Application of Geofence for Safe Interaction with Emergency Vehicles

Tereza Kunclova

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Department of Science and Technology
Linköping University
SE-601 74 Norrköping, Sweden

Institutionen för teknik och naturvetenskap
Linköpings universitet
601 74 Norrköping

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Tereza Kunclova

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Department of Science and Technology **Institutionen för teknik och naturvetenskap**
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Applicering av geofence för säker interaktion med utrycknings-fordon

Tereza Kunclová

Supervisor : Ivan Postigo, MSc.
Examiner : doc. Johan Olstam, Ph.D.

External supervisor : Kajsa Emanuelsson, MSc.

CZECH TECHNICAL UNIVERSITY IN PRAGUE

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Application of Geofence for Safe Interaction With Emergency Vehicles

Aplikace Geofence pro bezpečnou interakci s vozidly IZS

Master's thesis

Tereza Kunclová

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- Analysis of data from the experiment
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                               vývoje výrobku - aplikace v automobilovém průmyslu.
                               Praha: České vysoké učení technické v Praze, Fakulta
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                               Bosch Automotive Handbook. 10th Edition. Gerlingen:
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....
doc. Ing. Petr Bouchner, Ph.D.   prof. Ing. Ondřej Přibyl, Ph.D.
      head of the Department   dean of the faculty
       of Vehicle Technology

I confirm assumption of master's thesis assignment.

                              ....
                                   Bc. Tereza Kunclová
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Abstract

Since emergency vehicles face a higher risk in traffic due to exemptions from the traffic rules, many safety problems arise as a consequence. A combination of exceeding speed limits or running red lights and driving under time pressure leads to stressful situations for both emergency vehicle drivers and other road users. As a result, accidents involving emergency vehicles occur in urban areas with high traffic density, especially at intersections, as well as on motorways and in rural areas. In order to avoid impeding or endangering emergency vehicles by passenger vehicles, the present thesis focuses on applying geofencing to improve the safety and passability of emergency vehicles. The geofencing method digitally demarcates a geographical area with certain conditions, and users connected to the geofence must comply with these conditions. The aim of the thesis was to investigate if geofence instructions communicated via an in-vehicle human-machine interface (HMI) can have a positive impact on driver behavior when interacting with emergency vehicles. A total of $n = 64$ study participants were tested in a driving simulator on two different use cases without or with applied geofence instructions. The use cases were situated on an off-ramp and at an intersection. The results of the experiment demonstrated a statistically significant effect of the use of geofencing on the correct and timely reactions of drivers prior to the interaction with emergency vehicles. Furthermore, the use of geofencing indicated a potential to decrease collision risks and driving time of emergency vehicles. Although the HMI design needs to be improved for real-world geofence application, the study participants were positive about receiving the geofence instructions when interacting with emergency vehicles in their own vehicles in the future.

Keywords: Geofence, geofencing, geofence instruction, emergency vehicle, driving simulator experiment, driver behavior

Acknowledgments

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List of Abbreviations

ADAS	Advanced Driver Assistance Systems
C-ITS	Cooperative Intelligent Transport Systems
EMS	Emergency Medical Services
EVA	Emergency Vehicle Approaching
HMI	Human-Machine Interface
HUD	Head-Up Display
ISA	Intelligent Speed Adaptation
ITS	Intelligent Transport Systems
LCD	Liquid Crystal Display
NHTSA	National Highway Traffic Safety Administration
PSAP	Public Safety Answering Point
UVAR	Urban Vehicle Access Regulations
VR	Virtual Reality
VTI	Swedish National Road and Transport Research Institute
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
WHO	World Health Organization
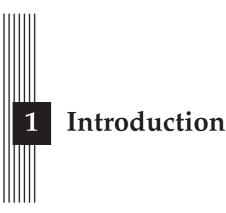
1 Introduction

Emergency vehicles are a special type of vehicles on our roads that provide help and assistance to people, especially in urgent situations such as accidents, health problems, fires, or criminal aspects. According to Parliament of the Czech Republic, the system of emergency services is made up of three main components – the ambulance service, the police, and the firefighting service. Their goal is to get to the destination of the situation as fast and safely as possible and provide the determined services immediately. Therefore, exemptions to regular road traffic rules are granted to emergency vehicles, such as exceeding the speed limit, being allowed to use restricted lanes or tram lanes, or passing through an intersection on a red light (Parlament České Republiky, 2000). Exemptions for emergency vehicles lead to stressful situations, driving under time pressure, and result in a high rate of accidents involving emergency vehicles, in terms of accidents per kilometre driven and fatality rates resulting from these accidents compared to other vehicles (Hsiao et al., 2018; Savolainen et al., 2009).

In order to reduce the risk of accidents, emergency vehicles are nowadays equipped with sound and visual signalling in the form of sirens and emergency lights. However, these signals are not always sufficient to enable drivers of civilian vehicles to react correctly. The problem arises that warning through these types of signalling comes too late to the driver of the civilian vehicle (Caelli & Porter, 1980), the drivers may be distracted by other sounds in the vehicle, which disables them from hearing the approaching emergency vehicle (e.g., Petrov et al., 2020), or drivers do not know how to react properly in certain situations (Lidestam et al., 2020).

However, the number of accidents involving emergency vehicles can be reduced by introducing technologies that improve the situational awareness of all road users and therefore overall road safety. In particular, by helping road users to orient themselves in certain situations quickly, react safely, and avoid risky, collision or even fatal situations. These technologies are intended to facilitate the smooth and safe passage of emergency vehicles to the location of an accident and the safe operation on site. Examples could include traffic lights, variable message signs, or in-vehicle assistance systems.

The present thesis investigates the impact of application of *geofencing* via a *human-machine interface (HMI)* on driver behavior, that could be implemented in a vehicle in order to improve the safety of interaction between drivers of civilian vehicles and emergency vehicles. Geofencing is a method used in geofence applications. It implies a digital demarcation of a geographical area with certain conditions that the subject using geofence applications has to

follow when moving in the area (Regeringkansliet: Infrastrukturdepartementet, 2021). HMI refers to a human-machine interface that conveys an interaction between a human and an artificial system (Orlický, 2021). Geofencing and HMI are described in detail in Chapters 2.2 and 2.3.

1.1 Aim and Research Questions

The aim is to investigate if and how geofencing in combination with an in-vehicle HMI can improve driver behavior when interacting with emergency vehicles. The master's thesis is intended to answer the following three research questions.

- Could geofencing assist drivers in responding timely and correctly when interacting with emergency vehicles in traffic, and thereby decrease the risk of accidents?

- Can geofencing improve the driving time of an emergency vehicle (i.e., decrease response time)?

- Do drivers believe that they would benefit from geofencing?

1.2 Methodology

A literature review was used to gather statistical data and information on accidents involving emergency vehicles. In particular, information on the most frequent accident locations involving emergency vehicles was collected. The findings were then used to propose various use cases of critical situations where geofencing might be useful to assist drivers in decision making and therefore to eliminate accidents with emergency vehicles. In addition, the review provided information about geofencing, its principle of application, and necessary information about HMI.

A workshop with representatives of authorities and organizations from both government and private sectors was organized to discuss the topic of geofencing. The representatives work in the field of geofencing, emergency vehicles, transport safety, etc. A total of seven proposed use cases were presented at the workshop and discussed together with the topic of HMI to gather input for the design of a driving simulator study. Two of the use cases were selected and implemented in a driving simulator.

Through a driving simulator study, driver behaviour was examined on a sample of Swedish drivers with valid driving licences. Differences in driver behaviour between the current state, when vehicles have no additional in-vehicle warning systems when interacting with an emergency vehicle, and a potential future state using geofencing via an HMI that gives clear commands to the driver on how to react, were investigated. The results of the experiment were analyzed to fulfill the aim of the thesis, therefore, to find out if geofencing is beneficial, effective, and appreciated by drivers. The goal of the experiment was to examine whether the driver is able to perceive, process, and follow the command, i.e., react correctly in the given use case, and if the reactions are favorable as compared to when no command is provided via the HMI. The simulator data were used to compare relevant measures, such as the differences between the reaction times of drivers without and with using geofence.

The driving simulator study was intended to answer the research questions through these measures. The first selected use case was designed to provide significant results to answer the first research question about the driver behavior. The second selected use case was designed to investigate the impact of civilian drivers on emergency vehicles to answer the second research question.

A questionnaire study was used to collect data on participants' subjective attitudes after the experiment to answer the third research question. The intention was also to obtain further information on if they appreciated geofencing during the experiment, where they saw

shortcomings, etc. Among other things, the study served to assess participants' knowledge of driver behavior when interacting with an emergency vehicle.

Data collected from the driving simulator experiment including the questionnaire were analyzed using both descriptive and inferential statistics, including measures of standardized effect size. The data analysis was performed in RStudio software.

1.3 Delimitations

The first limitation was that the technical solution of geofencing, which would be required to enable the application of geofencing in the real world case, was not investigated in the current work. The driving simulator experiment was limited to two selected use cases in which the impact of geofencing was assessed. A between-group design was used for the experiment and the participants of the study were drivers living in Sweden. There is a wide range of HMI possibilities and features on how instructions can be conveyed to the driver and the current thesis was limited to the use of only one HMI setup for the experiment.

1.4 Outline

The present thesis is structured as follows. In Chapter 2, background and theoretical information related to the topic is provided. Chapter 3 presents the Geofence workshop and proposed use cases. Furthermore, the details about the driving simulator experiment conducted for the present thesis are described in Chapter 4. Chapter 5 deals with the data analysis of the driving simulator experiment. The results and methodology used in the present thesis are discussed in Chapter 6, followed by Chapter 7 concerning the research questions and a final summary of the thesis.

2 Background and Theory

This chapter provides theoretical and background information including important definitions, studies, and research related to the topic of the thesis. The first section deals with studies and statistical data related to accidents involving emergency vehicles. Furthermore, general information about geofencing, its definition, and the principle of its application are presented, along with related work. Finally, the field of HMI is introduced.

2.1 Accidents Involving Emergency Vehicles

Traffic collisions involving emergency vehicles represents a common problem on roads around the world (Boldt et al., 2021; Lidestam et al., 2020; NHTSA, 2011). The problem of emergency vehicle collisions is, among other things, the significant consequences. If an emergency vehicle crashes while en route to the location of a rescue, the risk of injury or loss of life increases not only because of the collision itself, but also because of the need to replace the emergency vehicle going to provide aid. This then causes an overall delay in the provision of aid. In the event of a collision of an emergency vehicle, particularly an ambulance transporting a patient to a hospital or other facility, the likelihood of fatal consequences of the accident increases. These consequences illustrate just the main reasons why it is important to work on improving the safety of emergency vehicles in traffic.

This fact of frequent collisions is confirmed by the World Health Organization (WHO), which also states that emergency vehicles are very prone to accidents due to high speed and aggressive driving in traffic. Furthermore, the WHO mentions that other major differences can be found between high and low-income countries, due to the level of infrastructure and the overall difficulty in providing emergency assistance (WHO, 2004).

Between 1992 and 2001, a total of 302 969 accidents involving emergency vehicles were reported in the United States (Drucker et al., 2013). In the following decade, the accident rate increased even further and approximately 66 000 more accidents involving emergency vehicles were recorded than in the previous decade (Drucker et al., 2013). National Highway Traffic Safety Administration (NHTSA) of the United Stated reports that in both decades, 1992-2011, there was an average of 4 500 accidents per year in which a motor vehicle collided with an ambulance (NHTSA, 2015; NHTSA: EMS, 2014). Of these ambulance crashes, 65% were classified as resulting in destruction or damage to property, 34% resulted in injury to one or more persons and less than 1% were fatal (NHTSA: EMS, 2014).

With the overall increase in the number of vehicles and traffic intensity on the roadways, the overall vehicle accident rate has also risen, resulting in a higher number of risky situations involving emergency vehicles (Lidestam et al., 2020). Data from the National Safety Council (NSC) and their analysis of fatal crashes involving emergency vehicles shows that in 2019, a total of 170 people died on United States roads as victims of traffic crashes involving emergency vehicles. The majority of these victims died in interactions with police vehicles, while 33 people died in collisions with ambulances and 23 people died in collisions with fire trucks (NSC, 2020).

According to NTHSA document from 2015, persons injured or killed by an accident with an ambulance vehicle are in 63% persons travelling in another motor vehicle, 21% of persons are ambulance passengers, in 12% it is another road user, for example a pedestrian or cyclist, and 4% of these statistics are ambulance drivers (NHTSA, 2015).

Regarding the situation in Europe, Boldt et al. (2021) analysed data from 2014 to 2019 on ambulance accident statistics in Germany, Austria and Switzerland. This research was limited to freely available data, so possible biases, especially in terms of fatal consequences, should be considered. In Germany, they found a total of 597 ambulance vehicle accidents that were recorded in this time frame. In 453 of these accidents, 1 170 people were injured, which corresponds to 1,409 per 100 000 inhabitants. In 28 of these accidents, 31 persons were fatally injured. According to the report, there were a total of 62 ambulance accidents in Austria, with 47 of these accidents resulting in 115 injuries, equivalent to 1,294 per 100 000 inhabitants. A total of 6 of these accidents resulted in 7 deaths. In Switzerland, a total of 25 ambulance accidents were recorded, with 18 people injured in 11 of these accidents, corresponding to 0,211 per 100 000 inhabitants. Similar to the United States, ambulance accidents had the greatest impact on the number of deaths of third parties. Persons in other vehicles or other road users were the victims in more than 50% of all accidents. Accidents caused the death of the patient in the ambulance in approximately 30% of cases and the death of staff in approximately 13% of cases (Boldt et al., 2021).

These statistics clearly indicate that it is important to improve safety of interactions between drivers of civilian vehicles and emergency vehicles. Although some differences can be seen between the statistics of different countries and some of them manage to achieve lower accident rates involving emergency vehicles, the results of multiple accident analyses are still far from zero. By taking into account and analysing the factors that generate risk, new strategies can be established and new technologies can be developed to avoid these accidents. The causes of accidents usually involve one or more contributing factors simultaneously. A particular cause of accidents tends to be human error, especially those related to perception and incorrect driver reactions.

Based on a study in Staffordshire to investigate the interactions between road users and emergency vehicles using lights and sirens, over 60% of respondents had to manoeuvre out of their chosen position, i.e., give way to an emergency vehicle. 28% of respondents said they detected an emergency vehicle at a distance of less than 50 metres, a critical distance for a driver to react correctly to avoid a collision. In 86% of the cases, emergency vehicles used horns and sirens, but 25% of participants said they did not hear them. Emergency warning lights were not noticed by 30% of respondents and more than half of them did not hear the audible warning. In conclusion, approximately one third of participants found the interactions difficult to manage (Saunders & Gough, 2003). De Lorenzo and Eilers (1991) also states that although warning lights and sirens help emergency vehicles to announce their presence, they can have a strong negative and disturbing effect on both civilian vehicle drivers and emergency vehicle drivers themselves, as they significantly affect their mental state. Although further research needs to be conducted, the studies suggest that the current warnings in the interactions between road users and emergency vehicles are not always sufficient to prevent risky situations.

The factors of accidents occurring in traffic and including accidents between vehicles and emergency vehicles, can be divided into the following categories (Abdelwanis, 2013; Hsiao et al., 2018; Vrachnou, 2003).

- Environmental factor

- Driving behavior, driver's condition

- Vehicle type and its condition

- Crash description

With regard to the topic of this thesis, the following paragraphs focus on the environmental factor, specifically the most common accident locations and their circumstances. Based on this information, use cases for the workshop and the driving simulator experiment can be designed. First studies refer to accidents of emergency vehicles, the rest of the studies in the current section mention information about collisions involving only emergency medical vehicles - ambulances. Although the statistics about locations of collisions proportionally correspond to other emergency services, i.e., police and fire rescue, especially the collisions of police vehicles occur under different circumstances, usually in cases of high speed when they intend to catch the violator. Therefore they are excluded from the scope of the research.

Study Drucker et al. (2013) using NHTSA data reports that most fatal crashes between vehicles and emergency vehicles occur in urban areas, specifically at T-intersections or four-point signalized intersections. The cause of the accidents is primarily a combination of exceptions for emergency vehicles, that can pass through the intersection on red light, and simultaneously, the obstruction of drivers' vision, for example, by buildings or trees (Drucker et al., 2013).

Savolainen et al. (2009) and their study in Michigan states that most collisions occur at intersections and driveways. Angle collisions, head-on collisions, and side collisions are the prevailing crash types. Side collisions occur mainly when emergency vehicles are attempting to overtake other vehicles on their way to an incident. Speeding and overtaking are the most common causes of crashes (Savolainen et al., 2009).

