a combination of travelling and flashing lights, and hence a combination of concepts A1-B1 and A2-B2, which scored second and third place, respectively. By combining travelling and flashing lights, the advantages of both types of light patterns can be gained.

A2-B1 is another concept that uses both travelling and flashing lights. However, this concept was scored in fourth place compared to the winner A1-B2. This is because the travelling lights on the truck's rear are considered equally alarming as the flashing lights on the truck's rear. However, the travelling lights on the side of the truck are not considered as alarming as the flashing lights. Hence, the best warning is achieved when using travelling lights on the rear of the truck and flashing lights on the side of the truck, according to the results from the Kesselring matrix.

Concept A1-B3 uses lamps with travelling lights on the rear of the truck and projects arrows on the ground beside the truck. Compared to concept A1-B1, which uses travelling lights both on the rear and sides of the truck, concept A1-B3 is equally good at showing the direction of

the truck during the night. However, during the day, the visibility of the projected arrows is lower than the visibility of the lightning from the lights. Further, concept A1-B3 is not considered as alarming as concept A1-B1 due to the lack of lights on the sides of the truck. Concept A1-B3 is therefore eliminated.

Concepts A3-B1, A3-B2, and A3-B4 all project a warning triangle on the ground at the truck’s rear. Concept A3-B1, which uses travelling lights on the side of the truck, scores the highest points of the three concepts, followed by A3-B2 and A3-B4. The reason for this is that the travelling lights can be interpreted as a reversing truck easier than flashing lights and continuous lights. However, since the solution used on trucks today uses continuous white lights on the truck’s rear, adding continuous white lights on the side of the truck could be associated with reversing even more than using lamps with travelling lights. Evaluating the solution with continuous lights on the side of the truck further would be necessary before a decision can be made, and concept A3-B4 is therefore taken for further evaluation. Concepts A3-B1 and A3-B2 are eliminated since the travelling and flashing lights are better in combination with other solutions, according to the Kesselring matrix.

The concepts taken for further development are A1-B1, A1-B2, A2-B2, and A3-B4.

Table 20. Kesselring matrix.

		Solution alternative																	
		Ideal		A1-B1		A1-B2		A1-B3		A2-B2		A2-B1		A3-B1		A3-B2		A3-B4	
Criterion	W	V	T	V	T	V	T	V	T	V	T	V	T	V	T	V	T	V	T
Interpreted as a warning during the day	5	5	25	4	20	5	25	3	15	5	25	4	20	2	10	3	15	1	5
Interpreted as a warning during the night	5	5	25	4	20	5	25	3	15	5	25	4	20	4	20	5	25	3	15
Interpreted as reversing during the day	4	5	20	5	20	4	16	3	12	3	12	4	16	3	12	2	8	2	8
Interpreted as reversing during the night	4	5	20	5	20	4	16	5	20	3	12	4	16	3	12	2	8	2	8
T=sumTj		90		80		82		62		74		72		54		56		36	
T/Tmax		1																	
Ranking				2		1		5		3		4		7		6		8	
Further development				Yes		Yes		No		Yes		No		No		No		Yes	

### 6.5 Development loop of the selected concepts

Through the evaluation with the Kesselring matrix, eight concepts were narrowed down to the four concepts, A1-B1, A1-B2, A2-B2, and A3-B4, that were selected for further development

and evaluation. To further evaluate the concepts, it was considered necessary to test the concepts in practice to assess how VRUs perceive the reverse warning. Since concept A1-B2 is a combination of concepts A1-B1 and A2-B2, the project group decided only to evaluate concepts A1-B1, A2-B2, and A3-B4 in the tests. By doing so, it would be possible to assess how A1-B2 works by evaluating the results from how A1-B1 is perceived on the rear and how A2-B2 is perceived on the sides of the truck. Before the concepts could be tested, it was necessary to develop the concepts further, and another development loop was performed.

Since the concepts only consist of visual signals, the next step was to add audible signals by selecting appropriate sounds for the concepts and deciding on the behaviours of the visual signals. The evaluation of sounds performed in Sub-chapter 5.7.1 *Survey results and data analysis*, resulted in that the sounds that scored the highest points were *Bouncing Ball*, *Echo*, and *Tonal Original*. The selection of which sound should be assigned to which concept was made after discussions in the project group.

The visual concept A1-B1 consists of lamps with travelling lights and therefore the sound *Bouncing Ball* was considered appropriate as it could result in synergies between the visual and audible signals. The sound consists of one audible part, lasting one second, and a silent part, lasting 0,3 seconds. This results in a cycle repetition of 46 times per minute. The travelling lights, see Figure 50, were set to be lightened for 0,5 seconds each. More specified, the first lamp, which on the side would be the lamp closest to the cab of the truck and on the back, it would be the lamp located at the top, will be on for 0,5 seconds and then turned off. When turned off, the second lamp would be turned on for 0,5 seconds and then the third lamp would be turned on in 0,5 seconds. Thereafter, the cycle is repeated as long as the reverse warning is activated. This concept will further be called *Travelling*.

The visual signals for A2-B2, see Figure 51, were decided to be flashing in a repeated cycle of 0,5 seconds. The lamps are rapidly flashing two times during this time, and a short pause is included before the next cycle. *Echo* was selected to be the sound of the concept. This sound also consists of an audible part and a silent part, which equals 0,857 seconds and 0,261 seconds, resulting in a repetition of 54 cycles per minute. This concept will further be called *Flashing*.

Concept A3-B4, see Figure 52, consists of continuous white light and a projected warning triangle that is activated during the whole time the gear is set into reverse. During the day, the lights will be the most visible signal, it is deemed that the projection mainly will be visible when it is dark. Since the concept consists of white lights both on the back and sides of the truck, the ambition is to test whether adding white lights on the truck's sides can intensify the warning signal. Therefore, the sound *Tonal Original* was chosen for concept A3-B4, as the lighting on the concept is most similar to the original reverse warning on the truck. The sound *Tonal Original* consist of a 0,5 second audible signal and 0,49 second silent part. The cycle would thereby be repeated 61 times per minute. This concept will further be called *Projection*.

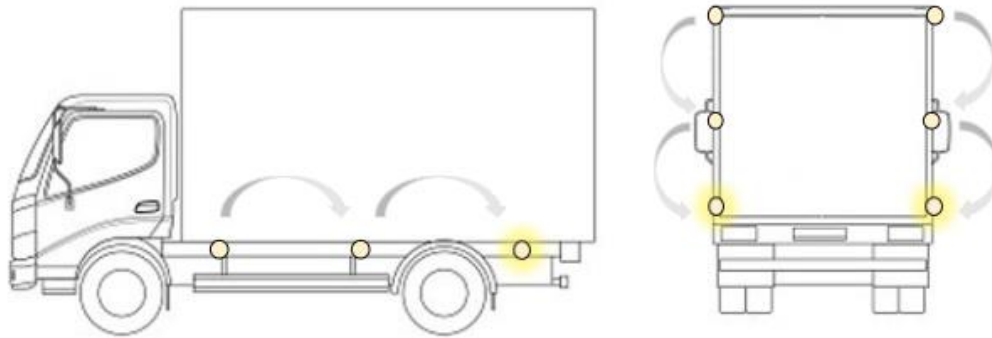


Figure 50. Concept “Travelling” consists of lamps with travelling lights on both the rear and sides of the truck, along with the audible signal “Bouncing ball”.

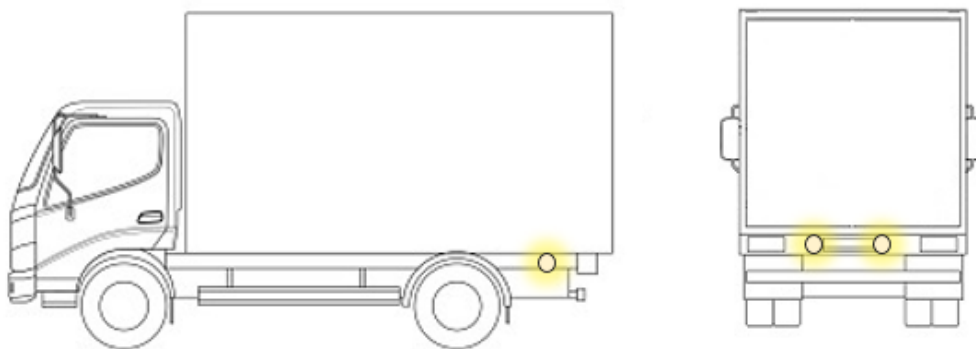


Figure 51. Concept “Flashing” consists of lamps with flashing lights on both the rear and sides of the truck, along with the audible signal “Echo”.

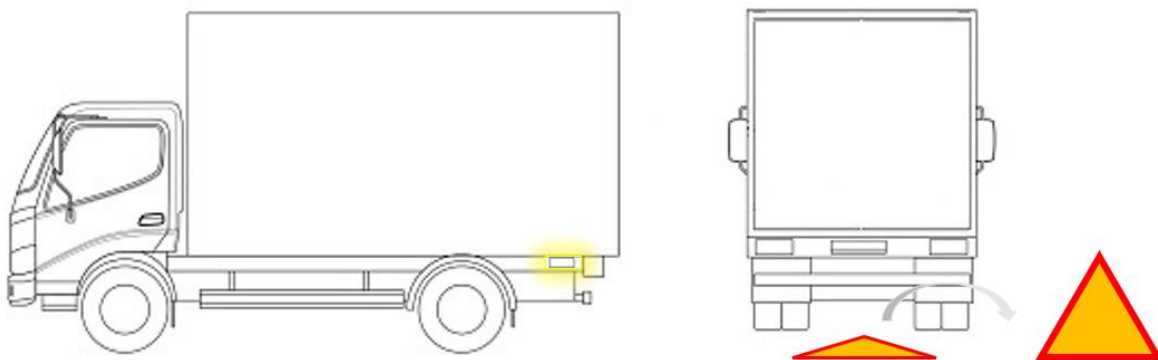


Figure 52. Concept “Projection” consists of a projected warning symbol on the ground on the truck’s rear and a continuous white light on the sides of the truck. The audible signal consists of the sound “Tonal original”.

## 6.6 Concept testing in Virtual Reality

Virtual reality (VR) is a computer-generated world where users can experience and interact actively in different situations (NE, n.d,b). VR was in this project used to test the three selected concepts and gather data that later were used to perform a final evaluation of the concepts. By conducting tests in VR, test persons could safely be exposed to situations that in real life could be dangerous, which ensures that the concept can be ideally tested. Performing tests in VR also enables tests to be repeated several times with different test persons, and the test circumstances remain unchanged. Additional benefits that could be retrieved by conducting tests in a virtual world would be that the test can be controlled and adapted to special conditions, e.g., night-time and weather.

Further, the test's planning, procedure, and result will be presented.

