Tampere University

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The Potential of Key Driver Assistance Systems to Improve Road Safety and Automated Driving Systems to Improve Pedestrian and Cyclist Safety

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ACADEMIC DISSERTATION
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of Tampere University,
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ACADEMIC DISSERTATION
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Road safety has been the most interesting topic to me in the field of transportation systems from the first years as a university student. In my first academic thesis, the bachelor's thesis, I examined the safety of young microcar drivers. It was easy to decide to focus on the road safety in the master's thesis as well. The master's thesis was about serious road injuries.

After these studies, I started to work at Transport Research Centre Verne, Tampere University (former Tampere University of Technology). At the same time when I was planning possible topics for dissertation, it seemed quite clear that an ambitious road safety target to decrease the number of road fatalities both in Finland and in the European Union by 2020 could not be met. Increasing use of driver assistance and automated driving systems is considered one of the most promising road safety actions, which was the main reason I decided to focus on the future safety potential of vehicle automation in this thesis. The vehicle automation can play a significant role in achieving the road safety targets.

The final topic of this thesis was finalized in the discussions with Associate Professor Heikki Liimatainen and Lecturer Markus Pöllänen. I would like to thank both of you for your valuable support. Heikki was also supervising the thesis. The role of Road Safety Manager Esa Räty from the Finnish Crash Data Institute (OTI) was also important for the dissertation, as Esa was OTI's contact person regarding the crash data, which were analysed in the thesis. Thank you Esa and the OTI for supporting the thesis. The crash data are based on investigations made by the crash investigation teams all over Finland. I would like to disclose that this thesis would not have been possible without investigators' valuable effort to investigate crashes.

Other colleagues at Transport Research Centre Verne have also been great support both inside and outside the office, thank you all! Many thanks also to Tampere University for funding the dissertation. Finally, I would like to give special thanks to Roosa for being with me throughout the process.

Tampere, 22.3.2021
Roni Utriainen

ABSTRACT

Safer road traffic is one of the key impacts advanced driver assistance systems (ADASs) and highly automated vehicles (HAVs) are predicted to deliver, but the potential safety impacts vary between different systems and are influenced by many factors. This thesis aims to evaluate the potential for preventing fatal road crashes in Finland by introducing passenger cars equipped with key ADASs or automated driving systems. In this thesis, key ADASs are lane keeping assistance (LKA), automatic emergency braking (AEB) and adaptive cruise control (ACC) systems. The potential of HAVs in terms of preventing crashes is assessed in pedestrian-car and cyclist-car crashes.

Four retrospective cross-sectional studies of fatal crashes were made to evaluate the potential of key ADASs and HAVs to prevent crashes in which a passenger car was involved in Finland in 2014–2016. Each case (n=479) that would theoretically be applicable to a certain ADAS was analysed individually using a qualitative, case-by-case study to identify those cases that could have been prevented by key ADASs. Using a similar method, the potential of HAVs in preventing pedestrian and cyclist crashes (n=64) were also assessed.

The results indicate that 29% of fatal passenger car crashes could potentially have been avoided by the combination of LKA, AEB, and ACC systems. HAVs could potentially have prevented 70–93% of fatal crashes between pedestrians and passenger cars. The range depends on whether pedestrian safety (93%) or efficient traffic flow (70%) is prioritised in HAV operation. Pedestrian-car and cyclist-car crashes could be most effectively reduced by HAVs when they are able to reliably assess the intentions of other road users.

The findings of the thesis show that the introduction of cars equipped with key ADASs or automated driving systems – as a replacement for cars controlled entirely by the driver – is an important action to promote road safety. Although many factors can reduce the potential safety impacts, such as low market penetration rates and driver behaviour, the impacts can also be increased by advancements in vehicle and infrastructure requirements. Prioritising safety over other ambitions in the road transport system would enable the safer operation of HAVs, especially in the initial stage of the introduction, but it would also support safer behaviour of drivers.

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Turvallisempi tieliikenne on yksi keskeisimmistä vaikutuksista, joita kuljettajaa avustavien järjestelmien ja automaattiautojen odotetaan mahdollistavan, mutta vaikutukset vaihtelevat järjestelmien välillä ja niihin vaikuttavat monet tekijät. Väitöskirjan tavoitteena on arvioida keskeisillä avustinjärjestelmillä ja automaattisen ajamisen järjestelmillä varustettujen henkilöautojen mahdollisuuksia estää kuolemaan johtaneita onnettomuuksia Suomessa. Tutkittavat avustinjärjestelmät ovat kaista-avustin (LKA), automaattijarrutus (AEB) ja mukautuva nopeudensäädin (ACC). Automaattiautojen mahdollisuuksia estää onnettomuuksia arvioidaan jalankulkijoiden ja autojen sekä pyöräilijöiden ja autojen välisissä onnettomuuksissa.

Onnettomuuksien estämismahdollisuuksien arvioimiseksi tehtiin neljä retrospektiivistä poikittaistutkimusta. Aineisto sisälsi Suomessa vuosina 2014–2016 tapahtuneet kuolemaan johtaneet onnettomuudet, joissa henkilöauto oli ollut osallisena. Jokainen tapaus (n=479), joka olisi teoreettisesti soveltuva jollekin tutkituista avustinjärjestelmistä, arvioitiin käyttäen laadullista tapaustutkimusta, jotta avustinjärjestelmillä mahdollisesti estettävissä olevat tapaukset voitiin tunnistaa. Samanlaista menetelmää käytettiin arvioitaessa automaattiautojen mahdollisuuksia estää jalankulkija- ja pyöräilijäonnettomuuksia (n=64).

Tulosten mukaan 29 % kuolemaan johtaneista henkilöauto-onnettomuuksista olisi voitu välttää LKA-, AEB- ja ACC-järjestelmiä käyttämällä. Automaattiautot olisivat mahdollisesti voineet estää 70–93 % jalankulkijoiden ja henkilöautojen välisistä törmäyksistä. Vaihteluväli riippuu siitä, priorisoidaanko jalankulkijoiden turvallisuutta (93 %) vai liikenteen sujuvuutta (70 %) automaattiauton toiminnassa. Jalankulkija- ja pyöräilijäonnettomuudet olisivat parhaiten estettävissä, kun automaattiautot pystyisivät luotettavasti arvioimaan toisten aikomuksia.