Regarding the Custalow and Gravitz (2004) study, more than 90% of accidents between vehicles and emergency medical vehicles occurred while driving, and the remaining in a parked position. Weather conditions did not have a significant effect on the occurrence of accidents. The majority of accidents occurred at intersections. Most of these crashes were so-called T-bone crashes, which are significant for cases where vehicles cross each others' paths. These accidents are very dangerous and usually result in injuries or fatalities. Other collisions, according to the study, occurred on the straight stretch of the motorway and on-ramp (Custalow & Gravitz, 2004).

Ray and Kupas (2007) also present, that surface and weather conditions do not have a significant effect on ambulance accident rates. The vast majority (82%) of ambulance accidents occur in urban areas. Nearly 70% of accidents in urban areas occurred at signalized intersections or intersections with stop signs. Each of these accidents generally involved more than one vehicle and more than four persons affected. In rural areas, accidents of emergency vehicles were predominantly fixed object crashes that did not involve a collision with a civilian vehicle (Ray & Kupas, 2007; Ray & Kupas, 2005).

Based on reports Heyward et al. (2009) and Weiss et al. (2001), ambulance accidents in rural areas occur primarily due to speeding on narrow roads without shoulders. Due to the limited space on narrow roads, head-on collisions occur as a result of driving in the opposite lane, especially when speeding, overtaking, or a combination of the two. Although accidents at intersections are more significant in urban environments, some of them also occur in rural areas, especially at unsignalized intersections (Sanddal et al., 2010). Road and weather conditions are more significant parameters than for accidents in urban areas (Heyward et al., 2009).

Table 2.1 summarises the most frequent locations of accidents between vehicles and emergency medical vehicles, together with the reasons of these accidents. A common and repeating reason, regardless of the area, is failure to yield the right of way to an emergency vehicle.

Table 2.1: Summary of Recurring Accidents

Environment	Location	Reasons of accidents
Urban area	Intersection	Crossing on the red light, high speed, obstructed driver's vision
Rural area	Narrow roads	High speed, dangerous overtaking, driving in the lane of opposite direction
Motorway	+ On and off ramps	High speed, dangerous overtaking

2.2 Geofence

In the following section, geofence is presented together with related work, which highlights its usage and applications.

The term geofence is currently not legally defined (Regeringkansliet: Infrastrukturdepartementet, 2021). So far, many different formulations of the definition of geofence can be found through search engines from different sources. Nevertheless, a memorandum "Liability for automated driving and new rules to encourage greater use of geofence" published in 2021 on behalf of the Swedish government brings a new proposal for an official definition. This memorandum also states that the general need for a definition was emphasised in the negotiations, inter alia to facilitate the establishment of requirements in tenders, etc. In addition, it was stressed that it is not possible to introduce into the road traffic rules the right of municipalities to fine vehicles connected to a geofence in case of non-compliance without defining what is meant by it (Regeringkansliet: Infrastrukturdepartementet, 2021). Therefore, the memorandum proposes a new formulation of the definition of geofence:

"Geofence refers to a digital demarcation of a geographical area with conditions for vehicles using geofence applications. Geofence applications refer to vehicle systems for adapting the vehicle in relation to a geofence" (Regeringkansliet: Infrastrukturdepartementet, 2021).

The principle of the geofence is that a digital demarcation can have predefined boundaries, such as a certain area, city, neighborhood, or road segment, or it can be dynamically generated, for instance as a radius around a point (Sadler, 2020). In the context of transport, it can refer to a dynamically created dedicated lane only for a certain type of vehicles or a certain area in relation to a moving point along a certain geographical object (road, river). Geofencing can be used for all connected devices, including vehicles, and users of connected devices who enter the geofence area need to comply with geofence regulations (Sadler, 2020). It could be beneficial to use geofencing in vehicles when they interact with emergency vehicles. The purpose would be to give direct instructions to the driver on what to do in these situations to avoid a collision and, in addition, to ensure a smooth and safe passage for the emergency vehicle.

Related Work

In the current section, examples of the geofence method usage are provided to give the reader a better understanding of the current capabilities of the method, functionality, and purpose of the applications. In addition, a brief overview of the related service emergency vehicle approaching warning system (EVA) is presented. The EVA also aims to improve safety and driver reaction when interacting with an emergency vehicle and is currently under development and testing (NordicWay, 2021).

Geofencing for Smart Urban Mobility

This SINTEF project focuses on the use of geofencing and Cooperative Intelligent Transport Systems (C-ITS) to develop new tools tested in GeoSUM. They plan to use geofencing for digital zones defined on a map in two pilot experiments. The pilot cases focus on air quality management and speed control in zones with vulnerable road users (Arnesen et al., 2020).

The first use case is shown in Figure 2.1. It can be seen that if a fossil fuel powered vehicle approaches a low emission zone, it receives a regulation alert. If a vehicle enters the zone, a fee must be paid, which is charged to the driver when leaving the zone (Arnesen et al., 2020).

Figure 2.1: Pilot Use Case 1 in GeoSUM

(Arnesen et al., 2020)

The second use case is similarly focused. However, it includes hybrid vehicles. In the case of a vehicle approaching a regulated area, its drive is automatically switched to electric only, via a link with the in-vehicle ITS system. An illustration of the use case is shown in Figure 2.2 below.
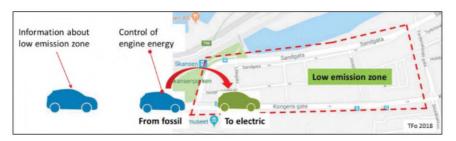
Figure 2.2: Pilot Use Case 2 in GeoSUM

(Arnesen et al., 2020)

The third and fourth use cases of the SINTEF project deal with the issue of speed limits in areas with a high density of vulnerable road users. The third use case proposes lowering the speed limit in an area so that a message is sent to drivers when they approach the area and the vehicle speed is automatically adjusted to comply with the limit. In the fourth use case, drivers would receive an audio-visual warning whenever they exceed the speed limit in the controlled zone (Arnesen et al., 2020).

Urban Vehicle Access Regulations

The Urban Vehicle Access Regulations (UVAR) is one of the tools in ReVeAL project, which aims to support cities in developing best practices in vehicle regulations (Sadler, 2020). The implementation of the tool is currently underway in six pilot cities. Within the urban area, geofencing is used to address similar use cases as the SINTEF project. In the first use case, geofencing actively switches a plug-in hybrid vehicle remotely to electric mode in an UVAR boundary. In a considered alternative, a driver would be responsible for using battery mode. An enforcement system would be more likely to be checked regularly in retrospect (e.g., every few months) as is done in other cases using passive technology, i.e., the engine would be passively monitored to determine if battery mode was used in the boundary. The document states that in the future it could be possible to use geofencing to prevent vehicles from entering the geofenced zone. In addition, some advantages and disadvantages of geofencing are also highlighted. The main advantages are identified to be that geofencing is flexible, can fulfill reactive regulations, and apply to geographic areas other than the zone itself. On the other hand, the disadvantages are that it requires digital maps, digitization of regulations, and satellite signal coverage (Sadler, 2020).

Emergency Vehicle Approaching Warning

Emergency Vehicle Approaching (EVA) is a service that notifies the driver in the vehicle of an approaching emergency vehicle. The aim is, as in the case of geofencing, to ensure the safe passage of emergency vehicles, avoid risky situations, and reduce the overall response time of emergency vehicles. Protocols and standards for messages and communication, issuing EVA, are being developed and demonstrated, for instance, within the European Union project NordicWay 2 (https://www.nordicway.net/).

Lidestam et al. (2020) investigated EVA in a rural area in three use cases and found that although an emergency vehicle is easy to detect, the EVA message has a significant effect on how soon drivers give way. When the emergency vehicle was difficult to detect, most drivers without the EVA message did not yield the right-of-way or did not detect the emergency vehicle until it overtook them. When they received the EVA message, most participants gave the right-of-way appropriately. The mean speed of participants who received an EVA message was lower. Another finding of this study was that novice and relatively inexperienced drivers did not know how to yield to an emergency vehicle or did not even know that they were required to yield (Lidestam et al., 2020).

Another study, Payre and Diels (2020), examining EVA alerts reported that 75% of drivers gave way when using an EVA when an emergency vehicle was approaching. When drivers were not exposed to an EVA, none of them gave way to the emergency vehicle. This study also confirmed that EVA warnings have a positive impact on driver behavior, can improve safety, and facilitate the smooth passage of emergency vehicles (Payre & Diels, 2020).

2.3   Human-Machine Interface

Human-machine interaction refers to the interaction between a human and an artificial system (Orlický, 2021). This interaction is always conveyed via some kind of medium, defined as a human-machine interface (HMI) (Orlický, 2021). Interaction between a driver and a vehicle is essentially a specific sub-discipline that brings together different scientific fields, both technical ones, such as the design and construction of machines or devices used in the automotive industry, and fields that deal with human cognition when driving or interacting with a vehicle (Novotný, 2014). HMI between a driver and a vehicle refers to user interface, which can provide information services and control elements to the driver in a variety of ways. These HMIs include, for example, the central infotainment system, the cluster or head-up display,

as well as the use of audio signals, haptic elements, torque in the steering wheel and other technologies (Hollifield et al., 2008; Orlický, 2021).

This section further focuses on the description of HMIs specifically in automobiles with respect to the context of the current thesis. However, some of the information presented would also be relevant for other types of vehicles.

Types of HMIs

The following section describes the types of HMIs that are the most widely used and most commonly implemented in cars nowadays.

Central Infotainment System

In-vehicle infotainment is a system located in the middle of the dashboard in the majority of today's cars (Holmes & Alaniz, 2019; Kinder, 2017). This panel primarily provides the driver entertainment and information services such as radio, navigation, connection to mobile phones, laptops and other devices, voice calling, etc. (Jorgersen, 2019). Before the central infotainment system is deployed in the vehicle, several phases are being sequentially resolved in order to achieve a suitable final form of the infotainment (Luna-Garcia et al. (2018). Developers need to deal with design, interaction, security, and connectivity (Luna-Garcia et al. (2018). In the initial design phase, the infotainment shall be specified to meet user requirements, fit into the cockpit system structure and determine the initial appearance of information communicated to users. The interaction factor is then linked to the design phase. In this phase interactive elements are determined to support and make the communication between the user and the display clear, intuitive and adjustable (Domínguez-Báez et al., 2020). The security phase should then ensure that the driver is not distracted by the infotainment during driving tasks and that the infotainment is only a useful and assistive element in the vehicle. Finally, the connectivity phase should address connectivity to available infrastructure elements to ensure the functionality of driver assistance systems and also facilitate connectivity to mobile, cloud and other services (Luna-Garcia et al., 2018).

Instrument Cluster Display

In the vast majority of vehicles today, the cluster display is located in the part of the dashboard behind the steering wheel ("Instrument Clusters", n.d.). These displays are primarily used to display the speedometer and vehicle status indicators, including fuel tank status, engine status, battery status, etc. ("Instrument Clusters", n.d.). Instrument clusters are usually designed to not include entertainment services that are not necessary for driving tasks . In recent years, analogue displays have in most cases been replaced by digital displays (Shah, 2021). Compared to the central infotainment system, this display is positioned closer to the driver's field of vision and should therefore be designed to provide the information the driver needs primarily while driving.

Head-Up Display

The head-up display (HUD) is a technology that projects important information and warnings onto the windscreen. It allows users to read information without having to put their head down on the dashboard. The HUD can thus avoid longer intervals when the driver is not fully aware of the surrounding environment, significantly reduce the driver's reaction time in certain situations and improve driver behaviour even in difficult conditions such as low visibility (Charissis & Naef, 2007). In particular, when designing head-up displays, the amount of information to be displayed needs to be appropriately chosen so that it does not degrade the visibility of the surroundings.

Audio Signals

Another way to inform or warn the driver is by using audio signals. Belz et al. (1999) states that even in cases of appropriately designed visual HMIs at an advanced level, visual perception can still be overloaded by a large number of subjects. The advantage of audio signalling is, that drivers are not distracted by a visual subject, so they do not have to change their eye gaze, as in the case of the use of displays. On the other hand, one of the risks of audible signals is that the driver may not hear the warning adequately. If the sound is not adjusted to the user's individual preferences, it may even distract the user and make driving more difficult. Thus, the setting of specific sounds should be one of the main subjects when designing audio signals. Zheng et al. (2008) and Ho and Spence (2005) demonstrated that a combination of audible and visual warnings can have a positive effect on drivers' reaction time, while at the same time having a lower error rate. An analysis of the use of audible signals in combination with either a central infotainment display or a cluster display showed that reaction times are lower when using a cluster display (Zheng et al., 2008).

General Recommendations for HMI Design

The HMI shall be designed in such a way to ensure clear reception of information by the drivers in order to provide them a support in stressful and unusual situations, and promote smooth and stable operation of the vehicle (Hollifield et al., 2008; Orlický, 2021). Hollifield et al. (2008) lists a few general rules when developing a new display design. According to this handbook, minimalism is the key, and it is particularly important to keep in mind the amount of information the user is able to register and react accordingly. The most important elements should always be clearly highlighted and be easily understandable for the user. Furthermore, colours should be used carefully and the traditional use of colours should be maintained, for instance, that red color indicates danger, etc. Elements should have a consistent legible appearance to avoid confusing the user. Moreover, it is important to limit the use of animated elements that can easily distract the user (Hollifield et al., 2008).

In cases of incorrect layout of elements or too significant signalling through HMIs, sudden and involuntary saccadic eye movements may occur (Murray et al., 1995). A saccade is a natural rapid movement of the eye between fixation phases (Goffart, 2009). The intended saccadic eye movement is controlled by the person. Involuntary saccadic eye movement, called exogenously controlled, is a mechanism in which the eye is rapidly attracted to external stimuli without any conscious action by a person (Goffart, 2009; Meeter et al., 2010). This eye movement is immediate and in most cases is caused by significant changes in the environment, such as unexpected quick movements of stimuli in the field of view (Biswas & Prabhakar, 2018; Goffart, 2009). It can be useful, for instance, in situations when a cyclist suddenly crosses the road, the driver registers the change and manages to stop. However, this type of eye movement is sometimes unnecessarily provoked, leads to distraction, and takes the driver's attention away from driving. Involuntary saccadic eye movement may be caused by phone ringing, flashing or unexpectedly strong signals on the infotainment display or head-up display, etc. For this reason, only properly designed HMIs can prevent dangerous situations, improve reaction times and facilitate situational awareness.

HMI Testing

Each new HMI or each extension function shall be tested in order to analyse driver behaviour during an interaction (Orlický, 2021). The options for this testing are twofold, either in real-world conditions using prototypes, or in laboratory conditions using driving simulators and eventually other technologies such as VR headsets. With regard to the topic of the thesis, this section focuses on the possibilities of testing HMIs in driving simulators.

A driving simulator is a machine designed to simulate driving a vehicle in conditions that replicate real road conditions (Novotný, 2014). An experiment in a driving simulator is par-

ticularly advantageous because of its safe environment in laboratory conditions during the testing and lower costs. Also, the progressive development and extension of technologies contributes to the improvement of simulators of any type. As a result, there are simulators available nowadays, that provide virtual reality as a form of complex simulation and allow full human immersion in the simulated environment (Novotný, 2014). However, experiments may still be limited in terms of simulator capabilities and features. As simulators have different levels of fidelity, the degree of reality that can be portrayed varies (Orlický, 2021).

As mentioned above, simulators are used, among other things, to investigate driver behaviour and can therefore be used to test driver behaviour under non-standard and stressful conditions, to test the amount of information the driver is able to perceive and process while driving, etc. Based on the findings from the driving simulator experiments, specific solutions can then be suggested or modified for the final product, for instance, the optimal placement of control and information services in the car, its visual representation, etc. (Orlický, 2021).

Vehicle simulators can be divided into partial and full-featured or fixed-base and full motion simulators (Novotný, 2014). The basis of partial simulators is usually general equipment such as a steering wheel, seat, and pedals, sometimes part of a car cockpit, and the scene is usually projected onto a projection screen or LCD screen in front of the cockpit. Information about current steering wheel, pedal and gear positions is sent to the simulation system, and information about speed, revs or steering wheel settings depending on the current speed is sent back. Partial simulators are in most cases fixed-base, i.e., without a physical mechanism of movement, and one of their advantages compared to full-featured simulators is that they can be easily rebuilt or supplemented with certain features according to the needs of the experiment. Full-motion simulators can provide a closer approximation to reality. These simulators can be equipped with up to 6 degrees of freedom - 3 translational and 3 rotational movements, and can thus realistically simulate movements during driving. What is referred to as a full-featured simulator includes front, side, and rear projection, is fully movable, and in its complexity is well set up and tuned to make the driver feel like being in and driving a real vehicle (Novotný, 2014).