### 6.6.1 Planning of Virtual reality tests

To create tests of specific situations in VR, an expert at Volvo was consulted. The expert had a VR world of a city environment available in the development platform Unity, where a suitable location was searched for. The project group wanted to find an area where the animated truck would initially not be visible to the test person, e.g., the truck is standing hidden behind a building, but as the test person gets closer, the truck will be visible. This was believed to be an accurate test set up of a common situation in city environments since similar situations were observed during the city observations. A suitable alley was found in the provided VR world, see Figure 53.



Figure 53. The red circle marks the area in the virtual world where the scenarios will be played.

When the location was selected, the project group started to plan different situations to be tested. For easy visualisation and clear communication of the planned scenarios, the test situations were visualised by setting up the scenarios on the provided picture of the location and later sent to the VR expert with a short description. The factors that had to be set were; where is the starting- and endpoint of the VRU and truck, how should the truck and warning signals behave in each situation, and what will occur if the VRU does not slow down or stop. The VR test creator was also asked to include distractions, e.g., other trucks, cars, and VRUs, to mimic a natural city environment. Three review sessions with the VR expert were held to give input and see the development process of the test. After discussion with the VR creator, one of the planned situations involving a bicyclist was removed. This was done since it was challenging to design a situation with a bicyclist at the chosen location to be realistic.

Each performed test was planned to be observed and analysed. However, it was deemed to be of most importance to collect data regarding the test person's experience of the concepts. The formulated questions were aimed to provide answers on how well the test person perceived the truck's intended pathway, how well the visual and audible warning was able to warn, if the concept was able to warn more or less than the existing standard solution, and specific question regarding each concept. All questions can be seen in Appendix E. The collected answers were planned to be used to enable the final evaluation and elimination of concepts. The VR test was stated as one of the verification methods in the requirements list, see Table 14. Therefore, some questions were specifically formulated to collect data that could be used to verify the concept against the formulated requirements. A short questionnaire was also designed to collect data regarding the test person's experience of the test and some background information, e.g., prior VR experience, which can be viewed in Appendix F. The

reason for the questionnaire was to be able to validate the method of testing concepts in VR. Before the test was conducted, an initial test person was invited to perform the test and answer the question to ensure that the questions were understood.

Further, the different planned situations will be presented.

#### 6.6.1.1 Scenario one

In this scenario, the VRU will pass an idling truck where the reverse warning signal is on; the truck will not start moving during the whole test. This scenario was designed to evaluate the test person's experience when passing behind an idling truck that signals for a reversing manoeuvre but does not perform it. As seen in Figure 54, the VRU is a pedestrian that starts at point one and moves in a straight line towards point 2. The truck is positioned in the alley, in an idling state. The reverse warning signals will be turned on when the pedestrian passes the red line.



Figure 54. Test scenario one.

#### 6.6.1.3 Scenario two

Scenario two, the VRU, a pedestrian, starts at point one and moves around the corner and towards point two. The truck will drive forward towards the crossing where the truck stops and starts a reversing manoeuvre into the alley. The pedestrian will move in parallel to the truck when it is reversing, and a collision will occur if the VRU does not act and control the speed. The scenario aims to evaluate how the pedestrian acts when walking beside the truck while it is reversing and how the test person experiences the added visual signals on the side of the truck. The scenario is visualised in Figure 55.



Figure 55. Test scenario two

#### 6.6.1.4 Scenario three

In the last scenario, see Figure 56, the truck will reverse out of the alley, and the pedestrian will move from point one toward point two. This scenario will mimic night-time. The truck will be hidden behind the building and not visible to the VRU before passing the corner. When the VRU passes the red line, the truck will start reversing, and the warning signals will be turned on. The audible warning signal will be heard before the truck is visible. A collision will occur if the VRU does not act and control the speed. The scenario is designed to evaluate the experience when the warning signal is heard, but the truck is not seen at first and how fast the test person reacts when the truck is visible.



Figure 56. Test scenario three.

### 6.6.2 The performed VR test

All three concepts were tested in each scenario to evaluate each concept fairly, resulting in 9 test scenarios. The aim was to test each scenario ten times, which would result in 90 tests. One test person was believed to be able to only perform two or three scenarios each because of the similarity of the tests. The resemblance was believed to induce a risk that the test person would become conscious of the scenarios, and thereby the test result would be less valid. A decision was taken that each test person would perform all three scenarios for one concept. By this, the test person would have enough time to comprehend the concept and hopefully be able to answer the follow-up questions. The scenarios were played in alternating order to ensure that the same scenario was not the first conducted scenario each time. This was decided since it was believed that the first scenario the test person would be exposed to would be affected by the test person's unfamiliarity with the test setup. A total of 30 test persons were required to reach the aim of 10 tests for each scenario and concept. The test persons were to be internal employees at Volvo to ease the test process, and interested workers were able to book a time slot in a document sent out.

During the test, one test person at the time performed the test. The person was equipped with VR goggles, headphones, and a hand console, see Figure 57. The test person could see the animated world and look around with the VR goggles. Figure 58 shows an example of what the participant would see when approaching the truck in one of the scenarios. Sounds that mimic a natural city environment, e.g., wind, car engines, and birds, were heard in the headphones and the audible reverse warning sounds. With the hand console, the test person was in control of the speed of the VRU and thereby able to slow down, speed up, and stop. Their behaviour and actions were documented and later analysed. After each test, the test person was asked the specified questions and the answers were noted and audiotaped. Last, the questionnaire was given to the test person to fill out.



*Figure 57. A test person is equipped with VR goggles, headphones and a hand console.*

Additional views from the VR world can be seen in Appendix G.



Figure 58. View from the virtual world where the truck is standing still in the alley.

### 6.6.3 Result and analysis of the VR test

Twenty test persons conducted the test, resulting in that each concept was tested seven times, except the last concept (Projection) with the *Tonal Original* sound, which was tested six times. Further, the results from each tested concept and the rated results of the overall experience will be presented.

#### 6.6.3.1 Summarised result of each evaluated concept

Table 21 summarises the results from the general concept questions, where the test person was asked to answer yes or no on some questions and in other questions, they were asked to rate the concept on a scale of one to five. As a whole, all concepts were rated high as being able to warn and indicate a reversing truck. However, concepts *Flashing* and *Projection* were rated higher in the questions regarding sound and visual signals. The visual signals on concept *Travelling* were rated relatively low. This was most often because the test person did not recognise the lamps at all. This was also the case when asked about the continuous white lights placed on the truck's side in concept *Projection*. However, the warning triangle included in this concept was recognised by all participants.

Table 21. The table shows the summarised results from the general questions asked during the test.  
 \*The test person did not remember the flashing lights, which was interpreted as a “No”.

		Travelling	Flashing	Projection
1. Were you warned by the sound from the truck?	Yes	6	7	6
	No	1	0	0
2. How well did the sound warn you on a scale of one to five?	Average	3,4	4,1	4,6
3. Did you associate the sound with a reversing truck?	Yes	4	3	6
	No	3	4	0
4. Were you warned about the visual signals on the truck?	Yes	3	6	6
	No	4	1*	0
5. How well did the visual signal warn you on a scale of one to five?	Average	2,6	3,8	3,25
6. Did you associate the additional visual signals with a reversing truck?	Yes	0	2	2
	No	7	5	4
7. Were you warned about the concept as a whole, and did you perceive that the truck was reversing or intending to reverse?	Yes	5	7	6
	No	2	0	0

All test persons were also asked to answer some more elaborative questions specified for each concept. For concept *Travelling*, questions regarding associations of the travelling lights and if the lights signalled a direction were asked. Four persons did not recognise the lamps and did not register a pattern. The persons who identified the lamps expressed associations to hazard warning lights, or that work is being performed around the truck, e.g., unloading. When asked to compare the concept against the traditional reverse warning solution, several persons stated that the lights were not clear and attentive enough, but the sound was more pleasant. When asked about the flashing lights that the concept *Flashing* consisted of, several test persons expressed that the signal was related to that the truck was reversing or intending to reverse. Compared to the existing solution, concept *Flashing* was believed by the test group to perform better in relation to both sound and visual signals due to its less annoying beeping sound and visual signals that are more attentive. The concept *Projection* was equipped with an additional white light on the side and a projected warning triangle on the ground. All test persons did not recall the white light that was continuously lightened when reversing, indicating that the placement of the lamp was problematic or simply just that the triangle overpowered the other visual signal. However, the projected triangle was stated to be a good visual signal for the intended purpose. Several expressed that the solution could have benefits for people with reduced hearing. Some also said that it was easier to see if the truck was moving or not when looking at the triangle and that it also specified the danger area behind the truck. Figures 59-61 show some chosen quotes that the test persons have said during the performed VR test.

*“The visual signal is clearer than today's solution and I think the sound is more pleasant than the other sound that is today. I still understand that the vehicle is in reverse.”*

*“I think it's a pleasant warning because I think the sound is better than the current beep sound. It sounds softer and with quality.”*

*“The sound is better I would say, and it is still indicating that the truck is reversing. But I was lacking some visual signals or maybe I did not see them.”*

*“The warning signal said something, it calls for attention, but I did not connect directly to reversing.”*

*“The sound is a bit nicer to your ear, it is not as intense and high pitched as the current beeping sound.”*

Figure 59. Quotes gathered during the VR test regarding concept “Travelling”.

*“When the reversing signals were on, but the truck did not reverse, I became confused. My understanding is that if I only see the flashing light, I think that it is something that is about to happen but that the sound is more connected to when something is happening”*

*“I felt warned like shit something is about to happen”*

*“I did not associate the sound with a reversing truck, but the flashing light is better than a continuous light”*

*“I thought the visual signal was much better than just a steady light. In a way, I think it's good that it's a different signal because you are kind of got used to the fact that the current beep sound is connected to reversing, but this new sound makes you look a little extra and be more attentive”*

*“The beeping sound is more disturbing, which can be an important aspect. This sound signalled for increased attention but was not as annoying”*

*“I think of hazard lights when I see flashing lights and that you should stay away from that area”*

Figure 60. Quotes gathered during the VR test regarding concept “Flashing”.

*“Yes, I would say that the concept signals a clearer warning. The warning triangle indicates on the ground where the truck will move”*

*“In reality, I would look a lot at the ground, so if it had been for real, I would probably have seen the triangle first”*

*“If you go and look down into the ground, as you often do, you will see this”*

*“Associated the triangle as a direction and since it was behind, I thought something would happen there”*

*“It warns of an area where the truck will later be located”*

*“I think it's good with the triangle for people who do not hear”*

*“I may not associate it with reversing more than the current, but I was warned more”*

Figure 61. Quotes gathered during the VR test regarding concept “Projection”.