Tulokset osoittavat, että keskeisten avustinjärjestelmien tai automaattiautojen käyttöönotto täysin kuljettajan hallinnoimien autojen sijaan olisi tärkeä turvallisuutta parantava toimenpide. Vaikka monet tekijät voivat pienentää vaikutuksia, kuten järjestelmien hidas yleistyminen tai kuljettajan käyttäytyminen, vaikutuksia voidaan myös lisätä kehittämällä ajoneuvo- ja infrastruktuurivaatimuksia. Turvallisuuden priorisointi mahdollistaisi automaattiautojen turvallisemman toiminnan erityisesti käyttöönoton alussa, mutta se myös tukisi kuljettajien turvallista käyttäytymistä.

CONTENTS

ORIGINAL PUBLICATIONS

Publication I — Utriainen, R., Pöllänen, M., Liimatainen, H. (2020). The safety potential of lane keeping assistance and possible actions to improve the potential. IEEE Transactions on Intelligent Vehicles. 5 (4), 556–564. DOI: 10.1109/TIV.2020.2991962.

Publication II — Utriainen, R., Pöllänen, M. (2020). The safety potential of automatic emergency braking and adaptive cruise control and actions to improve the potential. International Journal of Vehicle Autonomous Systems. Accepted for publication.

Publication III — Utriainen, R., Pöllänen, M. (2020). Prioritizing safety or traffic flow? Qualitative study on highly automated vehicles' potential to prevent pedestrian crashes with two different ambitions. Sustainability. 12, 3206. DOI: 10.3390/su12083206.

Publication IV — Utriainen, R., Pöllänen, M. How automated vehicles should operate to avoid fatal crashes with cyclists? Proceedings of the 9th International Cycling Safety Conference. Lund, Sweden. November 10–12, 2021. Accepted for publication and selected for consideration in the special issue of Accident Analysis and Prevention.

Roni Utriainen was corresponding author of each publication. He was responsible for the study design, literature reviews, methodological decisions, crash data analyses, conclusions and major part of the text and other content in each publication. In publications I-IV, Markus Pöllänen commented and revised the manuscripts and wrote some parts of the discussion and conclusion sections. In publication I, Heikki Liimatainen commented and revised the manuscript.

1 INTRODUCTION

1.1 Background

Safety is one of the central concerns in road traffic. Annually, 1.35 million people lose their lives and 50 million are injured on roads, and therefore road traffic crashes are a major public health problem worldwide (WHO 2018, pp. 75–76). Fatalities among car occupants are the most common, as 47% of the fatalities in the European Union (EU) and 62% in the United States are passenger car and delivery van occupants (European Commission 2018a, p. 15; IIHS 2019). The safety of vulnerable road users – i.e. pedestrians and cyclists – is an increasing concern, because the number of fatalities has decreased slowly compared to passenger car occupants in previous years. The number of cyclist fatalities even increased in the EU between 2010 and 2018 (European Commission 2020a).

Increased safety is one of the key impacts driver assistance and automated driving systems are predicted to deliver. Some studies (e.g. Fagnant and Kockelman 2015) have evaluated that levels 4 and 5 of driving automation (SAE 2018), which are referred to as highly automated vehicles (HAVs) in this thesis, could prevent almost all motor vehicle crashes by replacing human drivers. In HAVs, an automated driving system performs dynamic driving tasks and a human is not expected to respond to a request to intervene – i.e. the user does not need to be fallback-ready (SAE 2018). It should be noted that motor vehicles are not involved in all serious road traffic crashes, and hence new vehicle technology will not be the only solution to road safety problems, even if the most promising scenario on the potential safety impacts of the HAVs was realised. However, HAVs represent a promising safety countermeasure from the perspective of Vision Zero (see e.g. European Commission 2019a), because people will always make mistakes, but the mistakes should not lead to serious consequences. HAVs can possibly avoid these human errors by replacing human drivers. Changing the driver's role does not imply that HAV operation would be risk-free. In particular, HAV operation in encounters with pedestrians and cyclists should be designed carefully, because confusing encounters with other road users are possible without means of understandable communication (Merat et al. 2018).

Although HAVs are currently being developed and tested, it has been forecasted that they will not become mainstream until the 2050s or 2060s (Ben-Haim et al. 2018; Litman 2020). The role of human drivers in road safety will remain important for a long time. Currently active safety systems and advanced driver assistance systems (ADASs), such as automatic emergency braking (AEB), adaptive cruise control (ACC), and lane keeping assistance (LKA), are becoming more common in the car fleet (Lähderanta 2018). Several forms of ADASs, such as AEB and LKA, will become compulsory systems in new vehicles in the European Union from 2022 (European Commission 2019b). Driver assistance and partial automation at levels 1 and 2 (SAE 2018) also promote safety by preventing or mitigating crashes (Sander 2017), but the safety impacts will presumably be less pronounced, because the driver is still responsible for dynamic driving tasks.

It is important to understand the operational differences between lower (levels 1 and 2) and higher levels (levels 4 and 5) of driving automation. At the lower levels, systems typically intervene momentarily in lateral or longitudinal vehicle motion control tasks, e.g. during safety critical situations, but the systems cannot provide continuous automated driving. In HAVs (levels 4 and 5), a driver is not necessarily needed, because the system is responsible for the driving tasks – a clear difference compared to the lower levels. Despite the differences between the lower (ADASs) and the higher levels of driving automation (HAVs), each level can possibly provide a safety benefit compared to no automation, but the potential safety impacts vary and are affected by several factors (Jeong et al. 2017; Koisaari et al. 2020), which need to be examined further. The recommended way to examine more closely the factors that affect ADASs' proper operation and potential safety impacts is to analyse data on in-depth investigated crashes (Sternlund 2020). By analysing such crashes, it can be shown how frequent the key factors preventing or enabling the proper operation of ADASs have been in recent crash situations. In regard to HAVs' potential safety impacts, the impacts on safety of pedestrians and cyclists should be especially examined, because few studies have focused on this topic (Tafidis et al. 2019). In addition, the idea that HAVs could prevent almost all crashes due to human error should be further investigated.