The use of a driving simulator in terms of its fidelity level depends on the purpose of each individual experiment and the information the researcher intends to obtain. For initial investigations, a simple partial simulator is often sufficient to obtain valid data. For comprehensive investigations that require a high degree of approximation to reality, advanced and complex simulators close to full-featured ones are used to provide participants with a higher degree of immersion in virtual reality.

The testing of participants in driving simulator experiments to compare different interfaces or different driving behaviors under different conditions can be divided into two study designs, namely between-group design and within-group design. In practice, this means that when using between-group design, participants are compared between groups with each group having different conditions. When using a within-group design, participants are tested and compared within one group, with each participant being exposed to identical conditions.

3 Workshop

The current chapter focuses on the workshop that was organized as part of the current thesis. The workshop was used to discuss the topic of geofencing and to obtain feedback on the application of geofencing in the interaction between civilian and emergency vehicles. The guests who were invited are personnel in related fields to the topic of the present thesis, for instance, geofencing, emergency vehicle systems, or in-vehicle systems. The outputs from the workshop were intended to contribute to the design of the driving simulator experiment.

Invitations to the workshop were sent to guests along with a questionnaire about their time availability. After receiving the majority of responses, a date for the event was set. Among the participating guests were experts on geofence, traffic information, connected vehicles, digitalization of road transport, PSAP (Public Safety Answering Point), and systems for emergency vehicles and emergency response. Concretely, they work for the following authorities and organizations.

- Trafikverket - Swedish government agency responsible for the construction, operation and maintenance of national roads and railways

- Volvo - automotive company

- Carmenta - company developing and supplying software for situational awareness to connected and automated vehicles

- Trafikkontoret Göteborg - authority responsible for traffic and outdoor environment

- SOS Alarm - company operating the 112 emergency number in Sweden

- Evam - company developing intelligent communication within V2V (Vehicle to Vehicle) and V2X (Vehicle to Everything)

3.1 Procedure

At the beginning of the workshop, the definition of geofencing was discussed. The purpose of the discussion was primarily to establish common terminology. Secondly to explore the

level of consensus within the group. The discussion was straightforward, all of the participating guests responded that they define and refer to geofencing as a method. The geofencing method is used and applied in specific applications, which are called geofencing applications.

After the discussion on the definition of the geofence, the background of the present thesis and its objective were explained to the guests, along with the research questions. Moreover, the aim of the workshop was explained in order to get feedback and input for the driving simulator experiment. After the introductory part, the presentation of the use cases and the discussion about them followed. The use cases were proposed based on previous research on emergency vehicle accidents, the experience of ambulance drivers, and consideration of risk situations in which the use of geofencing could be beneficial. At the end of the workshop, participating guests were asked to complete a questionnaire that included questions on the general evaluation of the use of geofencing in vehicle-emergency vehicle interaction and the evaluation of the individual use cases presented. The participants rated each use case on a scale from 1 to 7, with 1 indicating a negative impact of geofencing in the situation and 7 indicating a very positive impact of geofencing in the situation. The questionnaire was carried out in Google Forms.

3.2 Proposed Use Cases

Seven different situations were presented to the participants. These included two motorway, three urban, and two rural situations. An overview of these is given in Table 3.1. All the sketches of proposed use cases were carried out in the Easy Street Draw Mobile application from SmartSafety Software, Inc. The suggestion of the visual form of the instructions via the HMI was made only as an illustration, in order to be able to discuss the formulations of the instructions with the participating workshop guests. A modified version of the emergency vehicle warning icon was used from study (Payre & Diels, 2019).

The following principles emphasize the underlying idea of using geofence in a real-world application when interacting with emergency vehicles.

- It is a futuristic solution under the assumption that the infrastructure and technology used ensure the accuracy of applying geofence.

- The location and the route of emergency vehicle is known.

- Geofence demarcation zones are created dynamically and in real-time in relation to the emergency vehicle on its route and according to the road environment, i.e., they follow motorway, a road in a rural area, or an intersection.

- The dynamically created zones are divided into moving and fixed zones in the present work. Moving zone moves according to the movement of the emergency vehicle (motorway, rural road). Fixed zone is activated when the emergency vehicle is approaching and deactivated after its passing (intersection), or the geofence zone is created around the emergency vehicle or in relation to the emergency vehicle during the rescuers' operation on the spot.

- The dimensions of the geofence zone depend on the environment and traffic conditions.

- Other vehicles in the vicinity of the emergency vehicle, i.e., subjects to geofencing, receive instructions to which the driver of the receiving vehicle shall respond.

- Instructions given to receiving vehicles vary depending on their position relative to the emergency vehicle.

- The instruction is conveyed to the driver of the receiving vehicle via an in-vehicle HMI.

Table 3.1: Overview of the Use Cases

Order	Zone type	Location	Description of the location
Use case 1	Moving	Motorway	Motorway lanes
Use case 2	Fixed	Motorway	In front of an off-ramp
Use case 3	Moving	Urban area	In front of a signalized intersection
Use case 4	Fixed	Urban area	Two-lane road
Use case 5	Fixed	Urban area	Signalized intersection
Use case 6	Moving	Rural area	Two-lane road
Use case 7	Fixed	Rural area	Unsignalized intersection

Use Case 1: Moving Zone on a Motorway

The first use case is situated on a motorway and a schematic of this situation is shown in Figure 3.1. The red box indicates the geofence zone. The interval between the emergency vehicle and the furthest point of the geofence zone (i.e., the first point at which the driver is given the instruction) shall be sufficient to ensure an adequate driver response, in this case, estimated to be at least *400 - 500 m* in free flowing traffic. The example of instruction that was proposed to be given in this case to drivers moving in the geofence zone is shown in Figure 3.2. The red car indicates the position of the driver during the experiment in the driving simulator. To assess behavior, drivers would be instructed to keep as close to the speed limit as possible during the experiment, while other vehicles in the scene in the right lane would maintain a lower speed. This would force drivers to stay in the left lane. When an emergency vehicle approaches, drivers would be instructed via the HMI how to react.
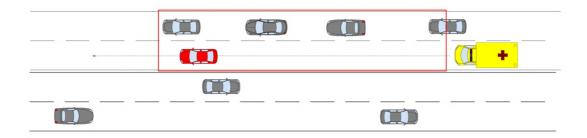
Figure 3.1: Use Case 1

Figure 3.2: HMI: Use Case 1

Feedback from participants

It was pointed out by the participants that the use of geofencing and the formulation of the instruction depends very much on the traffic density. One participant reflected on the change of instruction in case of congestion. It would be necessary to instruct drivers in the left lane to pull over to the left and drivers in the right lane to pull over to the right side in order to create a rescue lane for the passage of an emergency vehicle. Another participant mentioned an idea to use geofencing to dynamically generate the entire dedicated lane for the emergency vehicle. The advantage of this solution is that it could be implemented sooner as the solution would likely be less demanding to implement than, for instance, the use case above. All vehicles in the restricted lane would be instructed to move to another lane. On the other hand, it was highlighted that the disadvantage of this solution might be a higher likelihood of congestion due to oversaturation in the other lanes.

The overall use case assessment is shown in Figure 3.3. The results are consistent and participants believe that geofencing could have a positive impact in this situation. The average rating was 5.4/7.
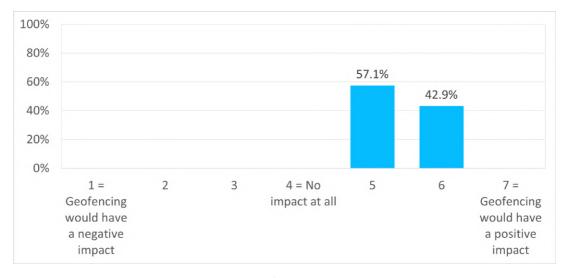
Figure 3.3: Evaluation: Use Case 1

Use Case 2: Fixed Zone on a Motorway

The second use case is situated again on a motorway, specifically on an off-ramp, and a schematic of this situation is shown in Figure 3.4. The red frame indicates the geofence zone that is dynamically generated in front of the off ramp when the emergency vehicle arrives at an accident location. The geofence zone is generated so that other drivers do not take the off-ramp but continue to the next one, to ensure safe conditions for rescuers providing aid at the accident. A suggestion of the instruction that has been proposed in this case for a driver approaching the geofence zone is shown in Figure 3.5. The red car approaching the geofence zone indicates the position of the driver in the driving simulator experiment who would receive the instruction via the HMI. The goal of this use case would be to determine if the drivers are able to follow the HMI instruction or if they would still enter the off-ramp to get to the desired destination. It is necessary to take into account the real situation for a large number of off-ramps. Drivers often cannot see what is happening on the off-ramp far enough in advance, particularly due to visual obstructions, for instance, in the case of more complex off-ramps, surrounding forests or buildings.
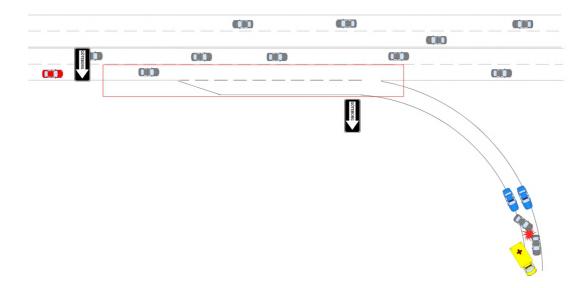
Figure 3.4: Use Case 2

Figure 3.5: HMI: Use Case 2

Feedback from participants

In this case, feedback on the proposed use case was mostly positive. Two of the participants had the idea to change "DO NOT TAKE THIS EXIT" to "ROAD/EXIT IS CLOSED" or "FORBIDDEN AREA" because the main instruction is already in the first line and one of these two alternatives would then better inform drivers why they should continue straight. It would also increase the likelihood that the driver would not bypass the instruction and not take the exit, knowing that it is not possible to pass anyway.

The overall use case assessment is shown in Figure 3.6. The results are consistent and most of the participants believe that geofencing could have a positive impact in this situation. The average rating was 5.3/7.
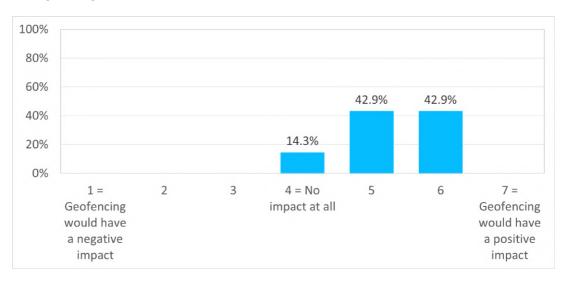

Figure 3.6: Evaluation: Use Case 2

Use Case 3: Moving Zone in Urban Area

The third use case is situated in an urban area in front of an intersection when an emergency vehicle is approaching the vehicle in the same direction. The presented use case refers to a signalized intersection, although it could also be applied to an unsignalized intersection or roundabout. The situation is illustrated in Figure 3.7. The red frame indicates the geofence zone, which is still at a certain distance in front of the intersection. In this case, it is proposed that the geofence instructs the driver of the red car to move to the right side and slow down to allow the emergency vehicle to pass smoothly towards the upcoming intersection. It should therefore prevent a situation in which the emergency vehicle would have to overtake a vehicle in the intersection or slow down significantly to ensure safety. The proposed HMI instruction in this case for the driver approaching and moving within the geofence zone is shown in Figure 3.8. In this particular situation, the same instruction could be applied to oncoming vehicles to provide the necessary space for the emergency vehicle to pass.
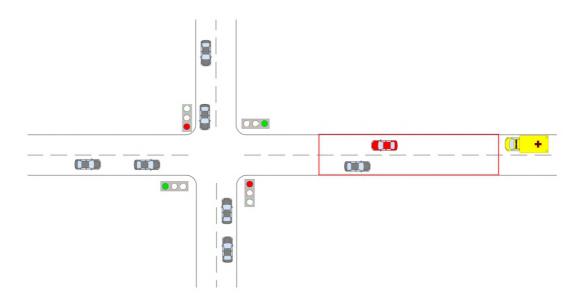
Figure 3.7: Use Case 3

Figure 3.8: HMI: Use Case 3

Feedback from participants

Feedback on this use case was more scattered than previous ones. Some of the participants pointed out that in their opinion only an EVA message about an approaching emergency vehicle would be more appropriate in this situation. In their opinion, there is still little knowledge about how emergency vehicle drivers behave in this situation. If we tell other drivers exactly what to do, it can lead to dangerous situations. A possible solution, in this case, they said, would be to also inform the drivers of emergency vehicles that the driver in front of them is pulling over to the right side and giving them the right of way. As for the geofence instruction, perhaps it would be better if it said "STOP" instead of just "SLOW DOWN". A better alternative to "KEEP THE RIGHT SIDE" might be "PULL OVER TO THE RIGHT SIDE". Linking to Advanced Driver Assistance Systems (ADAS) could be very beneficial in this case, for example, with feedback in the steering wheel to guide the drivers to the right side, and Intelligent Speed Adaptation (ISA) to make them slow down or stop completely. In the future, the HMI interface could be enhanced with a dynamic icon that would show how to perform a given task to make it easier to understand.

The overall use case assessment is shown in Figure 3.9. The chart shows a fairly wide variance of opinion in the participants' ratings. It is then difficult to reach an objective conclusion from the average rating of 4.0/7.
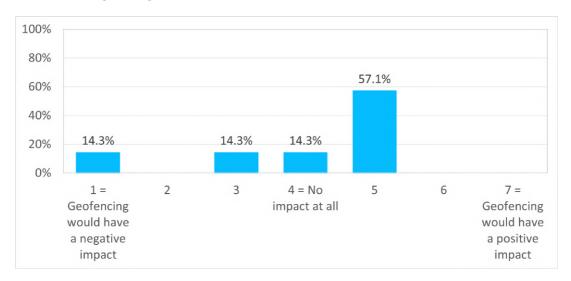
Figure 3.9: Evaluation: Use Case 3

Use Case 4: Fixed Zone in Urban Area

The fourth use case is situated in an urban area on a two-lane road, specifically an undivided road with one lane in each direction. The emergency vehicle is in a steady position on the roadside, partly on the pavement, see Figure 3.10. This situation is common in urban areas when an emergency vehicle arrives at a location to provide aid where no other parking options are available in the immediate vicinity. Rescuers need space to handle the patient or equipment and need to have a safe area around them to access the vehicle. Therefore, a geofence zone would be created around the emergency vehicle, which is marked with a red frame. In this use case, it would be necessary to issue instructions based on the lane in which the vehicle would be located. The proposed HMI in Figure 3.11 would target the drivers in the same lane as the red vehicle in this case.
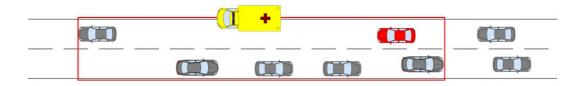
Figure 3.10: Use Case 4

Figure 3.11: HMI: Use Case 4

Feedback from participants

One of the notes on this use case is that it makes no difference whether the situation is in an urban area where the emergency vehicle is parked on the side or partially on the pavement, or in a rural area where it is stopped on the shoulder/edge of the road. It was stressed that in this case, the most important thing is to be aware of the stationary emergency vehicle. Therefore, according to some of the participants, it should be sufficient to use the EVA message to inform the drivers about the emergency vehicle. In the case of using geofencing, it might be safer to instruct drivers in the lane where they directly overtake the emergency vehicle to "YIELD TO

ONCOMING VEHICLES". In the same way as it should work in general with regard to the traffic rules. This in-vehicle instruction could enhance proper driver reaction.