6.6.3.2 Chosen concepts for further development based on the results from the VR test. Before a final decision on which concepts to take further, an analysis of if the concepts fulfil the relevant parts of the requirement specification was performed, see Table 22. The result shows that all concepts meet all requirements regarding sound. A rating of three or higher was deemed valid as a statement that the signal was interpreted as a warning. The optimal result would be that the concept fulfilled the requirement based on the number of people answering “Yes” on the question and rated the concept with a three or above. Concept *Travelling* did not fulfil any of the requirements regarding visual signals.

With the results from the validation against the requirement specification and the analysed results from the VR test, a decision was taken to go further with concepts *Flashing* and *Projection* into a final development loop. The decision was based on the superior results of the two concepts. The test results made it clear that concept *Travelling* was not as clear as the project group believed. The travelling lamps and their intended function of signalling a direction were proven not to function as good as initially thought. Additionally, the sound was not rated as high as the other two sounds. Therefore, the decision was made to eliminate the concept.

Table 22. Analysis of fulfilment of stated requirements.

Requirement	Metric	Travelling	Flashing	Projection
<b>Sound</b>				
1.1 The sound should be interpreted as a warning.	>80% of participants interpret the sound as a warning	85,7% answered yes	100% answered yes	100% answered yes
		85,7% rated the sound with a 3 or higher	100% rated the sound with a 3 or higher	100% rated the sound with a 3 or higher
1.3 The sound should be interpreted as a reversing vehicle.	>30% of participants interpret the sound as a reversing vehicle	57,1% answered yes	42,8% answered yes	100% answered yes
<b>Visual signals</b>				
1.1 The visual signal is interpreted as a warning	>80% of participants interpret the sound as a warning.	57,1% answered yes	100% answered yes	100% answered yes
		28,5% rated the visual signal with a 3 or higher	100% rated the visual signal with a 3 or higher	66,6% rated the visual signals with a 3 or higher
1.2 The visual signal is interpreted as a reversing vehicle	>30% of participants interpret the sound as a warning.	0% answered yes	28,5% answered yes	33,3% answered yes

### 6.6.3.3 Result and analysis of the VR test method.

The data collected from the questionnaire was transferred and summarised in a spreadsheet. Table 22 shows the results of the questionnaire. Out of the 20 test persons, 18 identified as male and two identified as female. The youngest participant was 23 years old, and the oldest participant was 60. The result shows that the participants overall had a good experience and perceived the virtual world as realistic. When asked about how they felt during the test, the majority answered that they were relaxed, happy, calm and/or full of expectation. Some test persons gave the project group feedback on the test setup, these are summarised below.

- Include a test round before the actual test to get familiar with the setup.
- Including the ability to move around freely during the test would increase the realistic aspect.
- Design the scenarios with more realistic pathways for the truck.
- Include a scenario where the test person would listen to music to test how well the concepts perform when the audible capability is reduced.
- Add more city noise.

As mentioned, the test persons' reactions and behaviour were documented by recording the screen on the computer where the view from the goggles was shown. This was done to understand how the test persons behaved in the test and if the test person seemed to behave realistically. The result was that most test persons seemed to act relatively realistic, e.g., the majority stopped and looked at their right and left before crossing the pedestrian crossing. No person was run over by the truck, and most people kept a safe distance from the vehicle. This result correlates well with the test persons' own experience, see Table 23.

Table 23. Results from the asked questions regarding the test set-up. The answers are presented as an average.

Question	Average
Age	38
To what extent do you have experience of being a vulnerable road user in urban environments with traffic? (1=Not at all, 5=Very often)	4
Do you have previous experience with Virtual Reality? (1=Not at all, 5=Very often)	2
How is your experience affected by not being able to control the direction yourself? (1=Significantly worse, 5=Not affected)	4
How well do your reactions in the virtual environment correspond to reality? (1=Not at all, 5=Very much)	4
Did you perceive the virtual environment as realistic? (1=Not at all, 5=Very much)	4
Did you perceive the sounds emitted from the truck as realistic? (1=Not at all, 5=Very much)	4
Did you perceive the visual signals from the truck as realistic? (1=Not at all, 5=Very much)	4



# Chapter 7

## Adaptive reverse warning

This chapter presents the development of solutions for making the audible reverse warning adaptive to take one step closer to realising the project's aim of reducing noise pollution.

### 7.1 Concept generation of an adaptive reverse warning

When generating ideas for an adaptive reverse warning, brainstorming sessions were performed. During the first round of brainstorming, the general purpose of the adaptive reverse warning was discussed to gather factors that impact when and how the sound volume should be adapted. The result of the initial brainstorming session was a realisation that the ambient noise level, number of VRUs present, and truck speed could impact the required sound volume. The factors can be seen in Figure 62 and are elaborated on in the following paragraphs.

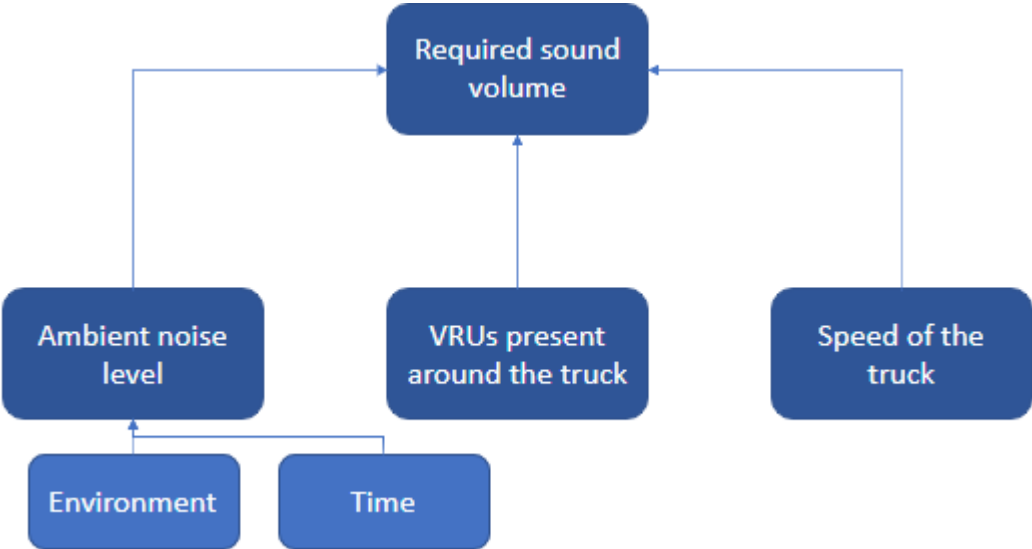


Figure 62. Factors that impact how the reversing sound should be adapted.

*Ambient noise level.* It is essential that the sound can be heard, and the ambient noise level directly impacts the required volume of the sound. The ambient noise level is affected by the environment, e.g., the noise is generally higher at a construction site and in the city. Another contributing factor is time; the noise level is usually higher during the day when work is performed on the construction sites and when people move around in the city.

*Presence of VRUs.* The presence of VRUs around the truck impacts the required volume of the sound. If there are no VRUs around the truck, there is a lower need to warn about the truck reversing. If there are VRUs present around the truck, there is a higher need to warn about the truck reversing. The environment and time, in turn, impact the number of VRUs present around the truck.

*Speed of truck.* Increased speed increases the risk of accidents in a reversing situation. Meanwhile, an idling truck does not expose the VRUs to any harm. Whether the truck is idling or moving and at what speed the truck is driving should be considered when adapting the sound volume.

The second brainstorming session generated ideas on the adaptive reverse warning. To ease the brainstorming process, one factor was considered at a time. The results of how and when to adapt the volume of the reverse warning can be seen in Figure 63. The generated solutions are explained in the following paragraphs.

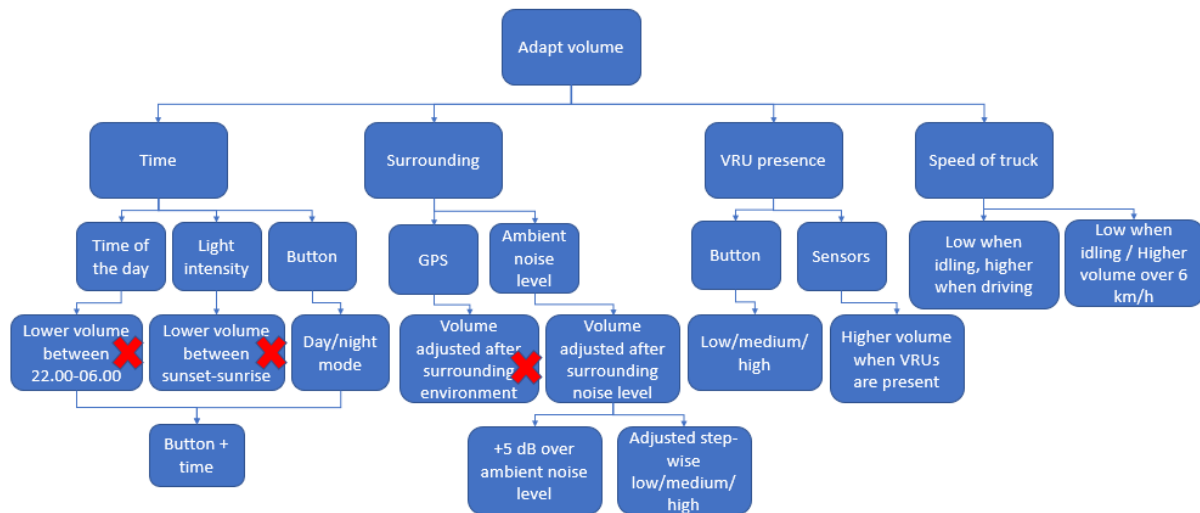


Figure 63. Generated ideas for how and when to adapt the volume of the reverse warning.

The first factor that was discussed in the brainstorming session was time. Since the sound levels are generally higher during the day, one generated idea is to reduce noise pollution during the night and early morning by specifying that the volume of the reverse alarm is lower between a specific time interval, e.g., between 22.00 and 06.00. Another generated idea is to adjust the volume depending on the light intensity by either measuring the light intensity or specifying a lower volume between sunset and sunrise. However, this idea was eliminated because it would not be feasible to implement in, e.g., Sweden, where the sun sets early in the forenoon during winter and late hours during summer. The third idea for adjusting the volume depending on the time is to have a button that lets the driver manually switch between day- and night mode from inside the truck, where day mode implies a higher volume, and night mode a lower volume the sound. The driver selects depending on the environment, time or presence or VRUs. The solution is illustrated in Figure 64.



Figure 64. Depending on the environment, time, and presence of VRUs, the truck driver chooses an appropriate warning sound volume.