1.2 Research questions

Building on an outlook of the current knowledge and research on the subject internationally, the thesis focuses on the potential safety impacts and concerns of

ADASs and HAVs in Finland. The thesis aims to evaluate the potential of preventing fatal road crashes by introducing passenger cars equipped with key systems that are equivalent to lower (i.e. SAE level 1–2) or higher levels (i.e. SAE level 4–5) of driving automation. Factors that have an impact on the potential for preventing crashes are also addressed.

In Publications 1 and 2, the safety potential of levels 1 and 2 of driving automation were evaluated, but these publications also build outlooks towards the higher levels of driving automation by assessing the potential for promoting the safety potential of ADASs. The publications focus on common ADAS systems, including LKA in Publication 1 and AEB, ACC, and intelligent speed assistance (ISA) in Publication 2. All typical types of fatal crashes were included in these publications from a passenger car's perspective, because LKA is able to prevent single-vehicle and head-on crashes (Logan et al. 2017), AEB intersection and rear-end crashes (Cicchino 2017; Sander & Lubbe 2018), and ACC rear-end crashes (Li et al. 2017). In addition, the ISA system could theoretically have an impact on the avoidance of different types of crashes, because the system advises the driver of the speed limit and limits the speed in the case of speeding. The selection of these systems is explained in section 2.2. In Publications 1 and 2, the following research questions are addressed:

1. Which crashes could have been avoided had the driver-managed car been replaced by an LKA-, AEB-, and/or ACC-equipped car? (Publications 1 and 2)
2. Why could not all of the crashes be avoided by the LKA, AEB, and ACC systems? (Publications 1 and 2)
3. How can the safety potential of LKA, AEB, and ACC be improved? (Publications 1 and 2)

Publication 3 focuses on encounters between HAVs and pedestrians by addressing the issue that greater safety benefits may not be realised if safety is not prioritised over other ambitions in the road transport system. It discusses and evaluates whether HAVs are able to provide safe encounters with pedestrians considering potential challenges related to the ability of HAVs to evaluate pedestrians' intentions. Similar challenges are predicted to concern encounters between HAVs and cyclists. In Publication 4, the operational features of HAVs were formed that would allow safe operation in encounters with cyclists. In addition, Publication 4 assessed which of

HAV's features are needed to avoid fatal crashes with cyclists. In Publications 3 and 4, the following research questions are addressed:

4. Which fatal crashes between pedestrians and driver-managed passenger cars could have been avoided, had the cars been replaced by HAVs? (Publication 3)
5. What features should an HAV have in order to manage safe encounters with cyclists? (Publication 4)
6. How would the formed features help to avoid crashes resulting in fatalities in actual crash scenes between cyclists and driver-managed passenger cars? (Publication 4)

The results of the thesis aim to show how important road safety measure the introduction of lower or higher levels of driving automation could be. The thesis evaluates the potential of the most common ADASs to prevent different fatal crashes in which a passenger car was involved. Therefore, an outlook on the safety potential of key ADASs concerns most fatal crashes including passenger cars' single-vehicle crashes, collisions between cars, and collisions between cars and vulnerable road users e.g. pedestrians and cyclists. The operation of HAVs is examined in collisions between driver-managed passenger cars and pedestrians and cyclists. Evaluations on the operation of HAVs in safety critical encounters with pedestrians and cyclists indicate possibilities to prevent cases when interaction is going to change due to the removal of a human driver. The discussion on HAVs' operation is also connected to the principles of Vision Zero, i.e. how likely is the realisation of the high hopes in terms of the safety potential.

1.3 Research philosophy and approaches

One of the main goals of traffic safety research is to support decision makers and authorities when they make decisions to implement safety measures and targets (Høye & Elvik 2019). Traffic safety research can be divided roughly into two different approaches: 1) crash analysis, which can enable the investigation of the causes and characteristics of the crashes, and 2) safety research, which aims to find elements of safe behaviour (Gstalter & Hoyos 1988). The first approach is probably more common, because traffic and road safety has typically been measured by the number of crashes and casualties (Wegman 2017). Traffic safety evaluation is a subgroup of crash analysis, which assesses the effects of road safety measures on the number of crashes or injuries, but a lack of a clear theoretical basis is common in traffic safety evaluation research (Elvik 2004). The randomness of crash occurrences is the main reason why traffic safety research does not have a solid theoretical grounding compared to more theoretically mature disciplines (Wang et al. 2013). Systematic traffic safety research based on theories has only begun to become widespread during the last decades (Hagenzieker et al. 2014).

In the 1950s, accident analysis looked for the cause of an accident in a way that attributed the cause to a road user, a vehicle, or a road environment (Hagenzieker et al. 2014). Later on, this approach developed towards a multi-causal approach, of which the Haddon Matrix is an example. According to the Haddon Matrix, a crash event consists of three phases – a pre-crash, a crash, and a post-crash – and each phase can be affected by a human, a vehicle, and the environment (WHO 2004, pp. 12–13). Today, the principles of Vision Zero and Safe System are dominant, i.e. the road transport system accepts people's mistakes and the system aims to prevent crashes involving fatalities and serious injuries by forming layers of protection so that a failure of one element does not lead to serious consequences (European Commission 2019a). In practice, the Safe System approach means e.g. high-quality road infrastructure, safer vehicles, and lower speeds. A corresponding system-based approach, Sustainable Safety, applies the safe system architecture by emphasising, e.g. a pro-active and integral approach in which the vulnerability of the human body, human limitations, and system gaps are considered (Wegman 2017).