The overall use case assessment is shown in Figure 3.12. The results are consistent and participants believe that geofencing could have a positive impact in this situation. The average rating was 5.3/7.
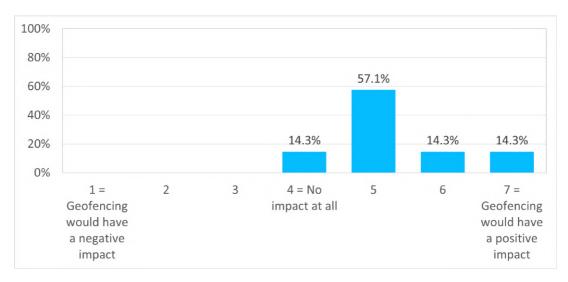

Figure 3.12: Evaluation: Use Case 4

Use Case 5: Fixed Zone in Urban Area

The fifth use case is situated in an urban area. The situation is shown in Figure 3.13 and is located at a signalized intersection. The emergency vehicle and the red vehicle are in a position where they would collide under the same driving conditions and without a mutual reaction, but in particular the reaction of the driver of the vehicle. The emergency vehicle has the right to drive through the intersection on a red signal, which leads to accidents if the drivers of the vehicles do not pay sufficient attention and drive through the green light without heeding the surrounding traffic situation. Another contributing factor that reduces a driver's ability to register an emergency vehicle is the obstruction of vision caused by surrounding buildings, trees, signs, or billboards. Based on previous research (Chapter 2.1), these situations are very common and lead to fatal consequences (Custalow and Gravitz, 2004; Ray and Kupas, 2007; Savolainen et al., 2009). Therefore, instructing drivers in the geofence zone, represented by the red frames, could increase the likelihood of registering an emergency vehicle in time and improve drivers' reactions. The proposed HMI can be seen in Figure 3.14. This particular instruction can be used as a preventive solution for all directions, i.e., for all vehicles in the red frames indicating the geofence zone. However, there would be potential for an advanced solution that could provide specific instructions for individual lanes depending on which lane the driver is in.
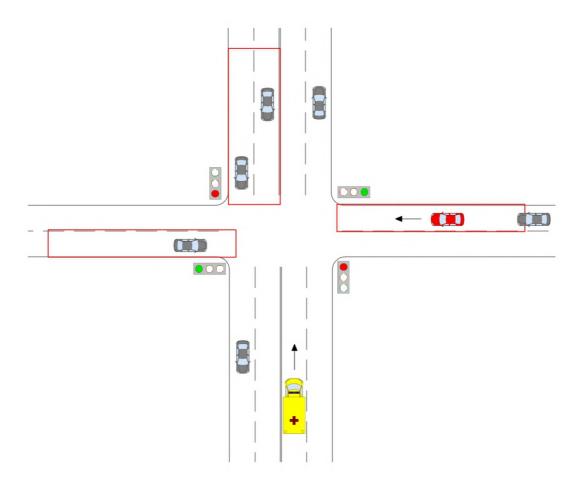
Figure 3.13: Use Case 5

23

Figure 3.14: HMI: Use Case 5

Feedback from participants

The main feedback from the participants on this use case was that it would be beneficial to provide absolute preference to the emergency services in the traffic light controller, thus giving them a clear path. Currently, traffic light controllers are still not always able to respond to a request for priority from an emergency vehicle. However, if the right of way for an emergency vehicle is not granted, an in-vehicle geofencing solution could provide drivers with an additional cue to avoid colliding with an emergency vehicle at the intersection. It was pointed out that the contradiction between the in-vehicle instruction and the external traffic light instruction can pose a major risk. Furthermore, for example, the word "STOP" could be excluded from the HMI instruction to avoid an impulsive reaction of the driver and a crash with following vehicles. A further suggestion from another participant mentioned that it could be beneficial for the driver of the vehicle to know from which direction the emergency vehicle is coming. In this case, the additional instruction could be worded as "BEWARE, EMERGENCY VEHICLE APPROACHING FROM LEFT". To reduce the number of words and fine-tune the HMI, the instruction "DO NOT DRIVE INTO INTERSECTION" could be used with a dynamic icon indicating the situation of the driver's vehicle and the approaching emergency vehicle.

The overall evaluation of the use case is shown in Figure 3.15. The chart indicates that the opinions on this use case differ significantly. Some participants are concerned about the use of geofencing in this case and some of them think that geofencing would have a very positive impact in this situation. The average rating was 5.0/7.
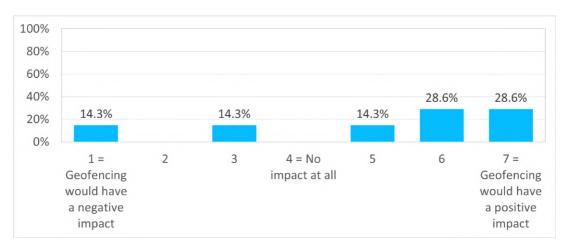
Figure 3.15: Evaluation: Use Case 5

Use Case 6: Moving Zone in Rural Area

The sixth use case is located in a rural area and is shown in Figure 3.16. The situation indicates an emergency vehicle about to overtake a red vehicle because in most cases it maintains a higher speed. A problem arises especially on rural roads without shoulders where there is not enough space and drivers usually have to slow down significantly to safely move out of the way of the emergency vehicle, or on curvy roads where drivers do not have sufficient visibility in all directions. Thus, they may have difficulties in recognizing an approaching emergency vehicle in time or may not be able to detect the emergency vehicle at all. The proposed HMI, shown in Figure 3.17, could be used for both directions and instruction well in advance could provide adequate space for the smooth passage of the emergency vehicle.

Figure 3.16: Use Case 6

Figure 3.17: HMI: Use Case 6

Feedback from participants

The feedback on this use case was mostly positive. One suggestion for an HMI was to inform the driver of the direction from which an emergency vehicle is approaching. This could be solved, for example, by using a dynamic icon to indicate the relationship between the vehicle and the emergency vehicle. Similar to the third use case, a better alternative for the instruction could be "PULL OVER TO THE RIGHT SIDE". Interfacing with ADAS could also be beneficial to help with driver reactions, especially with the use of steering wheel feedback and ISA.

The overall evaluation of the use case is shown in Figure 3.18. The results are consistent and participants believe that geofencing can have a rather positive impact on driver behaviour. The average rating was 5.1/7.
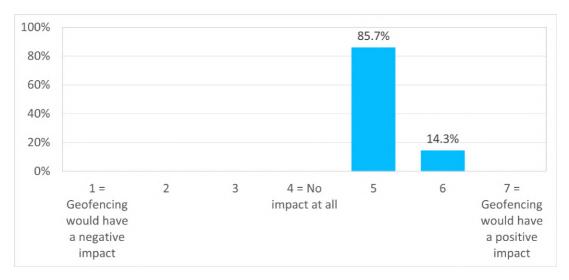

Figure 3.18: Evaluation: Use Case 6

Use Case 7: Fixed Zone in Rural Area

The seventh and final use case is situated in a rural area and is illustrated in Figure 3.19. The situation reflects the problem of dangerous intersections due to the surrounding environment that obstructs the driver's view, such as surrounding trees or hilly terrain. This use case represents a three-leg intersection and an emergency vehicle approaching the intersection from the minor road. In order to ensure a smooth passage of the emergency vehicle, a geofence zone would be established on the major road to ensure yielding to the emergency vehicle. The geofence zone is indicated by the red frame and the proposed HMI with the instruction that could be delivered to the driver in the zone is shown in Figure 3.20. The extent of the geofence zone depends on the route of the emergency vehicle. If the emergency vehicle was turning left, a geofence zone would be created for lanes in both directions. The wording of the instruction could remain the same. If the emergency vehicle continues to the right, as in this case, then the geofence zone is required for only one lane.
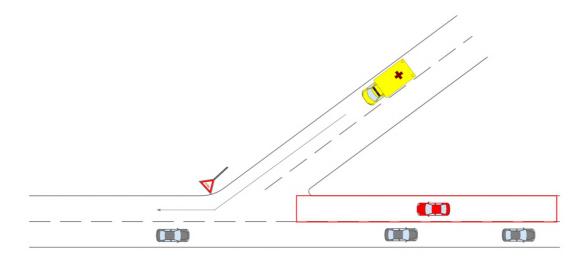
Figure 3.19: Use Case 7

Figure 3.20: HMI: Use Case 7

Feedback from participants

In this use case, the urgency of informing the driver of the location of the approaching emergency vehicle was again pointed out. An alternative for the wording of the HMI instruction could be "DO NOT DRIVE INTO THE INTERSECTION", which together with the dynamic emergency vehicle icon could be effective for collision avoidance. In conclusion, the feedback was mostly positive.

The overall use case assessment is shown in Figure 3.21. The results show that most of the participants believe that geofencing could have a rather positive impact in this case. The average rating was 5.4/7.
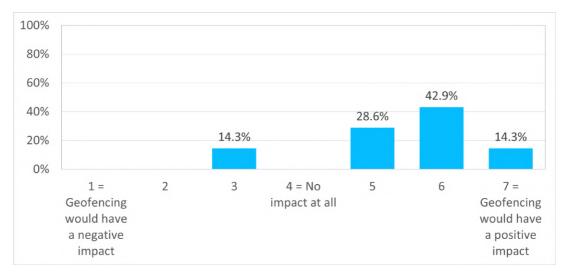
Figure 3.21: Evaluation: Use Case 7

3.3 Evaluation from the Workshop

The workshop proceeded successfully and all participants actively participated in the discussion and expressed their opinions. One of the outcomes of the workshop is that a consensus on the definition of geofencing was reached. The data collected from the questionnaire at the end of the workshop provides quantitative feedback.

Most participants believe that geofencing could improve driver behavior if instructions are provided in a timely, clear, and understandable manner and if the accuracy of geofencing is ensured. It was pointed out that even though the preference of traffic lights for emergency vehicles works or the conditions for drivers to handle the situation when interacting with an emergency vehicle may seem easy, geofencing can be an enhancement to increase the likelihood of correct reactions for the vast majority of drivers. Therefore, the crashes with emergency vehicles would minimize. On the other hand, driver behavior could worsen if the instruction is unclear and causes driver overload, impaired perception, and distraction. Moreover, if there are a large number of erroneous alerts, drivers may start to ignore them.

In conclusion, Figure 3.22 shows the assessment of the participants attending the workshop regarding the potential overall contribution of geofencing in the interaction between vehicles and emergency vehicles. The resulting chart and the average rating of 5.4/7 is a promising indicator for continued research.
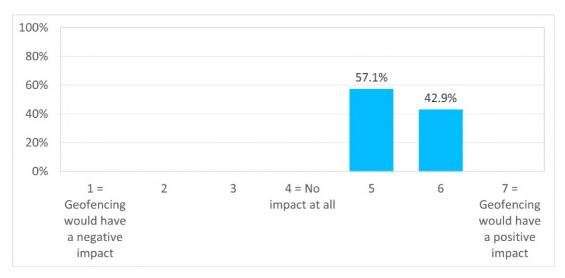
Figure 3.22: Overall Evaluation

4 Driving Simulator Experiment

This chapter describes a driving simulator experiment conducted for the present thesis. Firstly, selected use cases implemented in the scenarios for the simulator study are described. Furthermore, information about the recruitment of the study participants, the equipment used, and the setup of the driving simulator is provided. Finally, the chapter describes the procedure of the experiment.

4.1   Description of the Use Cases

The following section contains a description of two use cases implemented in the scenarios for the driving simulator study. The implemented use cases were selected based on feedback from the workshop in order to answer the research questions. After the workshop, the situations were partially modified and optimized.

The first selected use case was situated on an off-ramp and corresponds to Use case 2 presented at the workshop (3.2). This use case was chosen based on the positive evaluation from the participants attending the workshop and the expected significance of the results, concerning if the driver is able to detect and follow geofence instructions. The output obtained was expected to answer the first research question. A sketch of the use case is shown in Figure 4.1.

The participants of the experiment were invited to drive on a motorway under free-flowing traffic conditions. According to the road signs, they were supposed to take an off-ramp directing them to the desired destination, the town of Trosa. The road signs to the town were placed 500 metres apart in front of the off-ramp and they are depicted in Figure 4.1.

In the scenario, an accident involving two vehicles, a truck and a passenger car, was located on the off-ramp along with an emergency vehicle providing aid at the spot. When approaching the off-ramp, half of the drivers were instructed to continue straight via an HMI using geofence method. The instruction was delivered based on the presence of emergency vehicle operating at the accident spot. The accident could not be seen prior to the participant choosing whether to take the off-ramp or not because of the surrounding vegetation obstructing the driver's view.

The accident could not be detected until the last tens of metres of the auxiliary lane, when it was still possible to change direction and continue driving on the motorway. Drivers who received the instruction, therefore, had to fully trust the in-vehicle HMI and react accordingly

to avoid braking abruptly and stopping on the off-ramp due to an accident. This would increase the likelihood of a potential collision or a collision with other vehicles. Drivers who were not instructed were assessed in terms of their driving behavior in the situation on the off-ramp and the actions they would take in such a situation.
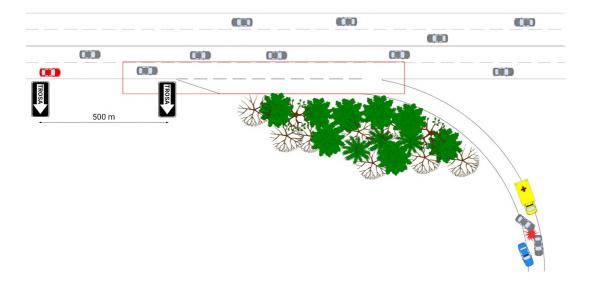
Figure 4.1: Off-ramp Use Case

The HMI design of the geofence instruction used in the first scenario is shown in Figure 4.2. It was assumed that the majority of the participants in the study would be Swedish drivers, thus the instruction was formulated in Swedish. The translated instruction means "CONTINUE STRAIGHT Exit closed". The visual HMI was extended with an audio transmission of the instruction repeated three times.

Figure 4.2: Off-ramp HMI

The second selected use case was located at a signalized intersection and corresponds to Use case 5 presented at the workshop (3.2). The feedback from the guests attending the workshop was significantly scattered. Some of them expressed their opinion of a highly positive impact of geofencing in the situation, while some had a completely opposite opinion. The apparent lack of consensus on this use case was one of the factors behind the decision to assess this particular situation. In addition, a large proportion of accidents involving emergency

vehicles occur at intersections (Custalow et al., 2004; Drucker et al., 2013; Savolainen et al., 2009). Finally, the selected use case was intended to answer the second research question concerning the impact on the driving time of an emergency vehicle.

In order to maintain realistic conditions, the emergency vehicle was programmed to slow down from *50 km/h* to *30 km/h* before the intersection. When the intersection was clear, the emergency vehicle began to re-accelerate at the midpoint of the intersection. When a risky situation with the potential to lead to a collision occurred, the emergency vehicle reacted by stopping and re-accelerating as soon as the situation allowed it. A sketch of the use case is shown in Figure 4.3.

The initial situation presented at the workshop was simplified for the purpose of the experiment. The result was a four-legged intersection with two lanes on each leg, one lane in each direction. The intersection was placed between buildings simulating urban environment and the participants were driving in free-flowing traffic. The red car in Figure 4.3 indicates a participant of the experiment. When approaching the intersection, half of the drivers were instructed to stop before the intersection via an HMI using geofence method. The instruction was delivered based on the position of the emergency vehicle and the upcoming interaction with the vehicle. The emergency vehicle was programmed to approach the intersection at approximately the same time as the driver to evaluate the drivers' reactions.
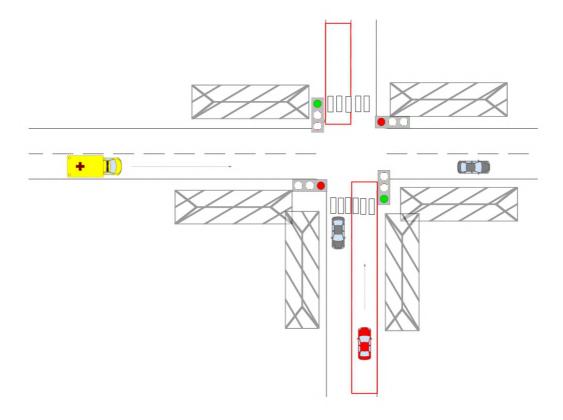
Figure 4.3: Intersection Use Case

The HMI design of the geofence instruction used in the second scenario is shown in Figure 4.4. Also this instruction was formulated in Swedish and its translation means "STOP BEFORE THE INTERSECTION". The visual HMI was extended with an audio transmission of the instruction repeated four times.

Figure 4.4: Intersection HMI

4.2 Recruitment of Participants

A minimum of 60 participants were required for the study to ensure obtaining enough data and to increase the likelihood of valid outputs. Drivers had to have a valid driving license for passenger cars, which means at least category B in Sweden. In addition, drivers were invited to participate based on the following criteria; not easily get motion sick in cars, buses, or other means of transport; not have been involved in a serious traffic accident. Participants were recruited via email from the VTI database, on the VTI website, or through social media advertising. They signed up for a suitable time slot via the booking system. Each participant received a movie gift card worth approximately SEK 100 as a reward for participating in the study.

Participants were divided into four groups according to the use case and whether they were given the geofence instruction, as indicated in Table 4.1. A between-group design was used in the study, meaning that each participant drove one scenario with only one use case involving interaction with an emergency vehicle, either without or with the given geofence instruction. The between-group design was used to avoid any priming effect, i.e., to avoid any anticipation of an upcoming event based on recent experience. Each participant was assigned to one of the four groups listed in Table 4.1.