The second factor discussed during the brainstorming session was the trucks surrounding environment. Since the ambient noise level generally depends on the truck's environment, one idea was to use a GPS that senses the environment and adjusts the volume depending on the truck's location. For example, this would imply a lower volume on a residential street, a medium volume in a city environment, and a higher volume at a construction site. This idea was, after some consideration, eliminated due to the realisation that it would be much more reliable to sense the sound levels in a specific environment. By doing so, the sound of the alarm can be adjusted stepwise by sensing the ambient sound level and adapting the sound of the reverse warning to high, medium, or low. Another alternative is to adjust the sound of the

reverse alarm to always be, for example, 5 dB above the ambient noise level. Adapting the sound based on the ambient noise level in the environment is considered more reliable than only sensing the environment since the conditions in a specific environment often change. The solution is illustrated in Figure 65.



Figure 65. Depending on the ambient noise, the volume of the warning sound is automatically adapted.

The third factor that ideas were generated for is the presence of VRUs. The presence of VRUs could be used as input when adapting the volume by letting the driver manually control the sound volume by pressing a button when the area around the truck is crowded, thus requesting a higher volume. Another idea is to install sensors on the truck that sense VRUs in the area around the truck and automatically adjust the volume depending on the presence of VRUs. The later solution is illustrated in Figure 66.

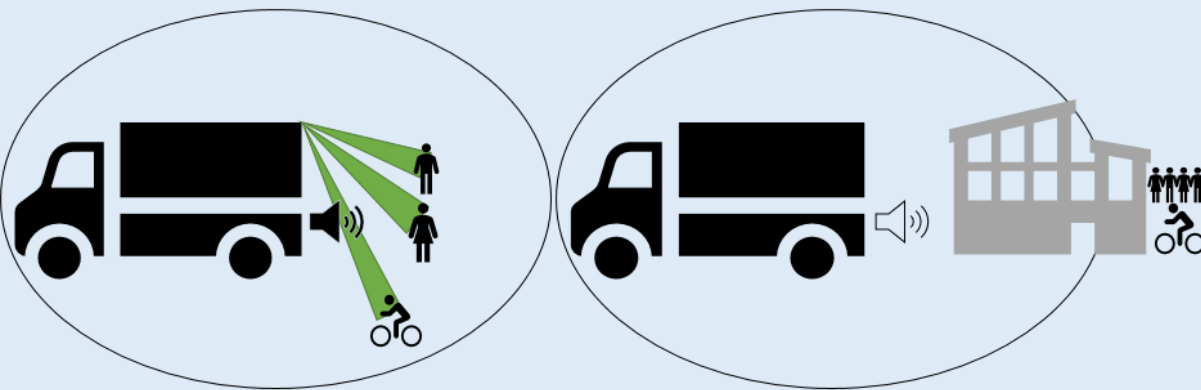


Figure 66. Depending on the presence of VRUs, the volume of the warning sound is automatically adapted.

The fourth factor discussed was the state and speed of the truck. One way to lower noise pollution is to reduce the sound when the truck is idling. When the truck is idling, it cannot cause any danger, and therefore the same volume is not required as when driving. One idea is to have a lower volume when idling and a higher volume as soon as the truck moves. Another idea is to have a lower volume when idling and a higher volume when the truck passes a specific speed, for example, 6 km/h. The solution is illustrated in Figure 67.



Figure 67. Depending on the truck's status and speed, the volume of the warning sound is automatically adapted.

To summarise the results from the idea generation, the following solutions were chosen to proceed with:

- Adapting the volume of the sound manually with a button that the driver controls from inside the truck depending on the environment, time, or presence of VRUs. The button has a day/night mode or high/medium/low mode.
- Adapting the sound volume automatically by sensing the ambient noise level. The sound is either stepwise adapted or adapted to always be, for example, 5 dB higher than the ambient noise level.
- Adapting the volume of the sound automatically based on the presence of VRUs.
- Adapting the sound volume automatically based on the truck's state and speed.

## 7.2 Evaluation of solutions for an adaptive reverse warning

In this chapter, the previously presented solutions will be evaluated by listing the advantages and disadvantages of each idea and determining for which segment the solutions are most suitable.

### 7.2.1 Methodology for evaluating solutions for an adaptive reverse warning

When evaluating the generated solutions for an adaptive reverse warning, pros and cons lists were chosen as the primary evaluation method. The pros and cons lists are selected over evaluation matrices because the solutions can be suitable for different segments. It would be hard to produce evaluation criteria that result in a fair assessment of the solutions. Another reason for not choosing evaluation matrices is that they have been used throughout the previous concept evaluation process of the reverse warning, and it is suggested to use a set of different evaluation methods in a product development project to evaluate solutions from different perspectives (L. Almefelt, personal communication, January 18, 2021). The pros and cons lists were produced by performing brainstorming sessions and performing literature studies.

### 7.2.1 Results from the evaluation of solutions for an adaptive reverse warning

#### 7.2.1.1 Adapting the volume of the sound manually with a button

The advantage of using a button to adapt the sound manually is that the driver has high control of the emitted sound. When the driver wants to reverse in a crowded place and needs the gain attention from the VRUs passing, the driver can choose to press a button to emit a higher volume sound. In the opposite situation, with no VRUs present around the truck, the driver can choose to emit a lower volume sound from the truck. The advantage is thus that the

driver can adapt the sound based on the driver's judgement of the environment, time, and presence of VRUs.

The disadvantage of the solution is that the driver might not bother to adapt the sound at all and only use the preset setting. This is likely to happen if the selection must be made every time the truck starts reversing, as it increases the risk of the driver forgetting to make the selection or refusing to add another step in the start routine. Another disadvantage is the driver's risk of misjudging the situation and causing higher noise pollution or lower safety for the VRUs. As the driver controls the sound volume from inside the truck, it is easy to misjudge the ambient noise level outside of the truck and lose track of VRUs located in the driver's blind spots. The driver could also misuse the control by emitting a high sound in situations that do not require a high sound, for example, to get VRUs to move out of the way faster.

#### 7.2.1.2 Adapting the volume of the sound automatically based on the ambient noise

The advantage of adapting the sound automatically based on the ambient noise level is that the driver is released from the duty of analysing each situation and selecting a sound level before initiating a reversing manoeuvre. The driver can instead focus on the road and keep track of VRUs, while the sound of the warning is automatically adapted. Besides this, the driver might be more alert when a higher sound is emitted, as the driver knows that this could imply a busy area and a need to be more cautious. Another advantage is that the solution guarantees that the sound of the reverse warning will always be heard, as it is always adapted to be higher than the ambient noise level. This increases the safety, as the VRUs will always be able to hear the sound. Further, the noise pollution is reduced as a lower volume of sound is emitted in areas with low ambient noise, which is especially advantageous during deliveries in late evenings and early mornings. The advantage of adapting the sound stepwise by emitting either a low, medium or high volume depending on the ambient noise is that the emitted sound contains more minor variations than when adapting the sound to be 5 dB over the ambient noise. However, the advantage of adjusting the sound constantly to be 5 dB over the ambient noise is that the volume of the emitted sound is always optimal.

The disadvantage of this solution is the sensitivity and possible risk of high variations in sound output. A potential risk is that minor signals, such as a car honking, will result in a sudden increase in sound volume. The hypothesis is that the solution that adjusts the sound volume always to be 5 dB higher than the ambient noise will contain high variations in sound volume that might cause irritation and ultimately increase noise pollution. However, further evaluation is needed to decide which solution is more suitable.

#### 7.2.1.3 Adapting the volume of the sound automatically based on the presence of VRUs

The advantage of adapting the volume of the sound automatically based on the presence of VRUs is that higher volumes will only be emitted when truly needed. This will, in turn, reduce noise pollution even more than with the previously presented solution because there is no need to emit a high sound when the ambient noise level is increased if there are no VRUs present. With this solution, the driver might be even more alert when a higher sound is emitted, as the driver knows that this implies that VRUs are in the danger zone and that there is a need to be more cautious.

The disadvantage of this solution is that it depends on the sensor's input, and if the sensors do not register a VRU, the safety is decreased. The VRU might not be able to hear the sound if

the ambient noise level is high, and the driver might think that no VRUs are present as a higher volume sound is not emitted. Another disadvantage when not registering the ambient noise level and only VRUs, is that the sound must be emitted with a high volume to guarantee it is not masked by the ambient noise, which might lead to increased noise pollution. Another identified disadvantage is that VRUs approaching the truck from behind a corner might be registered only when behind the truck. This is a disadvantage, especially for visually impaired persons, who might be frightened by the sudden higher volume sound.

#### 7.2.1.4 Adapting the sound volume automatically based on the status and speed of the truck

Adapting the sound volume based on the truck's status and speed is advantageous as it decreases noise pollution by lowering the sound volume when the truck idles. In busy streets, the truck drivers often need to wait a long time before reversing as they make sure no VRUs are behind the truck. Since the truck does not expose the VRUs to any danger when standing still, emitting a high-volume sound in these situations causes unnecessary noise pollution. The disadvantage of this solution is that the VRUs might not respond to the lower sound of the warning when the truck is idling. If the warning volume is low, it might not be enough to signalise that the truck is ready for movement. The risk is that VRUs would not move out of the way of the truck, which would make it hard for the truck driver to perform the reversing manoeuvre.

### 7.3 Recommendation

After evaluating the advantages and disadvantages of each solution for an adaptive reverse warning, the solutions are evaluated against the different truck segments. The aim is to recommend which solution is suitable for each segment. The segments have previously been described, see Sub-chapter 3.1 *Market segmentation*, which is used as a background to the evaluation.

#### 7.3.1 City distribution

City environments are characterised by being hard to manoeuvre the truck due to narrow streets and many road users, such as VRUs and cars. A truck moving on the city's narrow streets often needs to perform reverse manoeuvres, as there is seldom enough space to turn the truck around.

Because the trucks reverse frequently, adapting the sound volume manually would not be optimal in the city environment. Performing frequent reversing manoeuvres increases the driver's risk of forgetting to adjust the sound before driving. As the environment is considered challenging to manoeuvre the truck, the driver is often occupied with tracking traffic. Further, the varying ambient noise levels and many VRUs present would put a lot of responsibility on the driver to choose the right sound volume. Since the environment is already demanding to drive in, the driver should not be responsible for more steps than what is currently needed. Adapting the sound volume automatically is therefore considered more suitable.

Adapting the volume automatically depending on the presence of VRUs would be challenging in a city environment. The observations performed in the city environment, see Chapter 4, showed that trucks often cross intersections when reversing. A potential risk is that the sensors used to sense VRUs would not notice VRUs behind corners. Activating the reverse warning when the VRUs appear behind the truck can be too late. In addition, VRUs with visual impairments need to be warned before crossing intersections to choose whether to wait or walk further.

Adapting the sound volume automatically depending on the ambient noise level would be more suitable for trucks moving in city environments. The ambient noise in the city varies depending on the presence of other road users, such as cars and trams, and construction work performed nearby, among others. The sound of the reverse warning should be adapted to be above the ambient noise level to ensure that the sound volume is optimal for the VRUs passing near the truck.