This thesis applies crash data analysis, which is one form of traffic safety research. This approach was chosen because it enables the evaluation of a potential change in the number of crashes when driver assistance or an automated driving system is introduced. The evaluation is connected to the principles of the Safe System approach. It is accepted that people make mistakes and other measures or layers than driver-related measures are needed to maintain safe actions on roads. Vehicle automation can support the driver to maintain safe behaviour, or it can replace the driver behind the steering wheel in the case of HAVs. In terms of ADASs, the thesis suggests measures for decision makers, transport authorities, and other stakeholders regarding how they could promote road safety by developing vehicle and infrastructure requirements. Consequently, vehicle automation systems could provide a stronger layer of protection as part of the Safe System.

Ultimately, safety measures aim to influence human behaviour (Elvik 2004). Driver assistance systems would have theoretically prevented some crashes from occurring if the suitable system had been applied in the pre-crash event. However, behavioural adaptation may change the driver's behaviour in such a way that the system cannot avoid the crash. For instance, some studies have found that drivers can focus on secondary tasks when a driver assistance system is active, which in turn influences the driver's attention (Lin et al. 2018; Smiley & Rudin-Brown 2020).

The principles of a driver's behavioural adaptation were introduced by Wilde (1998) in his risk homeostasis theory. According to the theory, people compare the amount of perceived risk and desired risk (i.e. target level of risk) and adjust their behaviour when these two risks are different. Consequently, a measure to improve road safety does not necessarily improve safety at all or the impact is smaller than expected if road users change their behaviour to balance the risks. However, several weaknesses are associated with the theory that have been discussed by Høye and Elvik (2019). For instance, behavioural adaptation cannot be assessed by the risk homeostasis theory, even if it is important to have a tentative assessment for safety impact evaluation. So far, we have little detailed evidence on behavioural adaptation related to ADASs. Therefore, this study mostly focuses on the engineering effect of ADASs in pre-crash events, thus reflecting the best possible situation in terms of the potential safety impacts of the specific system. These issues are discussed in more detail in section 5.4.

However, some driver-related factors are considered, e.g. the effect of speed and driving under the influence of alcohol or drugs on the usage of ADASs is discussed to cover issues involving human behaviour. In addition, political decision making and people's attitudes towards road safety are included in the evaluation of HAVs' potential to prevent crashes with pedestrians, which provides one way to assess how the potential attitudes and behavioural changes could influence the engineering effect. This assessment is made by considering how HAVs would operate in a way that prioritised pedestrian safety or efficient traffic flow. This approach provides outlooks on situations where behavioural adaptation is likely needed because other road users cannot communicate with the driver, e.g. by eye contact, if HAVs replace drivers (Rodríguez Palmeiro et al. 2018). The evaluation of the potential safety effects of HAVs is also directed to pre-crash events, in which automated driving systems could possibly operate differently compared to human drivers to avoid the crash.

Some topics related to the systems' potential safety impacts are not addressed in this thesis. Potential new safety risks due to the deployment of ADASs and HAVs are not specifically assessed. Due to uncertainties related to possible new crashes that ADASs and HAVs can cause, the total change in the number of crashes may not be reliably evaluated. In terms of the introduction of HAVs, the potential impacts of prioritising the different ambitions in road transport and the possible changes different ambitions can bring about are discussed. In addition, the safety potential is only evaluated in terms of crash reduction potential, and hence the potential to mitigate crash consequences is not evaluated, even though the mitigation of the crash consequences is discussed in relation to HAV operation.

1.4 Research process and structure of the thesis

The thesis consists of four publications that seek to answer six research questions. By addressing the research questions, the thesis aims to evaluate the potential to prevent different fatal crashes in Finland by introducing vehicles that are equipped with lower or higher levels of driving automation (Figure 1). Even though multiple crashes were analysed, the thesis applies qualitative research rather than quantitative research. By examining data on in-depth investigated fatal crashes, each crash that is included in the specific publication was analysed individually (i.e. case-by-case) to recognise the conditions that would prevent or enable the proper operation of a driver assistance or automated driving system. With this information, the possibility of avoiding the crash by the use of ADAS or HAV can be evaluated. A case-by-case analysis is described in more detail in section 3.

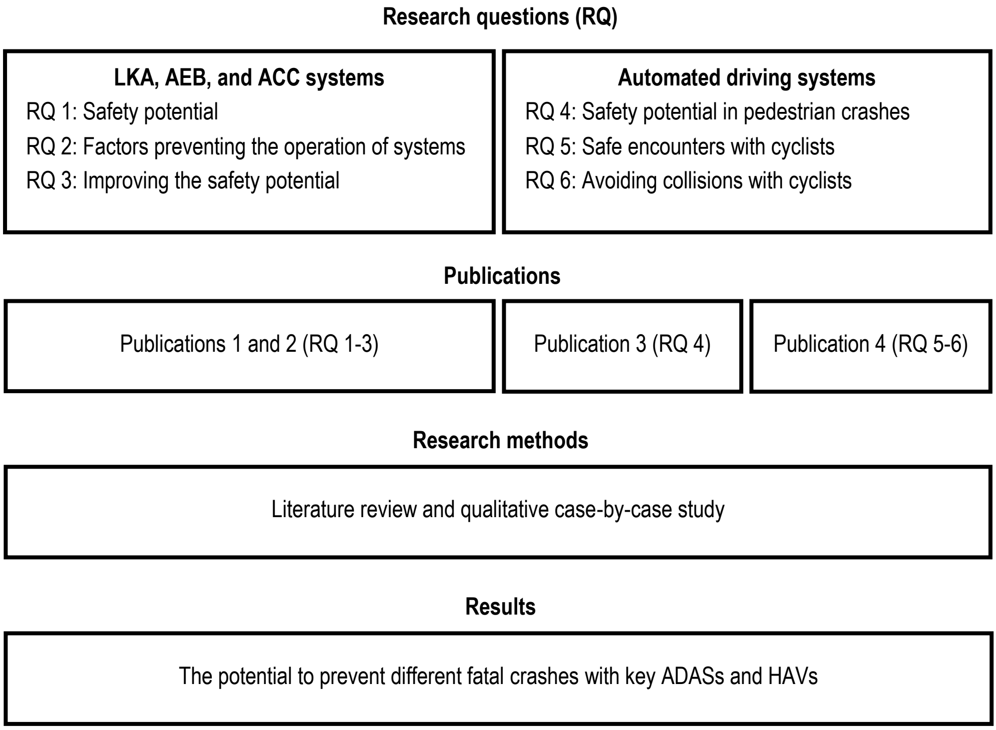

Figure 1. Structure of the thesis.