Table 4.1: Study Division by Groups

Group	Use Case	Geofence Instruction
1	Off-ramp	No
2	Off-ramp	Yes
3	Intersection	No
4	Intersection	Yes

4.3   Materials and Settings

A fixed-base driving simulator was used for the experiment. The perceptual cues were visual and auditory in the study. Visual cues were displayed on three 55-inch LCD screens over which the scene was transmitted, including the display of rear-view mirrors. The driving simulator was equipped with an instrument cluster behind the steering wheel which displayed visual geofence instructions. The simulator setup is shown in Figure 4.5.

Figure 4.5: Simulator Setup

The auditory cues were generated by simulating ambient sounds of the engine, other traffic, air resistance, etc. The stereo system in the driving simulator was switched off, except for the audio transmission of instruction, which extended and enhanced the visual instruction. In both cases, the audio signal provided the driver with the same instructions as were displayed on the instrument cluster.

Based on the driver's speed, the geofence instruction was displayed to the driver *15 s* before the driver's estimated arrival at the accident in the Off-ramp scenario and *12 s* before the estimated interaction with the ambulance at the intersection in the Intersection scenario. Half of the participants in each use case did not receive the geofence instruction, while the other half did.

VTI simulation software was used to model the driving scenarios. The Off-ramp scenario consisted of a four-lane motorway divided into two lanes in each direction by a median grass strip with crash barriers. A demonstration of the scenario setup is shown in Figure 4.6. Other traffic appeared only in the opposite direction. The only road user with whom the driver interacted was the stationary emergency vehicle at the accident spot on the off-ramp. The motorway was designed without significant curves and elevation changes, with a speed limit *110 km/h*. The speed limit on the section starting *1 000 m* before the beginning of the auxiliary lane was *90 km/h*. The off-ramp was a single lane with a length of approximately *400 m* from the point of the start of the auxiliary lane to the accident spot. The speed limit from the end of the auxiliary lane was *70 km/h*.

Figure 4.6: Off-ramp Scenario Setup

The second scenario containing the Intersection use case consisted of a two-lane rural road with a speed limit *70 km/h* followed by a road in an urban environment with a speed limit *50 km/h*. A demonstration of the scenario setup in the urban area is shown in Figure 4.7. The urban road consisted of two lanes, with one lane in each direction, several parallel parking lots along the road, and one additional intersection located in front of the study area. Other traffic during the experiment consisted of cars driving in the opposite direction at a very low density, a few vehicles parked in parking lots, and a couple of pedestrians standing on the pavement. The driver had to interact with an emergency vehicle that was passing through the intersection.

Figure 4.7: Intersection Scenario Setup - Urban Road

Collected Metrics

Data gathered from the driving simulator study were recorded separately for each participant's run. Necessary metrics collected for further processing were time, distance, speed, brake pedal sensor, accelerator pedal position and road identification. Additionally, the ambulance data was collected in the Intersection scenario, including time, distance, ambulance speed, and the road identification on which the ambulance was traveling.

4.4 Experiment Procedure

The experiment lasted approximately 30 minutes per participant. Participants were first informed about the experiment in accordance with the ethical guidelines of Vetenskapsrådet (n.d.) and subsequently received written informed consent. Each participant was assigned an identification number under which the data were further processed and then filled out a pre-survey containing general information such as age, gender, or driving experience. The translated pre-survey is attached in Appendix A. Afterwards, familiarisation with the driving simulator followed. Participants were instructed to adjust the seat to their preference and to fasten the seat belt. They were also informed of the placement of the rear-view mirrors on the scene and noted that the car was equipped with an automatic transmission.

Participants tested in the Off-ramp scenario were instructed to drive and follow the traffic rules as they are used to. The driving scenario lasted approximately 6 minutes, giving drivers time to get used to the simulator features and to fully control the vehicle. The task was to follow the road signs to the desired destination, the Swedish town of Trosa. Towards the end of the drive, participants were directed by road signs to take the off-ramp. Driver behavior was examined through reaction to the geofence instruction before the off-ramp or driver behavior on the off-ramp. The first sign was placed *500 m* in front of the turn into the auxiliary lane (see Figure 4.8) and the second just in front of the lane (see Figure 4.11).

Figure 4.8: Road Sign - 500 m

The participants who did not receive or did not follow the geofence instruction were asked about the actions they would carry out when they reached the accident on the off-ramp. The situation is illustrated in Figures 4.9 and 4.10. The experiment was then terminated.

Figure 4.9: Approach to the Accident

Figure 4.10: Accident on the Off-ramp

If the geofence instruction was applied and the drivers followed it, i.e., continued straight, after a few seconds the message "Please stop the car" appeared in the scenario and the experiment was terminated. The situation where the geofence instruction appears on the instrument cluster is shown in Figure 4.11.

Figure 4.11: Application of Geofence - Off-ramp Use Case

Participants tested in the Intersection scenario were instructed that they were in a hurry. One of the reasons was to ensure their interaction with the emergency vehicle at the end of the scene. Another reason was to cause them to be slightly distracted. The entire run lasted approximately 7-8 minutes to give the drivers time to adjust to the functions of the simulator and to fully control the driving of the vehicle. The participants were specified that the key task was to stay as close to the speed limits as possible. Monitoring the instrument cluster for adherence to the determined speed caused the drivers to be more distracted, which in part in-

duced regular driving distractions caused by other traffic, noise, other road users, etc. At the end of the experiment, drivers were tested on the interaction situation with the emergency vehicle at the intersection. When the emergency vehicle passed through the intersection, drivers who reacted and stopped in front of the intersection could reaccelerate and continue driving. The experiment was terminated *12 s* after the ambulance passed through the intersection by the message "Please stop the car" appearing in the scenario. A demonstration when geofence instruction was used is shown in Figure 4.12.

Figure 4.12: Application of Geofence - Intersection Use Case

After the driving simulator experiment, participants were asked to fill out a post-survey. The survey consisted of questions regarding the participants' subjective attitudes and feelings about the experience. For Groups 2 and 4 that received geofence instruction, the survey included questions regarding the evaluation of the geofence instruction during the interaction with the emergency vehicle. All participants were asked to express the level of stress they felt during the situations. Among other things, participants were asked about their regular driving behavior when interacting with emergency vehicles in order to assess the level of driver knowledge on this issue. The post-survey for Groups 1 and 2, tested on the Off-ramp use case, is attached in Appendix B and the post-survey for Groups 3 and 4, tested on the Intersection use case, is attached in Appendix C. The questionnaires were prepared in Swedish for the participants of the study, the translated versions are enclosed in the present thesis.

5 Analysis of Data

In this chapter, the data from the driving simulator experiment are processed and analyzed. First, information about all participants in the study, such as gender, age, driving experience or behavior in certain situations, is presented. Afterwards, data from two scenarios with selected use cases are analyzed and presented separately. The analysis is based on the data from the driving simulator and the questionnaires the study participants filled out before and after driving. Data processing and resulting graphs were carried out using RStudio software.

5.1 Participants' Background Information

A total of $n = 69$ drivers aged 19 - 86 years, $M = 50.9$ years, $SD = 16.2$ years, with a total of 20 females and 49 males, participated in the study. The participants were divided into four groups by gender and age so each group was equally represented. The distribution of the participants by use case, age, and gender is shown in Table 5.1.

Table 5.1: Participating Drivers

	Off-ramp Use Case				Intersection Use Case			
Geofencing (Group)	Without (1)		Applied (2)		Without (3)		Applied (3)	
Age/Gender	Woman	Man	Woman	Man	Woman	Man	Woman	Man
18-25	1	-	1	1	-	-	1	1
26-45	-	3	1	-	2	6	2	4
46-65	2	7	3	6	2	4	3	7
65+	1	1	-	4	1	4	-	1
Total	**4**	**11**	**5**	**11**	**5**	**14**	**6**	**13**
Total per Group	15		16		19		19	

The participants were asked to state how often they would normally drive. A majority, 42 participants (60.9%) indicated that they would drive daily. 17 participants (24.6%) reported driving a few times per week. The remaining participants indicated that they would drive several times per month or more rarely. The distribution of driving habits is shown in Figure 5.1.
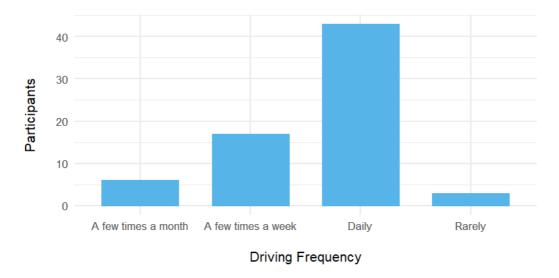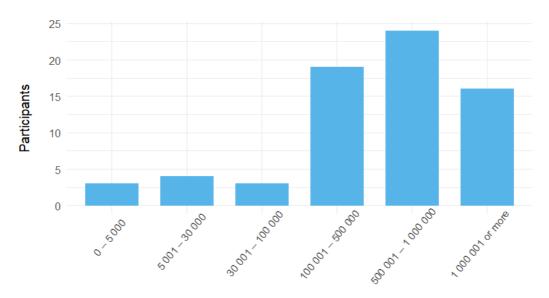
Figure 5.1: Frequency of Driving

Seven participants stated that they were professional drivers, i.e., they drive a car, bus, truck, or other motor vehicle in traffic as their occupation. Most participants were experienced drivers, with 40 of them (58.0%) estimating they had driven more than *500 000 km* in their lifetime. Figure 5.2 shows the approximate number of kilometres driven in their lifetime divided in intervals.

Figure 5.2: Driving Experience

45 participants (65.2%) stated that they were visually impaired and therefore have to wear glasses or contact lenses when driving. Of these, 14 participants (31.1%) were nearsighted, 13 participants (28.9%) had a combination of nearsightedness and astigmatism. Six participants (13.3%) were farsighted, two participants (4.4%) had a combination of farsightedness and astigmatism. Five participants (11.1%) reported having astigmatism. The remaining five participants (11.1%) were visually impaired due to aging.

After driving the participants were asked to fill out a post-survey, where the participants were asked further general information. Figure 5.3 indicated participants' habits of using navigation systems. Navigation systems can provide drivers with alerts or rerouting if an accident or other event is reported at the location of their route. This may, among other things, include accidents or events with emergency vehicles. Thus, some situations of interaction with emergency vehicles can be avoided if using navigation systems. It can be seen in Figure 5.3 that eight out of 69 (11.6%) drivers use navigation systems every time they drive. 22 drivers (31.9%) answered they use navigation often, even if they know the way. Assuming that navigation systems provide emergency vehicle alerts in the future, geofence instructions in the car would serve the drivers using navigation as a safety feature increasing the likelihood of a correct response by the driver. According to Figure 5.3, a larger proportion of the participants, specifically 35 (50.7%), use navigation systems only when they do not know the way, and 4 participants (5.8%) do not use them at all. For drivers who do not use navigation regularly or at all, geofencing may be the only tool to alert them before interacting with emergency vehicles and instruct them on how to act.
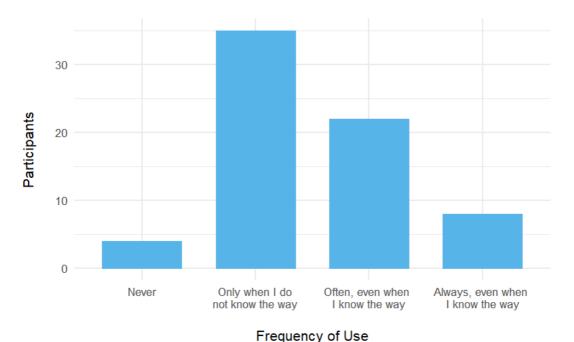
Figure 5.3: Usage of Navigation Systems

89.9% of the participants reported a value 5 or higher indicating a positive opinion of the use of ADAS in vehicles, as shown in Table 5.2. *8.7%* of the participants reported a value 4 expressing a neutral opinion of the use of ADAS and only one study participant stated a 3 (1.4%), a somewhat negative opinion regarding ADAS.

Table 5.2: ADAS Evaluation

Evaluation scale (1 = Very negative, 7 = Very positive)	1	2	3	4	5	6	7	M	SD
What is your opinion on ADAS?	0	0	1	6	14	20	28	**5.99**	1.05

Study participants were also asked about the estimated number of times in their lives in which they had driven and had to interact with an emergency vehicle. The number of interactions with emergency vehicles during their life time is displayed in Figure 5.4. 25 drivers (36.2%) reported over 100 interactions with emergency vehicles. 19 drivers (27.5%) indicated 25 interactions or less. The conversation during the experiment indicated that the difference in number of interactions may be due to the factor of the participants living in a rural or urban area. Most participants living in urban areas reported that interactions with emergency vehicles were common. Another factor is the number of years of holding a driving license.
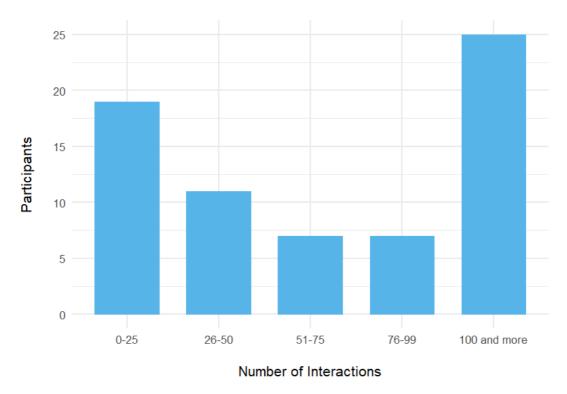
Figure 5.4: Interaction Situations With Emergency Vehicles During a Lifetime

5.2 Off-ramp Use Case

The following section presents the results of the drivers' behavior tested on the Off-ramp use case. Firstly, general information about the participants of the Off-ramp use case is given, and secondly, the data from the driving simulator study is analyzed.

Off-ramp Use Case Participants

A total of $n = 30$ participants aged 19 - 82 years, $M = 51.5$ years, $SD = 14.6$ years, with a total of 8 females and 22 males, were assessed in the Off-ramp scenario. One participant was excluded from the data processing of the driving simulator experiment due to not having driven a vehicle in the last 15 years. A majority of the participants, specifically 26 (86.7%), had their driving licenses 10 years or longer. Two participants received their driving license 6 years ago and two other participants were novice drivers having a driving license for less than 2 years.

Off-ramp Use Case Analysis

The main objective of the Off-ramp use case was to assess if drivers were able to follow the geofence instruction. The participants were told by the experiment leader to drive to the town of Trosa, which involved taking the off-ramp off the motorway. None of them were informed in advance of the purpose of the experiment, i.e., geofencing, the appearance of the geofence instruction via HMI, or the occurrence of an accident during the experiment.

All participants who got the instruction to continue straight obeyed it, whereas all participants who did not get this instruction took the off-ramp. A Chi-squared test of homogeneity was performed to test whether or not the use of geofence instruction (yes, no) affected the decision to refrain from taking the off-ramp (yes, no), $\chi^2(1, N = 30) = 30$, $p < .001$, yielding a statistically strong significant effect. The results are also illustrated in Figure 5.5.
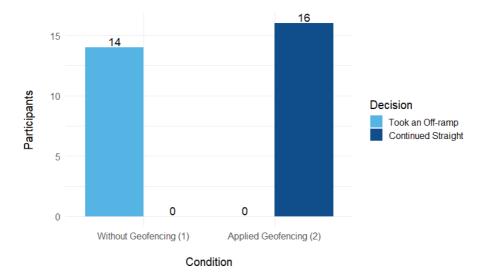
Figure 5.5: Comparison of the Participants' Decisions

Note. All Group 2 participants who received the geofence instruction followed it ($n = 16$), none of them took the off-ramp ($n = 0$). All Group 1 participants did take the off-ramp where accident was located ($n = 14$), none of them continued straight to avoid the impassable off-ramp ($n = 0$).

Another measure of driving performance was a comparison of the mean speeds of Group 1 and Group 2 drivers, which demonstrated the impact of geofence instruction on driver behavior. By observation from Figure 5.6 of the mean speed with *SE* (standard error) intervals, it seems that conveying the geofence instruction did not have a hazardous effect on driver behavior in terms of mean speed change.