As previously mentioned, the truck drivers often need to wait a long time before reversing in busy streets to make sure no VRUs are behind the truck. Besides adapting the sound based on the ambient noise, the final recommendation is to also adapt the sound to be lower when the truck is idling to reduce the noise pollution.

### 7.3.2 Construction

Construction sites are characterised by high ambient noise levels and trucks reversing at spots that lack proper indications, such as signs and road markings. Unauthorised people are usually not allowed on construction sites; the people present are mainly workers. Due to the high ambient noise, the workers typically wear hearing protection, making them less alert to the surroundings.

Because the trucks reverse frequently and manoeuvring the truck is difficult in the environment, adapting the sound volume manually is not considered suitable. The driver should not be responsible for more than what is currently needed, and an automatically adaptive solution is preferred.

Adapting the sound volume automatically based on the ambient noise is not considered suitable at a construction site. The high ambient noise level would result in a constantly high sound volume of the reverse warning, which ultimately results in increased noise pollution. Because other construction machines are used on the site simultaneously that emit warning sounds, the optimal solution would be to only warn workers present in the danger zone about the reversing truck.

Sensing the workers and only emitting a high sound when a worker is in a dangerous zone would increase safety because the workers would know that they should be more observant when they hear the warning sound. Further, the solution would decrease noise pollution by emitting a lower sound when no VRUs are present. Using radiofrequency identification (RFID) systems to sense the workers at a construction site instead of using advanced sensor technology is possible. The workers use specialised clothing, such as vests and hats, making it possible to equip the clothing with RFID tags. The system can then detect the RFID tags, thereby the workers, when they are present around the truck and emit a higher volume sound (IHSA, n.d.).

Adapting the sound volume depending on whether the truck is idling or moving is considered unsuitable at a construction site. Since the workers wear hearing protection, they might not hear the lower sound volume that signals the truck being ready for movement. The truck should instead be equipped with visual signals that indicate departure.

The recommendation is thus to adapt the sound volume depending on the presence of VRUs, in this case, workers at the construction site.

### 7.3.3 Long-haul and regional distribution

Long-haul and regional transportation is characterised by fewer delivery spots and hence fewer reversing manoeuvres. The trucks are often loaded and unloaded at loading docks where unauthorised people are absent.

Because the trucks are seldom reversed among VRUs, there is no need to adapt the sound volume automatically. Adjusting the sound volume manually with a button would be enough for this segment. The driver will have time to choose the right sound volume prior to reversing because the environment is often not demanding to drive in.



# Chapter 8

## Final concept

This chapter presents the results of the selection of audible and visual signals for the final concept, along with a solution for how the audible reverse warning should be adapted to reduce noise pollution. The results from the previously performed evaluations are used as a starting point for the selection, along with discussions in the project group.

## 8.1 Selection of visual signals

The previously performed evaluation in virtual reality showed that the concept with flashing lights and the concept with projections on the ground yielded the most satisfying results in terms of warning VRUs of a reversing truck. For the final concept, it was decided to combine the two concepts to obtain the benefits of both solutions. As a result, the final concept consists of lamps with flashing white lights on the rear and sides of the truck, along with a projected warning triangle on the ground at the rear of the truck, see Figure 69. The placement of the lamps for the final concept is the same as evaluated in virtual reality, one lamp is placed on each side of the truck, and two are placed on the rear of the truck. The lamps flash two times fast, followed by a short pause. The sequence “flash-flash-pause” takes 0,5 seconds in total.

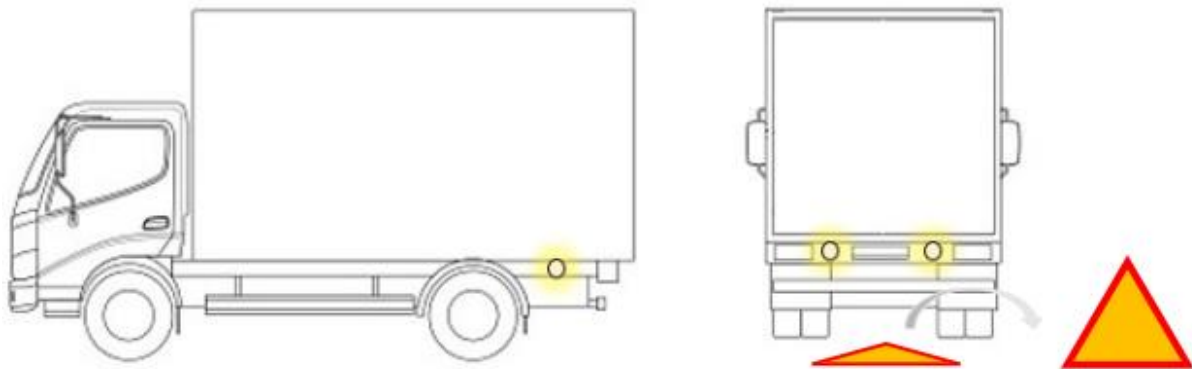


Figure 68. The visual signals of the final concept.

## 8.2 Selection of audible signals

The evaluations performed, both by surveys and in virtual reality, showed that the tonal sound used in today’s solution was best perceived as a warning for a reversing truck. The sound is well known for its purpose in society, and the results were therefore not surprising. Based on the evaluations performed, a decision was taken to keep the tonal alarm and implement an adaptive solution to reduce noise pollution. However, results from the evaluations have shown that it would be possible in the future to change the audible reverse warning to a sound that is perceived as less annoying but still call for the VRUs attention.

## 8.3 Selection of an adaptive solution

Since the project group’s recommendation is to keep the tonal sound, an adaptive solution is essential to reduce the noise pollution from the sound. In the previous chapter, various types of adaptive reverse warning solutions were discussed. The recommendation for the final concept is an adaptive solution that automatically adjusts the sound of the reverse warning depending on the ambient noise level. A stepwise adjustment of the sound is recommended for the final concept, where the sound is emitted in either a high, normal or low volume depending on the measured ambient noise level. The volume intervals for the solution must follow the required volume intervals presented in the UN regulations. Low level is between 62 and 77 dB, the normal level is between 77 and 92 dB, and the high level is between 97 and 112 dB (TF RWS, 2022). To decide on specific volume levels, it would be necessary to perform tests to find the optimal volume levels. Furthermore, the sound should be adapted depending on the status of the truck, i.e., whether the truck is standing still or moving. When the truck is standing still, a low volume sound, between 62 and 77 dB, should be emitted independently of the ambient noise level, since the truck does not expose VRUs to any danger when standing still. The proposed function of the adaptive solution is presented in Figure 70.

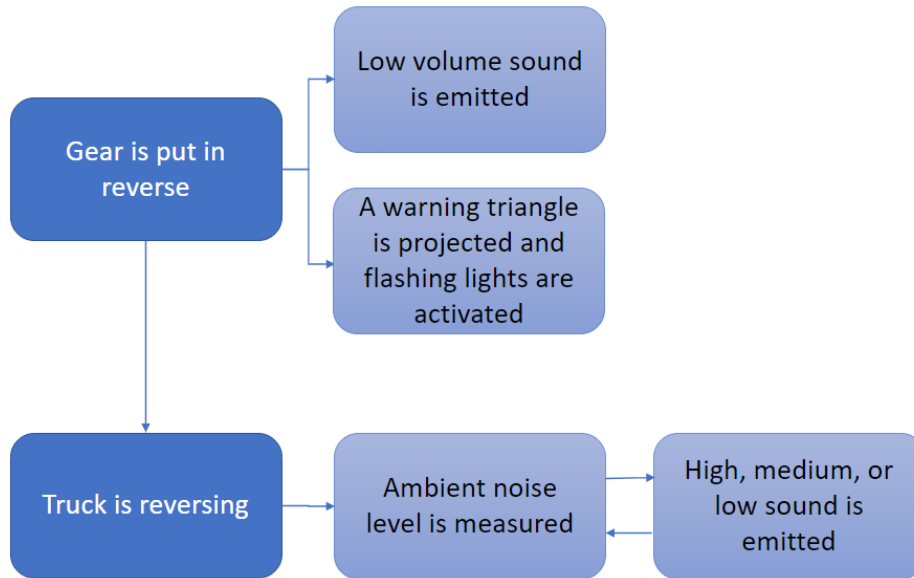


Figure 69. The function of the adaptive solution for the final concept.

## 8.4 Evaluation of the final concept's fulfilment of requirements

In Chapter 5, the developed requirements specification was presented. The final concept was evaluated against the requirements, to assess whether the final concept fulfils the requirements. Table 24 presents the result of the evaluation, where the fulfilment of each requirement is specified in the second column. The results show that the final concept fulfils 13 of the 20 stated requirements and that further investigation is needed to decide whether the final concept fulfils the remaining seven requirements.

The requirement “The sound should be environmentally acceptable” was stated as a wish in the requirement specification. The sound *Tonal Original* was considered as annoying by several survey responders, see Table 9. However, since the sound in the final concept is supposed to be adaptive, the concept is foreseen to be more environmentally acceptable. To assess whether the concept fulfils the requirement, further testing would be needed. The requirements “The sound should not be masked by the environment” and “The sound should be locatable” were not verified for the concept as the requirements were not included in the scope of the project. Before commercializing the concept, the requirements should be verified with tests to assess whether they are fulfilled. Finally, the requirements regarding the visual signals being visible in all light and weather conditions were also not included in the scope of the project and hence not verified. Before commercializing the concept, it would be necessary to investigate the visual signals, and especially the projected warning triangle, in terms of visibility.

Table 24. The final concept's fulfilment of requirements.