Firstly, it was evaluated which crashes could have been avoided had the driver-managed car been replaced by the LKA-, AEB-, and/or ACC-equipped car (research question 1). Prior to the evaluation, a literature review was conducted to identify the operational requirements of the studied ADASs. The user manuals of four different car models were reviewed to understand the operational requirements of the LKA, AEB, and ACC systems. A qualitative case-by-case study (i.e. each crash is evaluated individually to consider the operational requirements of the systems) was conducted to evaluate potentially avoidable crashes. In addition, the factors that would have prevented crash avoidance by the systems were identified (research question 2). Publication 1 answers the questions on the LKA system's safety potential and Publication 2 addresses the AEB and ACC systems' safety potential.

To address research question 3, scenarios on the possibilities to improve the safety potential of LKA, AEB, and ACC systems were formed and evaluated. These scenarios are related to future, more advanced systems, or the infrastructure advancements are expected to enhance the systems' operation, which would possibly increase the safety potential compared to currently available systems. A qualitative case-by-case study was carried out to similarly evaluate the safety potential of each scenario, as in the case of research question 1. Research question 3 is addressed in Publications 1 (LKA) and 2 (AEB and ACC).

In Publication 3, a qualitative case-by-case study was conducted to assess which fatal crashes between pedestrians and passenger cars could have been avoided had driver-managed cars been replaced with HAVs. To answer research question 4, crash avoidance was evaluated with two approaches considering the different ambitions in road transport and HAVs' possible deficiencies in assessing pedestrians' intentions. It was considered whether the HAV could have prevented the crash depending on whether pedestrian safety or efficient traffic flow was prioritised in HAV operation.

Literature review and qualitative case-by-case study aim to answer research questions 5 and 6 in Publication 4. Firstly, findings of the previous studies related to interaction between cyclists and driver-manager cars, and between cyclists and HAVs with a preliminary analysis of the crash data were used to form the features of HAVs that are needed for safe encounters with cyclists (research question 5). Secondly, a qualitative case-by-case study was carried out to assess how these features would help to avoid fatal crashes resulting from collisions between cyclists and driver-managed passenger cars (research question 6).

Publications 1 and 2 constitute an outlook on the potential to avoid fatal passenger car crashes by ADASs, which can momentarily support the driver in lateral and longitudinal vehicle motion control tasks. In addition, the safety potential of more advanced systems and additional infrastructure requirements were examined, which build an outlook towards HAVs. Publications 3 and 4 focus on the needed operational features and potential safety impacts of HAVs, in which drivers are not expected to participate in dynamic driving tasks. The HAV's hypothetical operation was examined in encounters with pedestrians and cyclists by analysing real-world pedestrian-car and cyclist-car crashes, and hence, the findings of these publications on the HAVs' safety apply to pedestrians and cyclists. The joint impact of Publications 1–4 concerns the potential to improve road safety by key ADASs and HAVs. The publications also indicate the differences between lower and higher levels of driving automation in terms of safety potential and operational requirements. The evaluation was made by examining fatal passenger car crashes and how the ADASs and the HAVs could operate before a possible collision and during a pre-crash event.

Of the different types of motor vehicles, passenger cars' driver assistance and automated driving systems were mainly considered in these publications to reduce the heterogeneity of the vehicles in the analysis. In Publications 1 and 2, heavy vehicles (e.g. trucks) were also considered to be equipped with the studied ADASs if the heavy vehicle was involved in a fatal passenger car crash. However, the number of types of motor vehicles other than passenger cars is small, as the crash data solely include crashes in which a passenger was involved. Publications 3 and 4, which analysed HAVs' safe operation, examined only passenger cars' automated driving systems in possible encounters with pedestrians and cyclists.

This thesis consists of six sections. In section 2, current state of road safety especially in Finland is described and a literature review on driver assistance and automated driving systems is presented. The research gap is also identified. In section 3, the data and methods used are described, and in section 4, the main results of each publication are presented. The findings are discussed in section 5, along with the validity and reliability of the thesis. Finally, in section 6, the key findings with practical and methodological contributions are summarised.

2 LITERATURE REVIEW

2.1 Current state of road safety

Road traffic causes major public health problems and costs. Even though the number of road fatalities declined by 23% between 2010 and 2019 in the EU, 22,800 people lost their lives on the roads of the 27 EU member states in 2019 (European Commission 2020b). In Finland, the preliminary number of road fatalities was 211 in 2019, which is 22% less than in 2010 (Statistics Finland 2020). The target in both the EU and Finland to decrease the number of road traffic fatalities by 50% between 2010 and 2020 will not be met (Figure 2). The target to halve the number of road fatalities has been extended, and the EU's new target is to cut the number of fatalities and serious injuries by 50% between 2020 and 2030. The number of seriously injured (i.e. maximum abbreviated injury scale three or more), which has been examined in Finland since 2014, did not decline between 2014 and 2018, but the number was clearly lower in 2017 than in 2018. The number of seriously injured was 953 in 2014, compared to 829 in 2017 and 956 in 2018 (Statistics Finland 2020).