The geofence instruction was delivered to the participants *15 s* before the estimated arrival to a location of the ambulance with the accident on the off-ramp (distance of *9 500 m* from the

starting point of the drive, see Figure 5.6). The estimated arrival was calculated based on the speed of the driver. Therefore, the geofence instruction was delivered to the participants via the instrument cluster at the indicated interval in Figure 5.6 between a distance of *9 150 - 9 250 m* based on the driver's speed. The instruction remained displayed until the end of the experiment. The difference in instruction delivery between the slowest and the fastest driver was approximately *5 s*. In addition, a road sign to the destination town of Trosa was placed at a distance of *9 200 m* from the starting point of the drive as indicated in the figure. Absolute measurements of reaction times on geofence instruction and its influence on drivers' speed were not the subject of the Off-ramp use case, so it is not possible to analyze how reaction times differed between drivers or its effect on the speed of drivers. The impact of geofencing can therefore be assessed only by observation from Figure 5.6.

Figure 5.6: Comparison of Mean Speeds with *SE* Intervals - Off-ramp

Even though, all the participants of Group 1 entered the off-ramp, all of them did make a complete stop in front of the accident (a distance of *9 500 m* in Figure 5.6). Therefore, none of them crashed into the accident or the steady emergency vehicle on the spot. Once they stopped, they were asked to freely describe how they would act if they were in the exact same situation in real life. Eight participants (57.1%) responded that they would just wait until the accident was cleared and the road was passable. Two of the participants (14.3%) responded they would pull over to the roadside and wait. Three participant responses (21.4%) included turning on hazard warning lights. Only one out of 14 participants (7.1%) noted that they would check the situation and if it was safe, they would wait outside the car to increase their own safety. The participants' responses are shown in Figure 5.7.
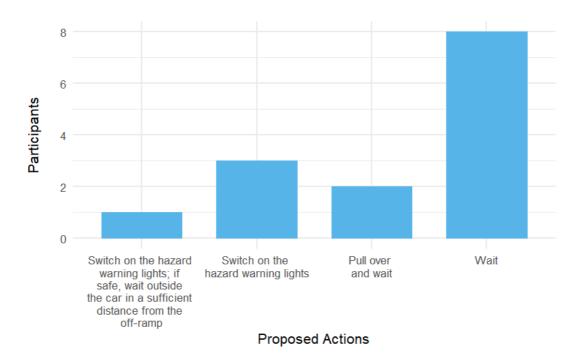
Figure 5.7: Actions of Drivers on the Off-ramp

A Chi-squared test of homogeneity was performed to test whether the factor of age (<=35, >35) affects the correctness of the response (yes, i.e., at least turning on the warning lights; no, i.e., waiting or pulling over and waiting), $\chi^2(1, N = 14) = 9.55$, $p = .002$. The results show a statistically significant difference of the knowledge of the participants aged 35 years and younger about how to behave in such a situation compared to the participants older than 35 years.

5.3 Intersection Use Case

The following section presents the results of the drivers' behavior tested on the Intersection use case. General information about the participants of the Intersection use case is presented firstly. Furthermore, data from the driving simulator study is analyzed.

Intersection Use Case Participants

A total of $n = 34$ participants aged 19 - 78 years, $M = 49.7$ years, $SD = 17.4$ years, with a total of 10 females and 24 males, were assessed in the Intersection scenario. Four participants were included in a test pilot. After running the pilot, a few adjustments to the scenario were made. Therefore, the participants of the pilot are not included in the data analysis. Out of the included participants in the Intersection use case 31 participants had had their driving license 10 years or longer. Three participants were novice drivers having had a driving license for less than 2 years.

Intersection Use Case Analysis

The main objective of the Intersection use case was to assess if the use of geofencing in passenger cars can improve the driving time of emergency vehicles. Other objective was to assess if drivers are able to react in a timely and correct manner when geofencing is applied. Similar to the Off-ramp use case, none of the participants were informed in advance about the

purpose of the experiment, i.e., geofencing, displaying geofence instructions via the HMI, or interacting with the emergency vehicle during the study.

The measure of driving performance was a comparison of the mean speeds between the participants without and with applied geofence shown in the resulting graph of the mean speeds with *SE* intervals in Figure 5.8. The green line in the figure shows the noticeable effect of the geofence instruction and the performed reactions indicated by the reduction of drivers' speed. The geofence instruction entailed a reaction of slower and gradual braking, more than 150 metres before the intersection. According to the observation of Figure 5.8, the participants of Group 4 reacted earlier as a result of the geofence instruction than the participants of Group 3 without the geofence instruction.
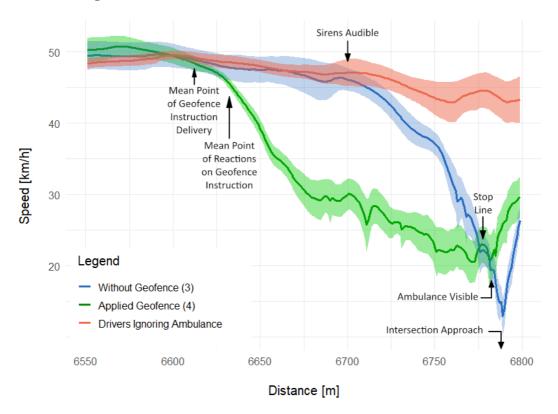
Figure 5.8: Comparison of Mean Speeds with *SE* Intervals - Intersection

The geofence instruction was delivered to the participants *12 s* before the estimated arrival at the intersection. The estimated arrival was calculated based on the drivers' speed. The average point at which the participants received the geofence instruction is indicated in Figure 5.8. The instruction was given at a distance interval between *6 570 m* for the fastest driver and *6 680 m* for the slowest driver.

A t-test was performed to test the impact of geofencing on earliness of the reaction before the interaction with the ambulance. The results of measuring how far in advance the participants performed the reaction before the interaction with the ambulance at intersection between Group 3 participants ($M = 3.479$ s, $SD = 1.29$ s) and Group 4 participants ($M = 15.967$ s, $SD = 0.96$ s) indicated a statistically significant effect of the geofence instruction on earliness of the reaction, $t(25) = 28.66$, $p < .001$, $d = 11.42$. The performed reaction was determined on the basis of braking if the participant had his foot off the acceleration pedal, otherwise taking his foot off the accelerator pedal.

Group 3 participants who did not receive the geofence instruction reacted by braking more abruptly and impulsively at a mean distance of 50 metres before the stop line. They seem to have reacted based on the sirens, which were audible *6.5 s* before estimated arrival

at the intersection approach as indicated in Figure 5.8. The mean speeds graph shows that, on average, the participants of Group 3 came to the lowest speed after the traffic lights and pedestrian crossing before approaching the intersection when the ambulance was visible approaching from the left arm of the intersection.

A comparison of the reaction times, i.e., the advance with which the reaction was performed before the interaction with the ambulance, of individual participants and also between groups is shown in Figure 5.9.
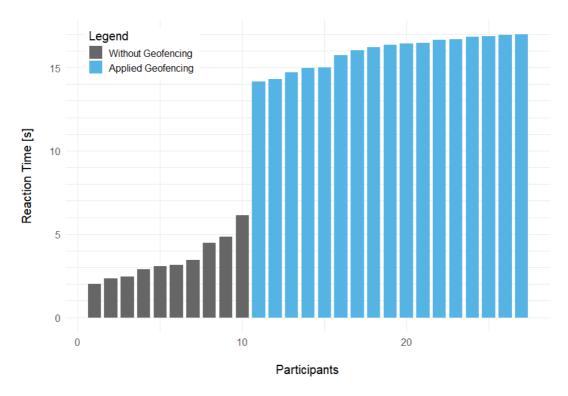
Figure 5.9: Reaction Times Prior to Interaction with the Ambulance

A separate red line in Figure 5.8 indicates a mean speed of $n = 7$ participants of Group 3 who did not receive the geofence instruction and drove through the intersection despite the sound of ambulance sirens. None of the participants who received the geofence instruction behaved this way. Subsequently, five participants commented on this action by saying they heard the sirens, looked in the rear view mirrors, and did not see the ambulance. Thus, they continued driving because they did not consider that the ambulance might be approaching from a different direction of the intersection. Two participants stated they thought the ambulance was far away, so they drove through the intersection without paying attention to the ambulance.

None of these participants who ignored the ambulance caused a collision with the ambulance, but they did expose themselves and the ambulance to a risky situation. By driving through the intersection directly in front of the ambulance, these participants caused the ambulance to be delayed. As a safety precaution, the ambulance was forced to stop before intersecting with the road the participant was travelling on in order to ensure it had a clear way before continuing. This process was programmed estimatively based on the physical characteristics of the vehicle. The impact on the ambulance's time of passing through the intersection is depicted in the graph in Figure 5.10.
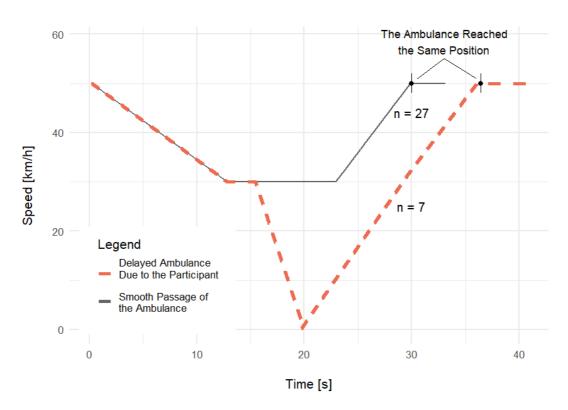
Figure 5.10: Delay of the Ambulance

Note. The red dashed line indicates the impact on the ambulance's speed of each of the $n = 7$ participants per individual without geofencing who caused the delay of the ambulance when it was passing through the intersection. The grey line indicates the ambulance's speed over driving time when interacting with each of $n = 17$ participants with applied geofence instruction and each of $n = 10$ participants without geofencing who did not affect the ambulance's driving time through the intersection.

The impact of each of seven drivers who ignored the ambulance and crossed the intersection directly in front of the ambulance is indicated by the red line in Figure 5.10. The grey line in the figure indicates the ambulance time of passing through the intersection when the participant did not affect the ambulance driving time, i.e., did not cause the ambulance delay ($n = 17$ participants of Group 4 with geofence instruction, and $n = 10$ participants of Group 3 without geofence instruction who stopped before the intersection and gave way to the ambulance). All drivers who passed through the intersection heard the sirens before entering the intersection. At that point, the ambulance was already close enough, thus driving through the intersection before the ambulance could not be considered as a proper reaction. The ambulance delay was $M = 6.2$ s, $SD = 0$ s. As the ambulance was driving according to the programmed behavior and these seven participants passed through the intersection before crossing with the ambulance, everyone of these seven participants caused the ambulance to be delayed by *6.2 s* each.

A Chi-squared test of homogeneity was performed to test whether or not the use of geofence instruction (yes, no) affected the delay of ambulance driving time (yes, no), $\chi^2(1, N = 34) = 8.81$, $p < .001$. None of the participants who received the instruction caused the ambulance to be delayed, while seven of the 17 participants who did not receive the instruction caused the ambulance to be delayed, which yielded a statistically significant effect of the geofencing.

Reaction times to the geofence instruction were assessed on behavior of Group 4 participants. The reactions were calculated based on the time the participants were given the geofence instruction via the visual and audio HMI, and the time they reacted to these cues. The timestamp of the reaction was determined based on participant braking if the participant had their foot off the acceleration pedal, otherwise removing their foot from the acceleration pedal based on pedal position. Figure 5.11 shows an overview of the participants' reaction times in intervals. As can be seen, the reactions of nine of the 17 participants ranged between *0.6 s* and *1.5 s*.
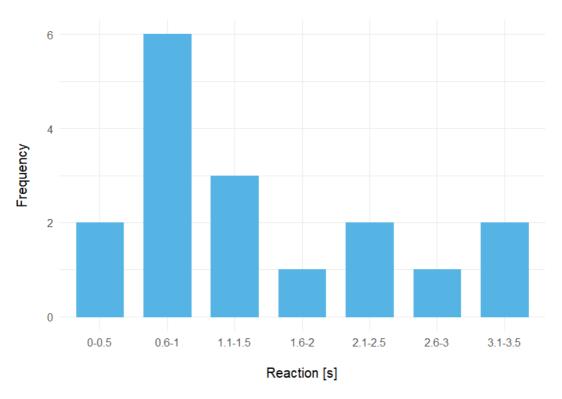
Figure 5.11: Reaction Times

5.4 Questionnaire Evaluation

This section presents the evaluation of the questionnaire the participants completed after the driving experience in the simulator. The results are divided according to the groups to which the participants were assigned. Since a between-group design was used, the differences in participants' opinions between the Off-Ramp and the Intersection use case are presented. The first section deals with a comparison of the use cases in which geofencing was not applied, and the second section concerns when geofencing was applied. To be able to compare participants' opinions between non-applied and applied geofencing, a within-group design would be required. However, this would introduce other risks, for instance, a priming effect of participants during an experiment. The last section provides a comparison of participants' attitudes towards receiving geofence instructions in their own vehicles, which is the only question that could have been asked of all participants in the study.

Groups 1 and 3 Without Geofencing

The following section presents the ratings from the participants of Groups 1 and 3 who did not receive the geofence instruction. The participants rated the given statements on a scale of 1 to 7 (1 = Strongly disagree, 7 = Strongly agree) based on their experience in the driving simulator. Descriptive statistics of participants' ratings for Groups 1 and 3 are presented in Table 5.3 along with inferential statistics of differences. For each of the statements, a t-test for independent samples was used to compare participants' experience between two scenarios with each testing on the different use case.

Table 5.3: Post-Survey Comparison of Participants' Opinions Without Geofencing

Measure	Group 1		Group 3		t	p
	M	SD	M	SD		
The situation made me feel stressed	1.79	0.97	2.59	1.28	1.93	0.06
I knew what to do, but I did not have enough time to react	2.71	2.02	3.24	2.25	0.62	0.51
In the future, I would like to receive instructions when interacting with emergency vehicles in my own car (complement to blue light and sirens)	4.86	1.75	5.24	1.68	0.61	0.54

The results of an independent samples t-tests indicated no statistically significant difference for any of the given statements between groups of participants who drove two different scenarios being tested on two different use cases.

64.29% of the participants tested on the Off-Ramp use case without geofencing rated positively they would like to receive instructions in the future when interacting with emergency vehicles in their own car, with four participants assigning a value of 5, two participants a value of 6 and three participants a value of 7. The same statement was rated positively by *64.71%* of the participants tested on the Intersection use case without geofencing, with two participants assigning a value of 5, four participants assigning a value of 6, and five participants assigning a value of 7.

Groups 2 and 4 With Applied Geofencing

The following section presents the ratings from the participants of Groups 2 and 4 who received the geofence instruction. The participants rated the given statements on a scale of 1 to 7 (1 = Strongly disagree, 7 = Strongly agree) based on their experience in the driving simulator, especially the geofence instruction feature. Descriptive statistics of participants' ratings for Groups 2 and 4 are presented in Table 5.4 along with inferential statistics of diffences. For each of the statements, a t-test for independent samples was used to compare participants' experience with geofencing and interaction situation between the two scenarios with each testing on the different use case. Two of the Group 4 participants were excluded from the following evaluation because their completion of the simulator experience section of the post-survey questionnaire was not valid.

Table 5.4: Post-Survey Comparison of Participants' Opinions With Applied Geofencing

Measure	Group 2		Group 4		t	p
	M	SD	M	SD		
The on-screen instruction made me stressed	1.81	1.17	2.73	2.31	1.41	0.17
The on-screen instruction was difficult to detect	2.19	2.14	1.87	1.96	0.43	0.67
The on-screen instruction improved my driving behavior	4.38	1.67	4.00	1.81	0.60	0.55
The on-screen instruction was useful	5.75	1.61	4.53	2.26	1.73	0.09
The voice instruction was helpful	6.63	0.72	4.33	2.38	3.68	<.001
It was easy to follow the instruction	6.44	1.50	5.40	1.99	1.64	0.11
I felt I could trust the instruction in the vehicle	6.00	1.55	5.27	1.87	1.19	0.24
I liked the visual appearance of the instruction	4.56	1.90	5.13	1.77	0.87	0.39
In the future, I would like to receive instructions when interacting with emergency vehicles in my own car (complement to blue light and sirens)	6.50	0.73	6.20	0.86	1.05	0.30

The results of an independent samples t-test indicated a statistically significant difference in opinion on whether the voice instruction was helpful between the Groups 2 and 4. The ratings of the participants tested on the Off-ramp use case (M = 6.63, SD = 0.72) and the

ratings of the participants tested on the Intersection use case (M = 4.33, SD = 2.38) showed a significant difference $t(29)$ = 3.68, p < .001, d = 1.32.

100% of the participants tested on the Off-Ramp use case with geofencing rated positively they would like to receive instructions in the future when interacting with emergency vehicles in their own car, with two participants assigning a value of 5, four participants a value of 6 and ten participants a value of 7. The same statement was rated positively by *100%* of the participants tested on the Intersection use case with geofencing, with four participants assigning a value of 5, four participants assigning a value of 6, and seven participants assigning a value of 7.