Requirement	Metric	Requirement fulfilment
<b>Audible reverse warning</b>		
<b>1. Requirements regarding improved safety for VRUs.</b>		
1.1 The sound should be interpreted as a warning.	>80% of participants interpret the sound as a warning	Fulfilled
1.2 The sound should be interpreted as emitted from a vehicle.	>50% of participants interpret the sound as a vehicle	Fulfilled
1.3 The sound should be interpreted as emitted from a reversing vehicle.	>30% of participants interpret the sound as a reversing vehicle	Fulfilled
1.4 The sound should be understandable without knowledge of a specific language.	Yes/no	Fulfilled
1.5 The sound should not be masked by the environment.	>90% of participants recognize the warning in noisy environment.	Further investigation is needed
1.6 The sound should be locatable.	>60% of participants can localize the source of the sound.	Further investigation is needed
<b>2. Requirements regarding decreased noise pollution.</b>		
2.1 The sound should be environmentally acceptable.	Participants perceive the warning as not irritating.	Further investigation is needed
2.2 The sound should be adaptive.	Minimum of 3 sound levels.	Fulfilled
<b>3. UN regulations regarding the audible reverse warning.</b>		
3.1 Sound level.	$62 < \text{dB} < 112$	Further investigation is needed
3.2 Number of repeated cycles.	24-120 cycles per minute	Fulfilled
3.3 Sound frequency.	$1000 \leq \text{Hz} \leq 3500$	Further investigation is needed
<b>Visual reverse warning</b>		
<b>1. Requirements regarding improved safety for VRUs.</b>		
1.1 The visual signal is interpreted as a warning.	>80% of participants interpret the sound as a warning.	Fulfilled
1.2 The visual signal is interpreted as a reversing vehicle.	>30% of participants interpret the sound as a warning.	Fulfilled

Requirement	Metric	Requirement fulfilment
1.3 The visual signal should be seen from the rear and sides of the truck.	Yes/no	Fulfilled
1.4 The visual signal is visible in all light conditions.	Visible from >10 m distance.	Further investigation is needed
1.5 The visual signal is visible in all weather conditions.	Visible from >10 m distance.	Further investigation is needed
1.6 The visual signal is only activated in reversing situations.	Not visible when not reversing.	Fulfilled
<b>2. Technical requirements.</b>		
2.1 The visual signal does not interfere with other functions.	Yes/no	Fulfilled
2.2 The visual signal does not disrupt other road users' view.	Yes/no	Fulfilled
2.3 The visual signal does not emit materials during use.	Yes/no	Fulfilled



# Chapter 9

## Discussion

This chapter provides a discussion of the methodologies used in this thesis and the results of the work.

## 9.1 Personas and market segmentation

Creating personas was rewarding since it contributed to extended thinking and the realisation that different VRUs will have different needs regarding the applied warning signals on a truck. The initially created personas were mainly built on assumptions about different types of personalities. These were later to some extent proven by the results from the performed observations and interviews. Therefore, the personas were deemed to be of relevance to serve as input in the concept generation process.

The personas do not cover all types of personalities, which would be impossible to achieve, but the personas were deemed to cover a broad range of personalities and needs. Producing a wider range of personalities might improve the result by including even more needs. However, this would have widened the scope of the project more, and the limited time would have been a problem in order to evaluate all needs.

The market segmentation was also rewarding to understand the problem, and in which segment most VRU encounters occur. By achieving this understanding, further work could focus on the segment with a higher need. The project group believed that a segment with less frequency of VRU encountering, a solution designed to work efficiently for a segment where the need is more significant, would work well. However, this needs to be evaluated further to ensure that each segment's important needs are not overlooked.

## 9.2 Observations

One of the project's research questions is investigating how VRUs perceive reversing trucks and what influences their behaviour. To do so, the project group performed observations where the focus was to spot reversing trucks and observe how vulnerable road users behave around the trucks. Performing the observations was very time demanding because the project group was required to be at the right place at the right time to spot trucks reversing where vulnerable road users are present. To make the observations more efficient, the scope of the observations could be widened to include trucks moving forward as well. Then it would be possible to investigate if a person's behaviour in traffic is similar, independent of if the truck is reversing or moving forward.

Furthermore, it is necessary to perform many observations to draw conclusions about how different VRUs behave. The validity of the results from the observations can therefore be questioned, as the number of observations performed is not enough to draw any definitive conclusions about how a group of people behave. The validity of the results could be affected since the observations were performed at different locations. However, this was deemed not to significantly affect the results in this thesis work since the observations aimed to gather a general understanding of behaviours and not analyse specific behaviours in specific reversing situations. However, the validity would perhaps increase if it had been possible to arrange a planned observation by hiring a truck and instructing the driver to perform the reversing manoeuvre multiple times at the same location.

To gain further knowledge of how vulnerable road users perceive situations with reversing trucks, the project group could have asked the observed VRUs some questions, e.g., what the VRUs were thinking in the situations.

During the reverse warning sound test, the aim was to observe how vulnerable road users react to the sound. The validity of the results can be questioned because the sound was

emitted from a speaker and the sound volume was lower than the volume of a real alarm. Further, no truck was used in the test, which decreased the validity of the test. If a truck had been parked around the corner where the sound was emitted, the VRUs would probably have reacted differently. With no truck available, it is only possible to study how the VRUs behave when approaching the corner.

### 9.3 Interviews

The semi-structured interviews were a promising approach for the performed interview sessions. The pre-formulated interview question enabled a structured interview where all interviewed truck drivers had to answer the same questions, and the group could later compare the answers. However, since a semi-structured interview allows the interviewer to add questions along the way, more elaborative explanations can be gained, and statements can be followed up.

The interviews were relatively short, approximately 10 minutes, depending on the respondent's elaborative answers. The interviews could have been designed to be longer since the number of performed interviews was relatively few. However, the project group felt that the provided answers fulfilled the aim of the interview, and a pattern could be found in the provided answers, which induced that no more interviews were needed. It was beneficial to interview drivers with diverse experiences since it gave the project an understanding of the problem and where the need for an improved reverse warning was needed most. The interviews gave inputs to formulate a market segmentation, and assumptions made when formulating personas were confirmed.

A recognised improvement to further similar interviews is to include a question where the driver should describe the current warning signals on the truck. Some companies equip their trucks with extra warning signals, often different lamps, which influence the driver's answers to some of the questions. Nevertheless, this information was most often retrieved during the interviews, but a specific question considering this information would have been helpful.

The KJ method was chosen as the analytical method for this interview, which was suitable. The KJ method visualises the provided answers and identifies similarities and differences. The interviews were chosen not to be transcribed since it is a very time-consuming method. Since comprehensive notes were made during the interview and the interviews were audio-taped, this was deemed enough to analyse the data. Both group members had also been present during all interviews, which made both members well aware of the information gathered during the sessions. However, the risk of missing statements or correlations between different interviews would be higher when transcription is chosen to be excluded.

No drivers with experience in driving at construction sites were interviewed, due to that, a decision was made to limit the scope to the market segment "City distribution". However, it would be interesting to investigate the need for workers located at construction sites to see if there are different needs than the needs discovered for users located around a reversing truck in a city environment.

## 9.4 Concept generation

Two different approaches were used to generate concepts in the concept generation process. With the thematic approach, the project group could develop concepts quickly by combining sub-concepts in the Morphological matrix using different themes as a starting point. The thematic approach was an opportunity to include the previously made personas in the concept generation process and develop concepts that satisfy their individual needs. The approach was more systematised than if the concepts had been generated randomly. The thematic approach helped unlock creativity in the project group and widened the understanding of the personas and their individual needs.

All concepts generated with the thematic approach were eliminated in the concept evaluation as they were considered inferior. When an iteration of the elimination was performed, where the sub-concepts of touch were excluded, only three of the twelve generated concepts passed the elimination. The reason for this was that the concepts consisted of inferior sub-concepts. When the sub-concepts were developed in the brainstorming sessions, all sub-concepts were taken further to the morphological matrix. Suppose the sub-concepts had been evaluated before they were put in the morphological matrix, sub-concepts that were considered inferior could have been eliminated or further developed into realisable sub-concepts. Then, more concepts generated with the thematic approach would be taken further. All ideas on sub-concepts were taken further because the generated ideas signalled warnings that were theoretically optimal. For example, smoke is a signal that could be recognised as a warning. However, in practice, the solution is not optimal to warn about a reversing truck. Among the concepts that passed the second elimination, two out of three were identical to the concepts generated with the other approach, which shows that the concepts are good because they proceeded in two different processes.

Among the sub-concepts evaluated during the elimination approach, only the best solutions were combined into concepts. By assessing the sub-concepts before combining them into concepts, the size of the morphological matrix could be reduced, and it was possible to take all combinations of solutions further. The risk with the approach is reasonable solutions being eliminated along the way because only a few sub-concepts were taken further in the evaluation. The sub-concepts evaluation was performed based mainly on assumptions about the concepts. This was done since there was no time to test the sub-concepts, and the project group needed to move further with the process. The approach was more time-consuming than the thematic approach, but it yielded many more concepts that were all realisable. If the project group would redo the concept generation process, the group would choose to combine both approaches again. However, before generating any concepts, the ideas from the brainstorming session should be evaluated to remove or improve the inferior concepts. The concepts generated with the thematic approach would then include realisable sub-concepts, and many more concepts would probably be taken further in the concept evaluation process.

## 9.5 Survey

The survey gave valuable insights into the project and enabled easy concept evaluation. Since most of the questions were designed with a rating system, the collected data was easy to analyse. The aim was to receive 50 answers. The result was 37 responses. However, this was a good result since the survey took approximately 20 minutes to complete, which was more time than intended. When analysing the collected answers for each sound, the project group could see a consistent pattern in how people would rate the concept. For example, it was rare

to see a concept rated with several low and high scorings for the same question. This could indicate that the number of responses was enough to conclude a result.

The nine sounds included in the survey were presented to the survey respondent in the same order. A continuous order could induce a risk that the later sounds would be evaluated with less accuracy; due to the respondent becoming tired of the test since all the questions for each sound were the same. This issue was thought of before the survey was sent out. However, no good solution of how the sounds could be shuffled was found. Nevertheless, if a similar survey were to be performed, a solution for this would be beneficial to gain results with higher accuracy.

The survey respondent did not receive specific information regarding the sound or its intended purpose and situation. The initial plan of the survey was that the provided information should not influence the respondent's answers. They were supposed only to give answers to their perception of the sound. However, the questions in the survey would have most definitely given the respondent an indication of the sound's intended purpose. The results would perhaps be different if the survey had told the respondent to answer the questions from a specific perspective, e.g., a VRU located in a city environment.

## 9.6 Concept evaluation with matrices

During the concept evaluation process, evaluation matrices were used. Through the evaluation matrices, it was possible to gain an understanding of how the concepts compare to each other.

For concepts that do not pass an evaluation matrix, it is recommended to investigate and see the reason for the elimination. If two concepts are eliminated, they could be combined to yield a concept that potentially passes. In this project, the project group did not focus on further developing the eliminated concepts due to lack of time and the project needed to move further. By not including more development loops in the concept evaluation process, there is a risk that some eliminated concepts were removed too fast.

It is recommended to perform Pugh matrices with different references until a trend can be observed. In the concept evaluation process, the Pugh matrices were only performed once for each category of solutions. The reason for this is that the concepts in each category were very similar as they consisted of the same visual signals on the rear of the truck, and there were few concepts. However, iterations of the Pugh matrix were performed during the sub-concept evaluation.

All evaluation matrices were performed based on assumptions about the solutions. For example, the project group assumed that lamps with travelling lights would indicate the direction of the truck better than lamps with continuous lights. Since this had not been tested, there are uncertainties in the evaluation. To evaluate the concepts with more evidence, concepts could have been tested earlier, and the results could have worked as a base. However, this would have been a very time-consuming process which would have been challenging to complete within the time frame of this project.