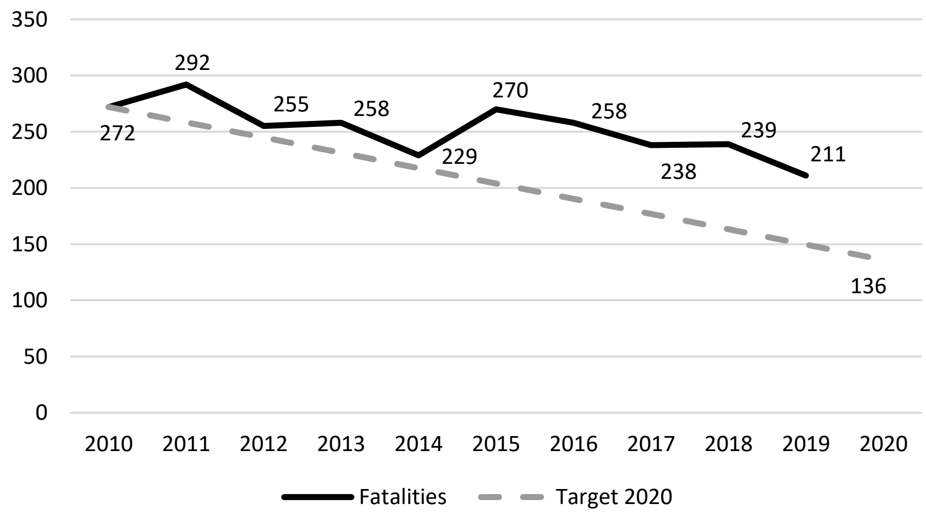

Figure 2. The number of fatalities in Finland from 2010 to 2019 and the reduction target for 2010-2020 (Statistics Finland 2020).

According to Statistics Finland (2020), fatal road crashes are typically associated with passenger cars, as passenger car occupants comprised 57% of fatalities in Finland between 2014 and 2018. Pedestrians accounted for 12% and cyclists 10% of the total number of road fatalities in these years. Single-vehicle (32% of all fatal crashes) and head-on crashes (31%) are the most common fatal crash types. In the statistics on serious injuries, which aggregate police-reported crashes and hospital records, the shares of road user groups appear differently compared to fatalities. Passenger car occupants comprised 31% of those serious injured in 2014–2018, which is almost the same as the 30% figure for cyclists (Statistics Finland 2020).

The desired increase in walking and cycling and a decrease in car traffic (Ministry of Transport and Communications 2018) may have an impact on the shares of different road user groups in crash statistics in the future. However, the prevention of fatalities and serious injuries to passenger car occupants seems to currently be the most efficient way to make crash reduction targets achievable, because passenger car occupants are the most dominant group in serious road crashes (37% of fatalities and serious injuries occur to passenger car occupants). It should be noted that the fatalities and serious injuries of other road users should also be prevented to make the target achievable. One way to promote the safety of e.g. pedestrians and cyclists is to make car traffic safer, as cars are usually involved in fatal crashes with pedestrians and cyclists.

2.2 Potential safety effects of ADASs

Road safety promotion is probably the most important reason for introducing ADASs, but these systems can also be manufactured to make driving more convenient (De Locht & Van Den Broeck 2014). Typically, single systems can either provide lateral or longitudinal vehicle motion control support or warn the driver of potentially dangerous situations. For instance, electronic stability control (ESC) system may prevent lane departures due to loss of control (i.e. lateral support) (Høye 2011). ACC can influence longitudinal vehicle motion control tasks by accelerating or decelerating to maintain a time-distance to a vehicle in front (Euro NCAP 2018). In addition, warning systems provide information for a human driver without the possibility of interfering with driving tasks. For instance, forward collision warning (FCW) system may perform a request to apply the brakes to avoid a possible collision (European Commission 2018b).

To support the driver in all essential dynamic driving tasks ADASs should be able to perform lateral and longitudinal vehicle motion control tasks. This thesis focuses on key active safety systems, i.e. LKA, AEB and ACC, that can perform these tasks. These systems can possibly prevent unintentional lane departures and avoid collisions with objects in front of the vehicle. LKA, AEB and ACC systems have also been emphasized as key ADASs in other safety-related studies (e.g. Stark et al. 2019; Vangi et al. 2019) and they, for example, form the basis of Volvo's Pilot Assist and City Safety functions (Volvo 2020). In addition, the operation of ISA system, which has been assessed to have potentially high safety impacts (European Commission 2018b), is discussed in connection with AEB and ACC systems.

Safer vehicles have been promoted as one of the key measures needed to make the crash reduction target by 2030 achievable (European Commission 2020b). Lower levels of driving automation (e.g. LKA and AEB) are one aspect of making safer vehicles. Several active safety systems will become compulsory in new passenger cars in the EU starting from 2022 (European Commission 2019b), which ensures that these systems are becoming more common in the passenger car fleet. This action aims mainly at promoting road safety, because ADASs are predicted to enhance safety by protecting different road users (European Commission 2019a). In Finland, LKA was found in 1–11%, low-speed AEB in 7–22%, and AEB with pedestrian detection in 2–8% of all passenger cars in 2018 (Lähderanta 2018), which indicates that passenger cars are rarely equipped with these essential active safety systems. It is expected that crash reduction potential cannot be realised unless ADASs become more common.

LKA system

The LKA system, which can momentarily interfere with lateral vehicle motion control tasks, is a key ADAS. The system can detect lane markings by camera and actively steer the vehicle back into the lane if the vehicle is about to cross centre or edge lines (Volvo 2018). LKA is potentially suitable for preventing lane departure crashes due to drifting (Logan et al. 2017).

According to the induced exposure analysis by Sternlund et al. (2017), the LKA system together with voice or signal warnings of lane departure (e.g. lane departure warning system, LDW) could potentially have prevented 53% of head-on and single-vehicle injury crashes in Sweden in speed limit areas of 70–120 km/h with a dry or wet road surface. In all roads and conditions, the effectiveness would have been 30%. Induced exposure analysis can be applied when the true exposure cannot be used. In this method, crash-involved cars with and without a specific system (e.g. LKA) are compared in cases that are sensitive and non-sensitive to the studied system. The study of Sternlund et al. (2017) was based on the exposure of 843 cars involved in injury crashes, of which 11 cars were equipped with LKA and 146 with LDW systems. Using a case-by-case analysis, Logan et al. (2017) assessed that LKA could have prevented 33% of the analysed 27 head-on and single-vehicle crashes in Australia and New Zealand. The range was 26–41% due to the random selection of the crashes. Scanlon et al. (2016) simulated 478 lane departure crashes and found that LKA could potentially have avoided 32% of lane departure crashes and 28% of serious injuries to drivers in the United States. The existence of lane markings was confirmed, but the visibility of lane markings during the crash situation was not assessed. It was also assessed that wide shoulders on roads would theoretically have enhanced the safety potential, as LKA could have prevented 78% of the crashes and 65% of serious injuries to drivers.