Comparison of Attitude

An independent samples t-test was conducted to test attitudes toward receiving geofence instructions in own cars in the future when interacting with emergency vehicles among groups of the participants who did and did not receive geofence instructions in the study. The results of ratings of the participants in Groups 1 and 3 who did not receive the instruction (M = 5.06, SD = 1.69) and the participants in Groups 2 and 4 who received the instruction (M = 6.35, SD = 0.80) yielded a statistically significant effect, $t(60)$ = 3.84, p < .001, d = 0.98. The participants who experienced the geofence instruction in the experiment had a significantly positive attitude about having this feature in their own car in the future, compared to the participants who did not receive the geofence instruction.

6 Discussion

The aim of the present thesis was to investigate whether and how geofencing applied via an in-vehicle HMI can improve driver behavior when interacting with emergency vehicles. Geofencing is a method used in geofence applications and refers to a digital demarcation of a geographical area with certain conditions (Regeringkansliet: Infrastrukturdepartementet, 2021). Anything or anybody connected to the geofence must comply with these conditions when moving in the geofence area. The geofencing method has the potential to be applied to instruct drivers on how to behave when interacting with emergency vehicles in traffic. A study in a driving simulator was conducted as an initial investigation of the impact of this application on driver behavior, implemented via an in-vehicle instrument cluster. The following chapter provides a discussion of the investigation with the findings presented to answer the following research questions.

- Could geofencing assist drivers in responding timely and correctly when interacting with emergency vehicles in traffic, and thereby decrease the risk of accidents?

- Can geofencing improve the driving time of an emergency vehicle (i.e., decrease response time)?

- Do the drivers believe that they would benefit from geofencing?

6.1 Results of Driving Simulator Study

Two use cases were selected to test driver behavior in interaction with an ambulance. Each selected use case was added to a scenario, and both scenarios were then implemented in the driving simulator. For the driving simulator study, a between-group design was used. Therefore, the participants were divided into four groups based on the use case they were tested on, and whether or not the geofence instruction was applied. The groups were equally represented by age, gender, and driving experience. *85.5%* of the participants were regular drivers who reported driving daily or a few times a week.

Results of Off-ramp Use Case

The first tested use case was situated on a motorway, including an off-ramp. The participants were told to follow the road signs and go to the town of Trosa. They started off on the motorway and were approaching an off-ramp leading to Trosa. However, an accident had occurred on the off-ramp. Due to the accident, an ambulance was operating on the spot, therefore, the participants who received the geofence instruction were guided to continue straight due to the closed road. The participants who did not receive geofence instructions had to react according to the situation they saw.

The results of the Off-ramp use case indicate a statistically significant and strong effect of the geofence instruction on the participants' driving behavior, $p < .001$. *100%* of the participants who received geofence instruction followed it and therefore avoided dealing with the situation on the impassable off-ramp. None of the participants who did not receive the geofence instruction behaved this way. All of them entered the off-ramp and had to react accordingly by stopping before the accident. The significant effect of the geofence instruction in the Off-ramp use case reflects that the participants were able to react correctly and promptly when they received the instruction. In addition, an interesting finding was that the participants who received the geofence instruction chose to obey it, even though the experiment leader had told them to go the town of Trosa. Within the further testing it should be investigated whether the participants would still follow the geofence instruction if there were other vehicles in front of them in the scene taking the off-ramp.

From the graph of the mean speeds of the participants in Figure 5.6, it appears that the geofence instruction had the effect of reducing the participants' speeds by approximately *10 km/h*. The resulting graph suggests the participants drove safely without impulsive braking after receiving the instruction.

All of the participants who did not receive the geofence instruction entered the off-ramp and had to stop in front of the stationary ambulance with the accident behind it. None of them seemed to have difficulties coming to a complete stop. Once they stopped, they were asked about the actions they would take in a real case in the exact same situation. Surprising findings were obtained as it was found that the participants did not have sufficient knowledge of what actions they should take to improve their safety and the safety of other road users when arriving and stopping at an accident scene on a higher speed road. A statistically significant difference in the correctness of responses was found between the participants aged 35 years and younger and the participants over 35 years, $p = .002$, with a better knowledge of the safety practices among the younger participants.

71.4% of the participants replied that they would wait or pull over and wait. As a result, most participants would put themselves in a risky situation as they would not alert the other drivers about the situation on the off-ramp. The remaining participants (28.6%) would switch on the hazard warning lights, which can be considered a satisfactory response from a safety perspective. Of these, only one participant, a novice driver, reporting learning how to behave when interacting with emergency vehicles and at accidents in a traffic school, responded that they would switch on the hazard warning lights and, if it was safe to do so, would wait outside the car in a sufficient distance from the off-ramp to increase their own safety. The most appropriate action would be reinforced by taking a reflective vest and placing a warning triangle at least *100 m*, on motorways *200 m* upstream (depends on the traffic rules of the country) if the situation allows.

Results of Intersection Use Case

The second tested use case was located at an intersection and involved an interaction with the ambulance approaching from the left side of the intersection. The participants with applied geofencing were instructed to stop before the intersection, while the remaining participants had to react according to the sound of sirens or the visual appearance of the ambulance.

The results showed a statistically significant and strong effect of the geofence instruction on the earliness of the participants' reaction by reducing their speed before the interaction with the ambulance compared to the participants who did not receive the instruction, $p < .001$, $d = 11.42$. The obtained results indicating earlier reactions of the participants receiving the instruction are consistent with other studies related to driver warnings before an upcoming interaction with emergency vehicles (e.g., Lenné et al., 2008; Lidestam et al., 2020). Nine of the 17 participants reacted to the geofence instruction between *0.6 s* and *1.5 s* after the instruction was displayed, which is equivalent to the norm of the average drivers' reaction times found in other studies when the driver is alerted to the need to brake (Green, 2000; McGehee et al., 2000; Sajdl, 2011). Two participants reacted faster ($M = 0.42$ s, *min* = 0.395 s) indicating a very good perception. Six participants had slower reactions ($M = 2.58$ s, *max* = 3.23 s) which may occur due to the driver's condition, age, attention, and unfamiliar or unusual perceptual stimulus. The last factor is particularly relevant in the present study.

The participants' average reaction to the geofence instruction is indicated by a speed deceleration. As can be seen from the graph in Figure 5.8, on average the participants seem to respond by gradual slowing down. Similar findings of the impact of warning alerts on drivers' speed were found in Lenné et al. (2008) study. As a result of the timely reactions, it can be observed that, on average, the participants who received the geofence instruction maintained a slower but consistent speed that allowed them not to have to come to a complete stop before the intersection. As the ambulance crossed the intersection in front of them, they could then continue driving.

The participants who did not receive the geofence instruction reacted on average *12.5 s* later than the participants with applied geofencing. The participants had to react based on the sound of the sirens and visual perception. Figure 5.8 shows that, on average, the reaction after hearing the sirens appears to be slow at the beginning, perhaps reflecting more of a slowdown due to the upcoming intersection. On average, the participants who did not receive the geofence instruction began braking significantly in the stretch *50 m* before the stop line as a reaction to the upcoming interaction with the ambulance, leading to a seemingly impulsive speed reduction. *70.6%* of the participants not receiving the geofence instruction reported after the drive or in the follow-up survey that they looked in the rear-view mirrors and did not see any approaching emergency vehicle, therefore it took them more time to consider the different arriving direction of the ambulance. Of these, *29.4%* participants did not stop before the intersection and put themselves and the ambulance in a risky situation.

A total of seven participants crossed the intersection in front of the ambulance, causing it to be delayed. All these participants drove without applied geofencing, which yielded a statistically significant positive effect of using the geofence instruction on eliminating the ambulance delay, $p < .001$. Five of the participants did not consider the arrival of the ambulance from the crossing road of the intersection and two of them believed that the ambulance was far enough from them to need to stop before the intersection. The behavior of the participants passing through the intersection caused a delay for the ambulance, as it needed to stop before the crossing road with the participants to make sure it had a clear way to continue. Everyone of these participants caused the ambulance to be delayed by approximately *6 s* each. The exact delay time would vary in a real case depending on different conditions, but the study mainly assessed the occurrence of delays and the potential effectiveness of geofence to eliminate them.

This significant difference leads to the assumption that geofence instructions have the potential to improve emergency vehicles' driving times, as all the participants who received the instruction did not impede or endanger the ambulance. Therefore, the ambulance could pass smoothly through the intersection without having to brake or come to a complete stop.

Summary of Use Cases

The results of the Off-ramp use case indicate that the participants were able to follow the geofence instruction timely and correctly. The use of the geofence instruction could particularly increase drivers' safety by avoiding forming traffic congestion behind the impassable spot. Consequently, drivers would increase a safety of operating emergency services at intervention spots, including the work of ambulance personnel, police coordinating the situation, or other services.

The findings that were obtained by the Intersection use case indicate that the participants were able to follow the instruction in a correct manner and on time. Moreover, it was found, that geofencing has the potential to help with decreasing the driving time of emergency vehicles. The results of the use case seem to be crucial in the real world case as a lot of accidents with emergency vehicles occur at intersections (Custalow et al., 2004; Drucker et al., 2013; Savolainen et al., 2009).

According to the results of the study, in the case of applied geofencing, the driver's decision-making process on how to act appears to be based on the received instruction. With the geofence instructions, drivers would not only have to anticipate upcoming situations of interaction with emergency vehicles themselves, which could have a good impact on improving driver behaviour to ensure smooth passage of emergency vehicles. In particular, the geofence instructions could have a positive contribution to minimizing close and risky interactions with emergency vehicles and improving the driving time of emergency vehicles.

A factor to improve drivers' safety is general education on how to behave at accidents, when interacting with emergency vehicles, or when encountering stationary vehicles making the road obstructed or impassable. Grant (2010) also reported a lack in drivers' education in terms of acting in interactions with emergency vehicles. The Off-ramp use case reflected the lack of drivers' knowledge about actions they should do when they approach an impassable spot on the road. A statistically significant difference in the knowledge on how to act in such a situation was obtained between the participants aged 35 or less and the participants aged more than 35 years, which could possibly indicate a better education in driving schools recently. *91.1%* of the participants over 35 years would not behave in a satisfactory way. It needs to be put into consideration, that the participants did not sit in a real car, therefore, their answers could eventually differ in the real situation. The Intersection use case indicated *41.2%* of participants who acted based on the current warning signals in real life (sirens, visual appearance) inappropriately by crossing the intersection and, therefore, exposing themselves to a risky situation which impeded the ambulance.

Results of Questionnaire

A statistically significant difference was found between the participants without and with applied geofencing in attitude towards receiving instructions when interacting with emergency vehicles in their own cars in the future, $p < .001$, $d = 0.98$. On average, both groups of the participants expressed a positive attitude towards the application of geofencing in their own cars. However, the participants who received the geofence instruction in the experiment expressed a significantly favorable interest. This result suggests that interest in this feature could likely increase once drivers have tried it and become convinced of its usefulness. Another factor to improve attitudes towards the use of geofencing could be a detailed explanation of how the feature works, the instruction is displayed, etc.

A statistically significant difference was also found in the ratings of voice instruction between the participants tested on the Off-Ramp and Intersection use case, $p < .001$, $d = 1.32$. The participants tested on the Off-Ramp use case found the voice instructions useful, while some participants tested on the Intersection use case reported that the voice instruction was abrupt, surprising, and too aggressive for them. These participants, therefore, felt that they tended to reduce their speed more sudden and significantly in advance. This side effect of

HMI should be eliminated to avoid counterproductive reactions such as aggressive braking and creating dangerous situations for other road users in the vicinity. A possible reason why the Intersection use case participants found the voice instruction less useful could be that they were more distracted while driving because they needed to maintain a determined speed and were driving in an urban area on a narrower road.

Other statistically significant effects between the Off-ramp and the Intersection use case without or with applied geofencing were not found. This result suggests that there were no significant differences in the level of stress during the interaction situations or significant differences in participants' opinions about the use of geofencing via HMI in both situations.

The important results are that the participants in both use cases with applied geofencing, on average positively rated that it was easy for them to follow the instruction (Off-ramp M = 6.44, Intersection M = 5.40), and they felt they could trust the in-vehicle HMI (Off-ramp M = 6.00, Intersection M = 5.27) and therefore, they did not ignore it.

The mean ratings of the statements that were close to neutral opinion (value 4) and the few negative opinions were mostly directed towards necessary improvements to the HMI. The participants stated in the free text questions that they liked the idea of giving instructions when interacting with emergency vehicles because it would improve their situational awareness. They also mentioned that it would make the process of deciding what to do in interaction situations easier and less confusing for drivers. However, there were recurring comments that visual and voice instructions should be improved to avoid distracting drivers. Some participants mentioned that they would have appreciated a different location for the instructions, e.g., a head-up display or a central infotainment system.

6.2 Discussion of Methodology

The limitations of the methods used and their possible implications for the results of the present thesis are described in the following section.

The driving simulator study allowed testing the same repetitive situations for multiple participants, however, it was not possible to assess the comprehensive impact of the use of geofencing on actual traffic. One of the technical limitations was the partial absence of other traffic in the scenarios, which did not correspond to the real situation.

A potential technical threat to the validity of the Intersection use case results is that the blue lights of the ambulance were not used because it would have been difficult to simulate the reflections of the blue lights from surrounding objects in the scenario. The sound of the sirens was designed to increase in volume when approaching the participants and decrease when leaving in accordance with the Doppler effect, however, in real situations there would likely be a variance in the sound. Another technical constraint was to ensure that the driver was about to interact with the ambulance at the intersection. The participants' speeds varied in the last tens of metres before the intersection, and it appeared that some participants slowed down significantly before approaching the intersection as a result of seeing the traffic lights, or as a result of knowing they were being tested without knowledge of the purpose. The behavior of some participants might therefore have been more cautious than in real life. The limitations of the driving simulator may also have affected the participants' reactions to how they would behave in real life if stopped in front of an ambulance and accident on an off-ramp. Some of the participants might have responded differently if they had been sitting in a real car and seen all the instruments on the car's dashboard.

A limitation for a broader evaluation of the questionnaire was a common limitation of a between-group design. As it was possible to ask participants in all groups about only one common statement, it was not possible to compare multiple opinions between the groups without and with geofencing. Moreover, as the participants filled out the questionnaire on their own after the drive, some of them made an error in the dividing question into sections regarding whether or not they had received the geofence instruction, therefore, all the data

were not obtained. This could be avoided by having separate questionnaires for participants based on the assigned group.

Despite the aforementioned limitations, the validity of the investigated parameters and, in particular, of the results of differences between the groups without and with applied geofencing is ensured, since all the participants were tested under the same conditions of the driving simulator, the same explanation of the tasks to be performed and the same questions to answer.

To increase the successful replication of the study the photos from the driving simulator study are attached in Chapter 4, along with the detailed description of the implemented scenarios with each tested use case, the described procedure of the study, and attached questionnaires in the Appendix.

6.3 Future Research

The results of the current study suggest a potential positive impact of the use of geofencing when interacting with emergency vehicles in the two use cases tested. Initial research in the present thesis shows the improvements in reaction times when using geofencing and the ability of drivers to follow in-vehicle instructions, which indicates a potential to further explore the use of geofencing.

Future research should target the use of geofence instructions in different use cases under different traffic conditions. Studies conducted in a driving simulator may indicate a potential impact on individual drivers, however, naturalistic studies in real life should also be conducted in the future to determine the comprehensive effect of geofence instructions.

Another focus of future research should be on dimensions of geofence areas in the context of different environments and different traffic conditions, i.e., how far in advance drivers should receive geofence instructions before interacting with an emergency vehicle. Geofence instructions should be issued to drivers in relation to geofence areas, not time assumptions, to be consistent with the intended technical solution.

It should also be investigated how to convey instructions to drivers in an appropriate way to encourage calm reactions and to avoid counterproductive effects. One idea to improve the visual appearance of the instructions could be the use of a moving icon indicating the position of the emergency vehicle in relation to the driver.

The results of driver behavior from the driving simulator experiments can then be used as input data for traffic simulations to investigate different penetration rates of vehicles equipped with geofence instructions and their impact in traffic. Simulations should be carried out for different situations and environments separately.

Last but not least, in order to be able to provide geofence instructions to drivers when interacting with emergency vehicles, the technical solution of the geofence application needs to be implemented so that the application can operate in the real world.