## 9.7 Concept evaluation with Virtual reality

Instead of building physical prototypes, virtual prototypes were used to evaluate the concepts. The evaluations in virtual reality yielded fast and easy testing of concepts, and multiple people were able to test the concepts during equal prerequisites.

Choosing only to evaluate one concept per person turned out to be a good decision. Even though each concept was presented in three different situations, the participants were, in many cases, not able to respond to how they perceived the signals. If more than one concept had been presented per person, it would have been harder to recognise each concept's signals and differentiate between them.

The participants could not always evaluate the concepts because they were not told to do so before the tests. The concept of the travelling lights was especially complex for the participants to review, as they did not reflect upon the lights when seeing the truck. When the participants were asked if the lights signalled any direction, none observed a specific pattern. If the participants had been told to observe the truck, the hypothesis is that the participants would have understood the signals better. However, the results would not have been reliable. The chosen methodology worked well for evaluating how warned the participants felt by the concepts without compromising the trustworthiness.

Another reason why some of the participants could not observe any signals was because they had had no prior experience with virtual reality. They might have focused more on observing the virtual world than acting as they would do as pedestrians. Including an introductory exercise before the evaluation could reduce the risk of getting caught up in the virtual world.

All participants in the tests were employees at Volvo, where the majority of the participants were men. Since all participants were adults, it was impossible to capture how all personas perceived the concepts. A more varied group of participants, including children, seniors and more women, would have been beneficial to evaluate if different personas perceive the concepts differently. Further, more aspects could have been included to get further insights into how the concepts are perceived. For example, letting the participants listen to music or look down as if they were looking at their phones. As a complement, the sound and visual signals could also have been tested separately to evaluate the separate solutions. When tested together, the two different signals have probably affected each other. However, it was deemed necessary also to test the solutions together to get the whole perspective of the warning signal. Worth mentioning is that some test participants mentioned that they felt warned of the engine sound from the truck and the visualisation of the truck itself. This could also have affected the perception of the warning signals. However, all concepts were tested on the same truck; thereby, the truck's natural sound and appearance would have equally affected all tested concepts.

## 9.8 Adaptive reverse warning

The development of an adaptive reverse warning was separated from the development of the reverse warning in this project. At first, the project group considered including the function "adapt sound" in the Morphological matrix and then combining concepts which included the sub-solutions for how to adapt the sound. However, after some consideration, it was decided first to develop a reverse warning and then give suggestions for adjusting the sound of the warning. This is because the adaptive solutions work with any reverse warning sound, and it was considered most optimal to find the solution that works best. Furthermore, it would be hard to select suitable adaptive solutions for the different themes before evaluating the solutions.

The concepts were evaluated with pros and cons lists, which worked well. The project group started to evaluate the concept with the Pugh matrix but quickly realised that it was hard to find proper criteria to use in the evaluation since the solutions are optimal in different

segments. The pros and cons lists were considered easier to carry out, and they were helpful when selecting which solution would be optimal in which segment.

The solutions for adapting the sound were never tested in VR because the tests already consisted of multiple situations and concepts. Including more factors to test would require more participants and time. Also, it is not sure that the participants would notice the differences between the adaptive solutions since they mainly control the sound's volume. The noise in the virtual environment is constant, so it would not be possible to test the solutions that adapt the sound volume based on the ambient noise level.

During the evaluation in virtual reality and performed observations in city environments, the project group could observe that the participants were often unsure about how to proceed when the truck was standing still with the reverse warning activated. Findings during the project yielded ideas of how an adaptive solution could be used to convey information about the vehicle's departure, which possibly could enhance safety even more. Adapting the audible and visual signals depending on the status of the truck, i.e., standing still or moving, could perhaps make it easier for VRUs to understand the intentions of the truck. This could perhaps be done by adjusting the sound volume, emitting different sounds in different stages, emitting a short distinct signal when the truck starts to move, e.g., a "ding", or adding visual signals that only warn when the truck moves. Considering the time limit and scope of the project, these solutions were not further evaluated. Still, the aspect of signalling departure could be of interest for further development of the reverse warning.

## 9.9 Final concept

Since the visual signals consisting of lamps only have been tested in one set-up regarding, e.g., quantity, placement, and flash rate, there could be of interest to assess whether there exists a more optimal solution for the chosen visual warning signal. Regarding the projection, alternative projected symbols could be tested to assess if the warning triangle is the most optimal solution, or if, for example projected arrows or a symbol of a reversing truck would work better. It would also be necessary to test the visibility of the projections in different light and road conditions.

The project group felt that not enough tests had been performed to suggest another suitable sound to the audible reverse warning. However, through the project, the project group managed to develop several sounds, of which some were perceived as warnings that would work well to warn about a reversing truck. Furthermore, the sounds were not perceived as annoying as the tonal sound used in today's solution. This could suggest that it would be possible to switch to a less annoying sound in the future. However, further tests would be needed to verify that the sound work as warnings and that society can recognise it as reverse warnings in a larger picture. It would also be necessary to ensure that the selected sound meets the requirements of an audible reverse warning before it is put into use. For example, ensure that the sound is locatable, that the ambient noise does not mask the sound, and that the sound waves from the emitted sound and vibrations on the truck do not interfere.

The literature studies showed that the white sound has several benefits compared to the tonal alarm. However, this sound was eliminated in this thesis since it received low ratings from the survey participants. Perhaps it could be argued that the white sound should have been taken further because it is an existing sound that has been recommended as a good audible reverse warning alternative through other studies.

## 9.10 Discussion of the research questions fulfilment and the final approach

Both provided research questions were of relatively broad scope. To answer the first research question and convey an answer with scientific evidence was perhaps not fully answered. However, a basic understanding of different VRU behaviour was provided, and the result was deemed reasonable considering the limited time frame. The research question that the project focused the most on was how to design the reverse warning to meet regulations and user needs while enhancing safety and minimising society's noise pollution. The final concept was developed by considering the stated aspects and performing relevant development activities. However, if the scope of the research question had been narrowed down, it would have been possible to deliver a more detailed final concept. For example, suppose the research question had been limited to only considering the audible reverse warning. In that case, the project group could perhaps have delivered a more detailed and more deeply analysed concept. Furthermore, it would have been possible to perform more tests to assess whether the final concept fulfilled all requirements. The proposal for an adaptive solution could perhaps also have been more deeply analysed if the development had been limited to an audible reverse warning. For example, the project group could have investigated how the adaptive solution could be used to improve safety. On the other hand, if the research questions would have been more narrowed down, the final result would not have covered as many aspects. With the wide approach, several different activities have been possible to perform, e.g., observations, interviews, creation of several sounds, and VR tests. The taken approach has resulted in several valuable results and an enlarged understanding of VRUs' needs that the project hope will be of value to Volvo.

# Chapter 10

## Conclusions and recommendations for future work

This chapter presents the project's aim along with answers to the research questions. Furthermore, recommendations for future work are given.

## 10.1 Project aim

As stated earlier in the introductory chapter, this thesis investigates how the reverse warning should be designed to meet regulations and user needs while ensuring the safety of Vulnerable Road Users (VRU) and minimising society's noise pollution. Therefore, it is necessary to study how VRUs behave around reversing trucks and what influences their behaviour.

### 10.1.1 Research question I

The first research question was:

*How do vulnerable road users perceive situations related to reversing heavy goods vehicles, and what influences their behaviour?*

The answer to this research question is based on the results from the reviewed literature, created personas, performed observations and performed interviews with truck drivers.

By reviewing the literature on how humans process information and warnings, some factors that influence the behaviour of VRUs could be identified. Social influence was mentioned as one of the factors. The behaviour of VRUs is affected by how people in the VRU's surroundings behave. Another factor mentioned is distractions from mobile phones. Taking a phone call, texting, or listening to music negatively affects a VRU's attention and encourages unsafe behaviour. Furthermore, personality is mentioned as a factor that influences behaviour. People with a cautious personality may act more cautious around reversing trucks; meanwhile, people with a risk-taking personality act less careful.

Through the created personas, the project group was able to visualise the behaviours of different VRUs, based on general beliefs about how different groups of people behave and findings from the reviewed literature. By observing VRUs in a city environment, it was possible to spot how different people behave in the situations, and patterns could be observed. The observations yielded valuable insights into how different VRUs behave, and the results could be used to complement the previously created personas. The observations confirmed how the earlier mentioned factors affect the behaviour of VRUs; persons being distracted by mobile phones did not act cautiously around the trucks, bicyclists showed risk-taking behaviour, and teenagers moving in groups were affected by social influences.

Interviewing truck drivers gained further insights into how VRUs behave around reversing trucks. The truck drivers confirmed that VRUs act differently depending on if they are pedestrians or bicyclists and depending on their age. The truck drivers described bicyclists as more prone to taking risks than pedestrians. Children were described as playful and not cautious. Older people were described as cautious; however, their slow reactions and decreased vision and hearing affect their ability to respond to different situations. Adults and teenagers were described as often being distracted by mobile phones. Furthermore, adults were described as often being in a hurry.

### 10.1.2 Research question II

The second research question was:

*How can the reverse warning be designed to meet regulations and user needs and enhance safety while minimising society's noise pollution?*

The answer to this question is based on the results from the various activities performed in the product development process.

To guide the design of the reverse warning, user needs were identified by answering the first research question, and regulations were explored by reviewing the literature. The collected user needs and legal requirements were compiled in a requirements specification used to align the generation of concepts and the later evaluation of concepts. Concepts were generated by seeking solutions for how to warn VRUs about a reversing truck better and enhance the safety of VRUs. Solutions for minimising society's noise pollution were explored by researching alternative sounds, developing new sounds, and developing solutions for how to adapt the sounds.

The generated concepts were evaluated using the Elimination matrix, the Pugh matrix, and the Kesselring matrix. The results of the evaluation with matrices were three concepts that were evaluated with tests in virtual reality. By assessing the concepts in virtual reality, it was possible to assess whether or not the concepts enhance safety and minimise noise pollution. The results from the evaluation were used to develop the final concept.

Through the project, the project group identified that the visual signal of the current reverse warning, i.e., the white reversing lights on the truck's rear, was not considered alerting enough. The final concept of the reverse warning is designed to enhance safety by adding visual signals. The visual signals consist of lamps with flashing white lights on the truck's rear and sides, which call for the VRUs' attention. In addition, a warning triangle is projected on the ground at the rear of the truck, which warns the VRUs to not enter the area behind the truck as it is reversing.

The final concept of the reverse warning is designed to reduce society's noise pollution by suggesting a solution for how to adapt the reversing sound. The reversing sound chosen for the final concept is a tonal sound commonly used in today's reverse alarms. According to the performed evaluations, the tonal sound was best perceived as a warning about a reversing truck. Hence it was chosen for the final concept. However, it was shown during the project that a different sound, perceived as more pleasant, could also be accepted as a reverse warning signal in the future.