It is important to consider operational requirements when evaluating the LKA system's safety potential. According to four different car models, LKA is not operational in adverse weather conditions (e.g. snowfall), when lane markings are not visible, and at low speed. In addition, there are other restrictions when the system may not operate properly, e.g. in urban areas, on tight curves, or at intersections. Previous studies have either used a case-by-case study (e.g. Logan et al. 2017), an induced exposure analysis (e.g. Sternlund et al. 2017), or a simulation (e.g. Scanlon et al. 2016) with different assumptions related to the system's operational conditions to evaluate LKA's safety potential, which complicates the comparison of the results. Previous studies have evaluated that current LKA systems could have prevented 30–33% of head-on and single-vehicle crashes in existing conditions with different assumptions. Consideration of confidence intervals would widen the range on the potential safety effects.

AEB and ACC systems

AEB and ACC systems can support the driver in longitudinal vehicle motion control tasks. The AEB system can avoid collision with objects in front of the vehicle by applying the brakes if the driver does not brake after the system has warned the driver. The system can use cameras, radars, and lidars to recognise obstacles (Euro NCAP 2020). The ACC system maintains a certain time-distance from the vehicle in front by controlling vehicle speed (Isaksson-Hellman & Lindman 2016).

According to simulations by Kitajima et al. (2019), the AEB system could have avoided 28% of all crashes in the studied urban area in Japan with an AEB market penetration rate of 50%. The crash reduction potential of the AEB system was mainly due to a decrease in the number of rear-end crashes. Tan et al. (2020) created a model to assess the realistic safety potential of the AEB system in China. According to the results, the number of road fatalities could be reduced by 3% with current AEB technology and by 8% with advanced AEB technology (i.e. AEB is able to operate in adverse conditions) if 60% of the vehicles were AEB-equipped in 2030. Cicchino (2017) compared the crash involvement rates of vehicles equipped with AEB and forward collision warning systems and found that the crash involvement rate of vehicles equipped with these systems was 50% lower in rear-end crashes and 56% lower in rear-end injury crashes compared to the corresponding rate of vehicles without the systems in the United States. Rizzi et al. (2014) made an induced exposure analysis and found that low-speed AEB, which is mainly designed to operate in urban areas, could have averted 35–41% of rear-end injury crashes in Sweden in 2010–2014. In speed limit areas of 50 km/h or less, the low-speed AEB system could have averted 54–57% of the rear-end injury crashes. The safety potential was found to vary in different car manufacturers' vehicles, which caused the range. Fildes et al. (2015) also used an induced exposure analysis to evaluate the safety potential of low-speed AEB. According to police-reported crash data from six countries, 38% (confidence interval 18–53%) of rear-end crashes could have been avoided by the low-speed AEB system.

Vehicles equipped with both an AEB and ACC system have the enhanced potential to prevent rear-end crashes compared to vehicles that are solely equipped with an AEB system. Isaksson-Hellman and Lindman (2016) compared crash parties with and without AEB and ACC systems and concluded that the number of all rear-end crashes in Sweden was 37% less for those cars equipped with AEB and ACC than cars without these systems considering exposures. NHTSA (2011, pp. 247–248) simulated the performance of AEB and ACC systems and concluded that these systems could potentially have avoided 8% of all fatal crashes by avoiding rear-end, pedestrian, and intersection crashes in the United States.

AEB systems are also able to prevent pedestrian and intersection crashes. Haus et al. (2019) modelled AEB operation and found that AEB with a pedestrian detection system would theoretically have reduced the fatality risk of pedestrians by 84–87% in the best possible scenario without latency and with early activation in the United States. The range is due to the different deceleration forces applied. The fatality risk would have been reduced by 36–39% with high latency and late activation. Using simulations, Lubbe and Kullgren (2015) evaluated that the AEB system with pedestrian detection may have reduced road crash casualty costs by 25–26% due to a decrease in the number of car-pedestrian injury crashes. The range is dependent on whether the driver could solely avoid a collision with an evasive action or the pedestrian could also avoid the collision. Sander and Lubbe (2018) evaluated that an intersection AEB with a field-of-view of 120 degrees could have avoided 66% of straight crossing crashes between cars and 81% of the fatalities and serious injuries in these crashes. With a wider field-of-view (i.e. 180 degrees), the corresponding shares would potentially have been 79% and 90%.

According to four different car models, AEB and ACC systems are not operational in adverse weather conditions, and the systems cannot avoid a collision with an obstacle (e.g. another vehicle or a pedestrian) in front of the vehicle if the sensors cannot recognise and identify the obstacle early enough. An essential factor to consider for the safety potential analysis is vehicle speed. The higher the speed is, the less time there is to activate the system and prevent the collision after the obstacle is identified. According to Sander (2017), the AEB system is unlikely to be able to prevent a collision with another road user with an intersecting trajectory when the speed of the vehicle travelling in a straight line is more than 60 km/h. Rizzi et al. (2014) found that the potential to prevent rear-end crashes with low-speed AEB is clearly better in speed limit areas of 50 km/h or less than in higher speed limit areas. Consequently, the AEB system's potential safety effects may be optimal in urban areas with low speeds. In previous studies, induced exposure analyses, simulations, and crash risk comparisons have been typical methods to evaluate the safety potential of AEB and ACC systems. Numerical conclusions and comparisons on these systems' potential safety effects cannot clearly be presented due to the different methods and research questions, but it seems clear that AEB or AEB with ACC are able to prevent rear-end, intersection, and pedestrian crashes significantly when these systems become more prevalent.