7 Conclusion

The aim of the present thesis was to investigate whether and how geofencing communicated via an in-vehicle HMI can improve drivers' behavior when interacting with emergency vehicles. Different methods were used to meet the aim of the thesis. Initially, a geofence workshop was organized to discuss geofencing and its use in a form of instructions when interacting with emergency vehicles. Then, the two use cases were selected as interaction situations for a driving simulator study. Once the scenarios with the use cases were created, they were used to test the participants in the driving simulator study. A between-group design was applied and therefore the participants were divided into a total of four groups based on the use case they were tested on and whether or not geofencing was used. Data from the driving simulator and the questionnaire were analyzed using both descriptive and inferential statistics. The results of the analysis were intended to answer the research questions.

RQ1: Could geofencing assist drivers in responding timely and correctly when interacting with emergency vehicles in traffic, and thereby decrease the risk of accidents?

Both Off-Ramp and Intersection use cases demonstrated that the use of geofencing can help drivers to react correctly and in a timely manner. The Off-ramp use case showed a statistically significant effect of using geofencing when the goal is to avoid entering an impassable road and to provide a safe work area for emergency vehicles. The Intersection use case indicated a statistically significant effect on the timeliness of the reaction when using the geofence instruction compared to the current ambulance warning signals, i.e. blue lights, and sirens.

RQ2: Can geofencing improve the driving time of an emergency vehicle (i.e., decrease response time)?
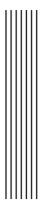
The Intersection use case showed a statistically significant difference between the participants without and with applied geofencing on causing ambulance delays. None of the participants who received the geofence instruction delayed the ambulance, while some of the participants reacting based on the sound of sirens and the visual appearance of the ambulance did. It was demonstrated that the use of the geofence instruction can improve ambulance's driving time through the tested intersection, which can be interpreted as a good

precondition for a possibility of improving the overall driving time of emergency vehicles.

RQ3: Do the drivers believe that they would benefit from geofencing?

The results of the questionnaires show a positive attitude of the participants towards receiving geofence instructions in the future in their own car when interacting with emergency vehicles. There was a statistically significant difference between the attitudes of the participants tested without and with applied geofencing. It suggests an increasing interest once drivers have tried the feature. The overall evaluation showed that, on average, drivers found the geofence instructions easy to follow and had no problems trusting the instructions. However, modifications need to be carried out to the HMI of geofence instructions in terms of user-friendliness.

The results of the present thesis show that geofence instructions have a potential to help drivers react correctly and timely when interacting with emergency vehicles. Future research is needed to improve the HMI of geofence instructions, however, the results indicate the potential of decreasing the driving times of emergency vehicles. In general, participants expressed a positive opinion of having the function of geofence instructions when interacting with emergency vehicles in their own vehicles, therefore it can be concluded that they believe they would benefit from geofencing.

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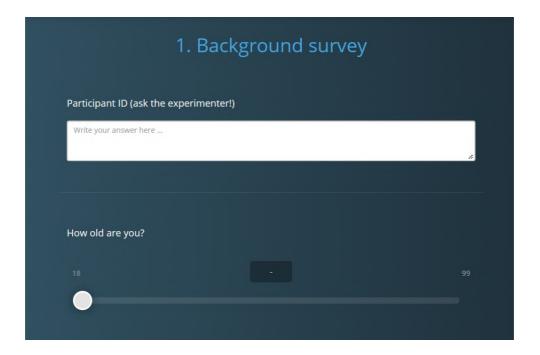
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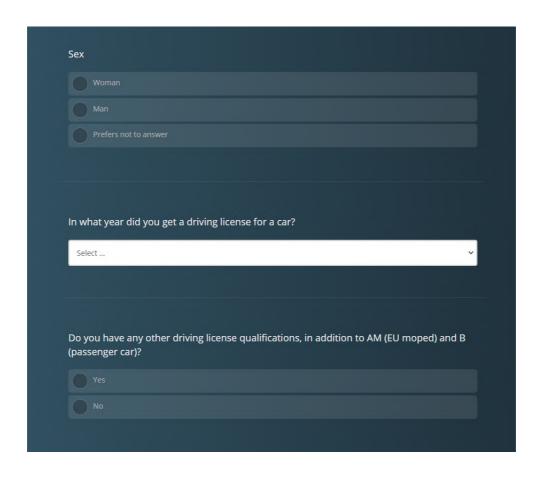
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Appendix

Appendix A

Sex

- ○ Woman
- ○ Man
- ○ Prefers not to answer

In what year did you get a driving license for a car?

Select ... ▾

Do you have any other driving license qualifications, in addition to AM (EU moped) and B (passenger car)?

- ○ Yes
- ○ No

If so, which ones?

Write your answer here ...

Are you a professional driver?
By professional driver we mean that you drive a car / truck / bus or other motor vehicle in traffic in your profession.

- ○ Yes
- ○ No

If so, specify the type of professional driver you are.

Write your answer here ...

How often do you drive a car?

- ○ Daily
- ○ A few times a week
- ○ A couple of times a month
- ○ More rarely

Number of miles driven in life?

- ○ 0 - 5 00
- ○ 501 - 3,000
- ○ 3001 - 10 000
- ○ 10 001 - 50 000
- ○ 50 001 - 100 000
- ○ 100 001 or more

Do you have a visual impairment that means that you wear glasses or lenses on a daily basis?

- ○ Yes
- ○ No

If so, what type of vision defect do you have?

- ☐ Farsighted
- ☐ Nearsighted
- ☐ Refractive error (Astigmatism)
- ☐ Otherwise, please enter

Appendix B

1. Survey after completed driving

Participant ID

Write your answer here ...

What do you think about driver support in general? *For example cruise control, adaptive cruise control, blind spot warning and lane departure warning*
(1 = I do not like it at all, 7 = I like it very much)

☆ ☆ ☆ ☆ ☆ ☆ ☆
1   7

Do you use a navigation system when driving a car?

○ Always, even when I know the way

○ Often, even when I know the way

○ Only when I do not know the way

○ Never

Do you work, or have you worked, in a blue light organization (police, ambulance, fire brigade)?

○ Yes

○ No

If so, please specify within which organization and your duties.

Write your answer here ...

Approximately how many times, from the time you took your driving license and before today's experiment, have you had to adapt your driving due to approaching emergency vehicles with switched on sirens or blue lights?

0   -   100 or more

How have you learned how to act when interacting with emergency vehicles?

- Through traffic school / driving lessons
- In the regular school
- Someone told me
- I have observed how other road users act
- I have asked a fellow traveler at the moment
- I never learned that
- Other, please enter:

What do you think the law says about how to act when emergency vehicles approach? (You can select several options)

- There is no law on this
- Use common sense
- Fold to the side
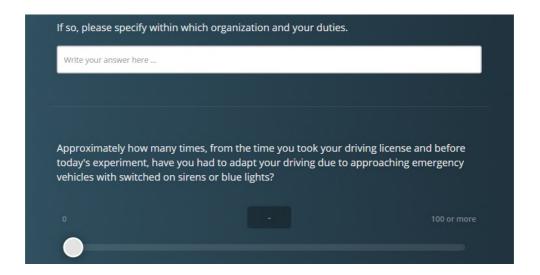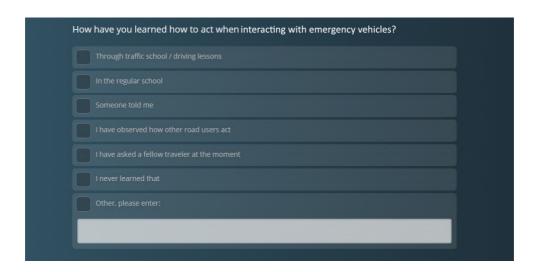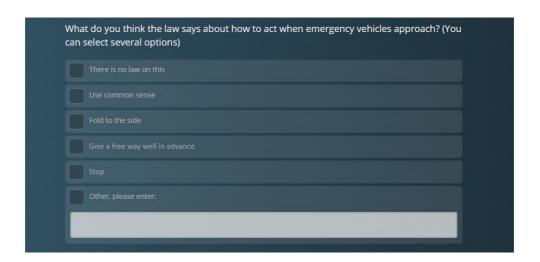- Give a free way well in advance
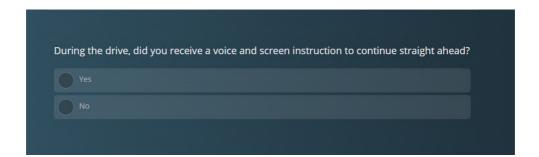- Stop
- Other, please enter:

What is your typical experience and actions when you interact with an emergency ambulance in real life?
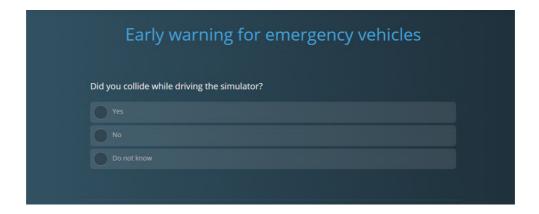**(1 = Disagree at all, 7 = Strongly agree)**

- I feel stressed

- I slow down

- I lower the volume on the radio to increase my concentration

- I am starting to think more about my driving behavior

- I adapt to how front and rear cars act

- I wait until the ambulance is very close before giving free way

- I immediately try to give free way, regardless of distance

- I try to give free way, even if it violates normal traffic rules

- I find it difficult to know how to give way when an ambulance approaches

In which cases are you trying to give free way to ambulances?
(Yes/No)

- Without signals = blue lights and sirens are off

- When only blue light is activated (but not sirens)

- When both blue lights and sirens are activated

Survey split: Questions for the participants who received the geofence instruction

Please indicate to what extent you agree with the following statements?
(1 = Disagree at all, 7 = Strongly agree)

- The on-screen instruction made me stressed

- The on-screen instruction was difficult to detect

- The on-screen instruction improved my driving behavior

- The on-screen instruction was very useful

- The voice instruction was helpful

- It was easy to follow the instruction

- I felt I could trust the instruction in the vehicle

- I liked the visual appearance of the instruction

- In the future, I would like to receive instructions when interacting with emergency vehicles in my own car (Complement to blue lights and sirens)

If possible in the future, where would you like to display instruction?
(Yes/No)

- In the instrument cluster, *as in the simulator*

- Head-up display, *projected image of e.g. the windshield*

- Central infotainment display, *screen in the car's center console*

Do you prefer...
(Yes/No)

- Instructions only on screen?

- Voice instruction only?

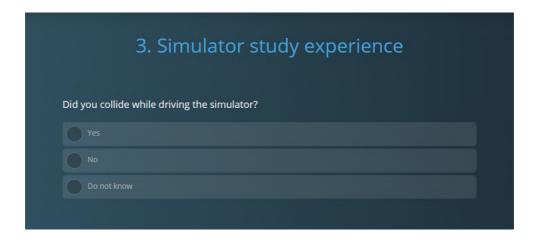- Combination of both screen and voice instruction?

What negative effects do you think such instructions can have? What did you *not* like?
(Free text answer)

What positive effects do you think such instructions can bring? What did you appreciate most?
(Free text answer)

Do you have any other comments or suggestions? (Free text answer)

Please indicate to what extent you agree with the following statements?
(1 = Disagree at all, 7 = Strongly agree)

- It was easy to follow the road signs to my final destination

- I knew what to do, but I did not have enough time to react

- The situation made me feel stressed

- In the future, I would like to receive instructions when interacting with emergency vehicles in my own car (Complement to blue lights and sirens)
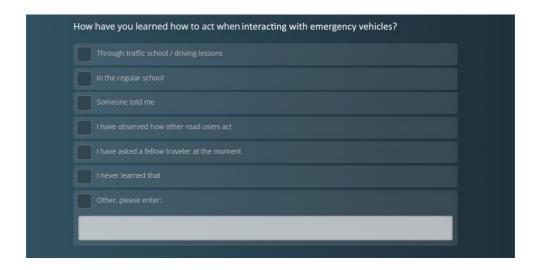
Do you have any other comments or suggestions?

Appendix C

1. Survey after completed driving

Participant ID

Write your answer here ...

What do you think about driver support in general? *For example cruise control, adaptive cruise control, blind spot warning and lane departure warning*
(1 = I do not like it at all, 7 = I like it very much)

☆ ☆ ☆ ☆ ☆ ☆ ☆
1   7

Do you use a navigation system when driving a car?

- Always, even when I know the way
- Often, even when I know the way
- Only when I do not know the way
- Never

Do you work, or have you worked, in a blue light organization (police, ambulance, fire brigade)?

- Yes
- No

If so, please specify within which organization and your duties.

Write your answer here ...

Approximately how many times, from the time you took your driving license and before today's experiment, have you had to adapt your driving due to approaching emergency vehicles with switched on sirens or blue lights?

0

-

100 or more

How have you learned how to act when interacting with emergency vehicles?

- [ ] Through traffic school / driving lessons
- [ ] In the regular school
- [ ] Someone told me
- [ ] I have observed how other road users act
- [ ] I have asked a fellow traveler at the moment
- [ ] I never learned that
- [ ] Other, please enter:

What do you think the law says about how to act when emergency vehicles approach? (You can select several options)

- [ ] There is no law on this
- [ ] Use common sense
- [ ] Fold to the side
- [ ] Give a free way well in advance
- [ ] Stop
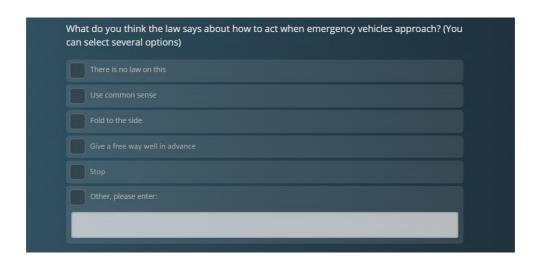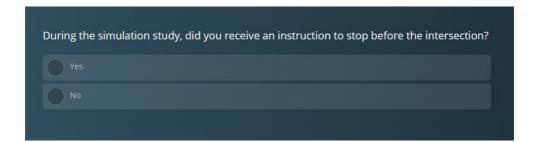- [ ] Other, please enter:

What is your typical experience and actions when you interact with an emergency ambulance in real life?
(1 = Disagree at all, 7 = Strongly agree)

- I feel stressed

- I slow down

- I lower the volume on the radio to increase my concentration

- I am starting to think more about my driving behavior

- I adapt to how front and rear cars act

- I wait until the ambulance is very close before giving free way

- I immediately try to give free way, regardless of distance

- I try to give free way, even if it violates normal traffic rules

- I find it difficult to know how to give way when an ambulance approaches

In which cases are you trying to give free way to ambulances?
(Yes/No)

- Without signals = blue lights and sirens are off

- When only blue light is activated (but not sirens)

- When both blue lights and sirens are activated

Survey split: Questions for the participants who received the geofence instruction

Please indicate to what extent you agree with the following statements?
(1 = Disagree at all, 7 = Strongly agree)

- It was easy to know how to behave when the emergency vehicle appeared

- The on-screen instruction made me stressed

- The on-screen instruction was difficult to detect

- The on-screen instruction improved my driving behavior

- The on-screen instruction was very useful

- The voice instruction was helpful

- It was easy to follow the instruction

- I felt I could trust the instruction in the vehicle

- I liked the visual appearance of the instruction

- In the future, I would like to receive instructions when interacting with emergency vehicles in my own car (Complement to blue lights and sirens)

If possible in the future, where would you like to display instruction?
(Yes/No)

- In the instrument cluster, *as in the simulator*

- Head-up display, *projected image of e.g. the windshield*

- Central infotainment display, *screen in the car's center console*

Do you prefer...
(Yes/No)

- Instructions only on screen?

- Voice instruction only?

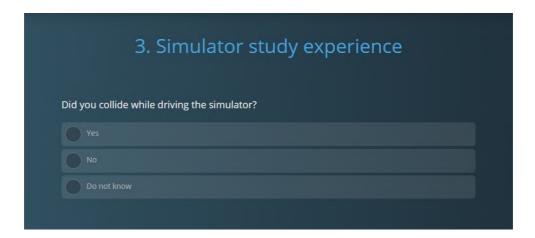- Combination of both screen and voice instruction?

What negative effects do you think such instructions can have? What did you *not* like?
(Free text answer)

What positive effects do you think such instructions can bring? What did you appreciate most?
(Free text answer)

Do you have any other comments or suggestions?
(Free text answer)

Survey split: Questions for the participants who did not receive the geofence instruction

Please indicate to what extent you agree with the following statements?
(1 = Disagree at all, 7 = Strongly agree)

- It was easy to know how to behave when the emergency vehicle appeared

- I knew what to do, but I did not have enough time to react

- The situation made me feel stressed

- In the future, I would like to receive instructions when interacting with emergency vehicles in my own car (Complement to blue lights and sirens)

Do you have any other comments or suggestions?