The audible reverse warning is automatically adapted depending on the measured ambient noise level. For instance, in quiet areas, the sound level is adjusted to a lower volume level, which would reduce noise pollution in society. Furthermore, the sound level emitted from the audible reverse warning device is adapted depending on the truck's status, i.e., if the truck is standing still or reversing. This solution decreases noise pollution further without compromising safety because a truck standing still with the gear put in reverse does not expose VRUs to any harm.

At last, the final concept's fulfilment of needs was evaluated with the previously made requirements specification. The evaluation showed that the final concept fulfilled all requirements that the project group could verify in this project.

## 10.2 Recommendations for future work

The recommendation for future work is to investigate further how VRUs perceive situations with reversing trucks by performing more observations and interviewing VRUs to identify user needs first-hand. Furthermore, performing co-ridings with truck drivers could be beneficial because the VRUs could be directly observed instead of relying on truck drivers to recall their experiences.

In addition, the recommendation is to evaluate the final concept further by performing tests with a more varied group of people, to assess whether the concept enhances the safety of all personas. Then, the next step is to enter the detailed design of the final concept. The recommendation is also to continue evaluating alternative sounds for the audible reverse warning, to further decrease noise pollution by emitting a less annoying sound.

Furthermore, the recommendation is to verify if the final concept fulfils the requirements that the project group could not verify in this project.

In conclusion, the recommendation is to further investigate if and how an adaptive solution can be used to enhance the safety of VRUs by, e.g., conveying information about the truck's departure or increased intensity of the audible reverse warning when a VRU is approaching.

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## Appendix A – Elimination matrix on visual signals

Solution alternative	Solves main problem	Fulfills all demands	Compatible/Realizable	Reasonable cost	Safe	Fits portfolio	Criteria fulfilment: (+) Yes (-) No (?) More info needed (!) Check with specification		
							Decision: (+) Continue (-) Remove (?) More info needed (!) Check with the specs		
							Comment	Decision	
Bouncing lamps	+	+	+	+	+	+			+
Pulsating LED-strips	+	+	+	+	+	+			+
Illuminating warning triangle	+	+	+	+	+	-	Does not fit the portfolio		-
Foldable warning triangle	+	+	+	+	+	-	Does not fit the portfolio		-
Slideable sign	+	+	+	?	+	-	Does not fit the portfolio		-
Rotating sign	+	+	+	?	+	-	Does not fit the portfolio		-
Sign on blind	+	+	+	?	+	-	Does not fit the portfolio		-
Flags	+	+	+	+	+	+			+
Serpentines	+	-	-	-	+	-	Feasible but might be too complicated with too many connections		-
Smoke	+	-	-	-	-	-	Might signal immediate danger or fire which would disrupt other road users. Might interfere with the sight on the road.		-
Projection	+	+	+	+	+	+			+
Laser	+	-	+	+	+	+	Bad visibility		-
Scrolling text	+	+	+	+	+	-	Too old school and bulky. Only interpreted when standing next to the truck. Language?		-
Lamps underneath	+	+	+	+	+	+			+
Phone notification	+	+	-	-	-	+	Difficult to realise. Might disturb the VRU. Irritating.		-

Flashing white light	+	+	+	+	+	+		+
Headlights on top	+	+	+	+	+	+		+
Jack in the box	+	-	-	-	-	-	Takes space and interferes with other functions	-
Sign that changes color	+	+	+	+	+	+		+
White reversing light on side	+	+	+	+	+	+		+
Arrows	+	-	+	+	+	-	Visible when not reversing	-
Wheel direction	+	-	+	+	+	-	Visible when not reversing	-

## Appendix B – Kesselring matrix on visual signals

Kesselring matrix: warn visually																								
		Solution alternative																						
		Ideal			Continuous light		Bouncing light		Flashing light		Continuous LED light		Bouncing LED light		Flashing LED light		Flags		Projection		Headlights on top		Switching sign	
Criterion	W	V	T	V	T	V	T	V	T	V	T	V	T	V	T	V	T	V	T	V	T			
Interpreted as a warning	5	5	25	3	15	4	20	5	25	3	15	4	20	5	25	4	20	2	10	2	10	4	20	
Interpreted as reversing	4	5	20	4	16	4	16	3	12	4	16	4	16	3	12	2	8	5	20	3	12	2	8	
Visibility in the day	5	5	25	4	20	4	20	4	20	4	20	4	20	4	20	5	25	2	10	3	15	5	25	
Visibility in the night	5	5	25	5	25	5	25	5	25	5	25	5	25	5	25	1	5	4	20	5	25	5	25	
Low cost of product	2	5	10	4	8	4	8	4	8	4	8	4	8	4	8	2	4	3	6	4	8	2	4	
Easy installation	2	5	10	4	8	4	8	4	8	5	10	5	10	5	10	2	4	4	8	4	8	3	6	
Easy maintenance	3	5	15	5	15	5	15	5	15	3	9	3	9	3	9	2	6	3	9	5	15	3	9	
Low annoyance	3	5	15	5	15	4	12	4	12	5	15	4	12	4	12	5	15	5	15	4	12	5	15	
High reliability	2	5	10	5	10	5	10	5	10	4	8	4	8	4	8	3	6	4	8	5	10	3	6	
Low space consumption	4	5	20	4	16	4	16	4	16	4	16	4	16	4	16	3	12	4	16	4	16	2	8	
T=sumTj		175			156		158		151		142		144		145		105		122		131		126	
T/Tmax		1			0,891428 571		0,90285 7143		0,86285 7143		0,811428 571		0,82285714 3		0,828571 429		0,6		0,697142 857		0,748571 429		0,72	
Ranking					2		1		3		6		5		4		10		9		7		8	
Further development					Yes		Yes		Yes		No		No		No		No		Yes		No		No	

## Appendix C – Created concept sounds

A link is provided to the sounds that the project group created themselves.

Sound concept 1 Future Tonal : [https://soundcloud.com/maja-malm/future-tonal/s-tH7B8J5Geak?utm\\_source=clipboard&utm\\_medium=text&utm\\_campaign=social\\_sharing](https://soundcloud.com/maja-malm/future-tonal/s-tH7B8J5Geak?utm_source=clipboard&utm_medium=text&utm_campaign=social_sharing)

Sound concept 4 white sound: [https://soundcloud.com/maja-malm/white-sound/s-5h0LjeohaRw?utm\\_source=clipboard&utm\\_medium=text&utm\\_campaign=social\\_sharing](https://soundcloud.com/maja-malm/white-sound/s-5h0LjeohaRw?utm_source=clipboard&utm_medium=text&utm_campaign=social_sharing)

Sound concept 5 The Owl: [https://soundcloud.com/maja-malm/the-owl/s-gRjpOGqXDbH?utm\\_source=clipboard&utm\\_medium=text&utm\\_campaign=social\\_sharing](https://soundcloud.com/maja-malm/the-owl/s-gRjpOGqXDbH?utm_source=clipboard&utm_medium=text&utm_campaign=social_sharing)

Sound concept 6 Echo: [https://soundcloud.com/maja-malm/echo/s-tfdnSePlukq?utm\\_source=clipboard&utm\\_medium=text&utm\\_campaign=social\\_sharing](https://soundcloud.com/maja-malm/echo/s-tfdnSePlukq?utm_source=clipboard&utm_medium=text&utm_campaign=social_sharing)

Sound concept 7 Bouncing Ball: [https://soundcloud.com/maja-malm/bouncing-ball/s-zygu4McayeB?utm\\_source=clipboard&utm\\_medium=text&utm\\_campaign=social\\_sharing](https://soundcloud.com/maja-malm/bouncing-ball/s-zygu4McayeB?utm_source=clipboard&utm_medium=text&utm_campaign=social_sharing)

## Appendix D – Updated concept sounds

Revised sound concept *Echo*: [https://soundcloud.com/maja-malm/echo2/s-e114SVAmGhr?utm\\_source=clipboard&utm\\_medium=text&utm\\_campaign=social\\_sharing](https://soundcloud.com/maja-malm/echo2/s-e114SVAmGhr?utm_source=clipboard&utm_medium=text&utm_campaign=social_sharing)

Revised sound concept *Bouncing Ball*: [https://soundcloud.com/maja-malm/bouncing-ball-2/s-yx1c53UaZyx?utm\\_source=clipboard&utm\\_medium=text&utm\\_campaign=social\\_sharing](https://soundcloud.com/maja-malm/bouncing-ball-2/s-yx1c53UaZyx?utm_source=clipboard&utm_medium=text&utm_campaign=social_sharing)

# Appendix E – Questions asked during the VR-test

## Questions to all concepts:

### Sound:

- Were you warned by the sound from the truck? (1-5)
- Did you associate the sound with a reversing truck?

### Visually:

- Concept-specific questions (can be seen down below)
- Were you warned about the visual signals on the truck? (1-5)

### General:

- Were you warned about the concept as a whole and did you perceive that the truck was reversing or intending to reverse?
- Do you perceive the signals of the concept, for warning about a reversing truck, as more clear than today's solution?

## Concept-specific questions:

### Travelling:

- What do you associate the lamps with?
- Did the lights signal a direction?

### Flashing:

- What do the flashing lights signal to you?

### Continuous:

- What do you associate the white lights on the side with?
- Before you rounded the corner, could you see the warning triangle before you spotted the truck?

# Appendix F – Questionnaire for the VR-test

## Background questions

1. Gender: \_\_\_\_\_

2. Age: \_\_\_\_\_

3. To what extent do you have experience of being a vulnerable road user in urban environments with traffic?

	1	2	3	4	5	
Not at all	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Very often

4. Do you have previous experience with Virtual Reality?

	1	2	3	4	5	
Not at all	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Very often

## Questions about the test

1. How did you feel during the test?

- Tense
- Relaxed
- Happy
- Nervous
- Stressed
- Calm
- Dizzy
- Nauseous
- Full of expectation
- Other: \_\_\_\_\_

2. How is your experience affected by not being able to control the direction yourself?

	1	2	3	4	5	
Significantly worse	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Not affected

3. How well do your reactions in the virtual environment correspond to reality?

	1	2	3	4	5	
Not at all	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Very much

4. Did you perceive the virtual environment as realistic?

	1	2	3	4	5	
Not at all	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Very much

5. Did you perceive the sounds emitted from the truck as realistic?

	1	2	3	4	5	
Not at all	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Very much

6. Did you perceive the visual signals from the truck as realistic?

	1	2	3	4	5	
Not at all	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Very much

7. Do you have any suggestions for how the test could be improved?

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# Appendix G – Concept pictures from the VR-test

## Concept – Travelling lights



Concept – Flashing lights



Concept – Projection on ground



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