2.3 Human factors

The development of vehicle automation systems is expected to provide safety benefits, i.e. the number of crashes is predicted to fall. The expectations are based on the elimination of human factors or human errors (Fagnant & Kockelman 2015). Human error is typically used to describe the cause of the crash when no clear evidence is found that the cause was related to the vehicle or the infrastructure (Noy et al. 2018).

In the context of vehicle automation, users' trust in driver assistance or automated driving systems plays a key role. People typically rely on automation they trust but refuse automation they do not trust (Lee & See 2004). Examples from industry and aviation indicate that people might deliberately or inadvertently use the system beyond its operational capability (Parasuraman & Riley 1997). These examples can be recognised in fatal road crashes in which vehicles equipped with lower levels of driving automation have been involved (e.g. NTSB 2018), which emphasises concerns related to human-machine interaction or interface (HMI, see e.g. Carsten & Martens 2019). However, according to a user survey, the traffic safety of HAVs seems to be a key concern among users (Liljamo et al. 2018). Consequently, users may be too confident with lower levels and sceptical towards higher levels of driving automation in the current phase of automatisation in road traffic.

HMI is a concern especially at levels 2 and 3 of driving automation (Kyriakidis et al. 2017). It is known that humans are poor supervisors of automation due to, e.g. the vigilance decrement (Parasuraman 1987). Another aspect involving the realisation of the safety potential is system usage. Even though a vehicle may be equipped with ADASs, the systems do not provide support in near misses and other situations if they are not turned on. It was found that the LKA system was turned on in 55% of LKA-equipped cars when the on-off status of the system was recorded at one point in Washington DC in the United States (Reagan et al. 2018). Straightforwardly, this means that the overall possibility to prevent lane departure crashes using the LKA system is about 50% of the maximum safety potential; hence, the crash reduction potential is clearly reduced.

At higher levels of driving automation, the impacts of human factors can be reduced, because the driver should not need to be fallback-ready or monitor the environment (SAE 2018). However, a supervisor is typically used to monitor the performance and environment during test drives and trials of HAVs (SAE level 4). Hence, the HMI is also a current and actual concern related to higher levels of driving automation. Some researchers have stated that the driver should be responsible for the driving tasks and be in the loop if HAVs cannot permanently take over all driving and monitoring tasks (Kyriakidis et al. 2017). This emphasises concerns over the driver's ability to react when the system makes a request to take over. In the longer-term, it is not desirable that the control of an HAV would be somehow shared between the driver and the system, but take over requests requiring an immediate response from the driver are already considered an undesirable development in the short term (Tabone et al. 2021).

Handover transition from an automated driving system to a human is likely a threat to road safety, as examples from aviation have indicated. The shorter-term threat is that the driver or pilot in this case loses situational awareness, and being constantly the supervisor of the automation diminishes manual flying skills in the longer term (Hampton 2016). In the best case scenario, automation would be responsible for driving tasks that it can perform better than the driver, and the driver would perform tasks in which a human performs better than automation (Noy et al. 2018).

In particular, at higher levels of driving automation, HMI does not only mean interaction between the system and the driver, but it also means communication between the automated driving system and other road users (e.g. pedestrians). Human factor researchers (see Tabone et al. 2021) have stated that means of interacting should be simple and appropriate for all people from different cultures, i.e. each pedestrian and cyclist should be able to interpret the intentions of HAVs. Researchers also suggest that the HAVs should rather express their intentions than instruct other road users.

2.4 Interaction between highly automated vehicles and pedestrians and cyclists

Most fatal crashes involving pedestrians and cyclists are caused by collisions with motor vehicles (Salenius & Sihvola 2020). An automated driving system replaces the driver in HAVs, which potentially delivers positive safety effects if the risks related to the driver – e.g. the driver's inattention, secondary tasks, or intoxicated driving – could be removed. The elimination of driver-related risks and human errors does not necessary mean that HAVs would operate without errors or risks, because these systems are designed by humans. In addition, all crashes attributed to driver error are not entirely the driver's fault, because poor roadway and vehicle design may enable the occurrence of errors (Noy et al. 2018). The cornerstone for safe encounters should be interaction, which is going to change, because, e.g. drivers will no longer make eye contact. Other ways to ensure safe encounters with HAVs may be needed (Lee et al. 2020).

Interaction between drivers and pedestrians and cyclists is complex. Observations of the encounters between the drivers of conventional vehicles and other road users likely help to design safer interaction features for HAVs (Uttley et al. 2020). Communication between drivers and pedestrians has been found to have a great impact on the pedestrian's decision to cross a street (Risto et al. 2017). Pedestrians do not always show a clear message (e.g. a hand gesture) that they are about to cross the street, but they usually look towards an approaching car (Dey & Terken 2017). Lee et al. (2020) observed encounters between drivers and pedestrians at intersections and found that drivers do not provide explicit messages to the pedestrians. Uttley et al. (2020) studied pedestrian-driver interactions in shared space areas and suggested that pedestrians tend to prompt drivers to make a clear decision to give way or not to give way by looking towards the driver. If a pedestrian looked towards the driver, the driver was more likely to stop or continue without deceleration. If the pedestrian did not look towards the driver, the driver more often decelerated without stopping.

When drivers are replaced by HAVs and the possibility for eye-contact is removed, it is unclear whether pedestrians need external light or text signals indicating that they have been recognised by the HAV. Conclusions from previous studies are two-fold. According to Ackermann et al. (2019), pedestrians want a confirmation to cross the street safely. Lundgren et al. (2017) also suggested that some communication is needed to ensure safe interaction. However, Rothenbücher et al. (2016) found that pedestrians would adapt to interact with HAVs without text or visual signals, because pedestrians already interact with vehicles in dark conditions, even though they cannot usually recognise the driver due to the dark. According to Rodríguez Palmeiro et al. (2018), the vehicle's speed and distance from the pedestrian crossing are more important indicators when planning to cross a street than interaction with the driver.

The interaction between cyclists and drivers is challenging too, because drivers sometimes obey their obligation to yield to the cyclists, but sometimes priority rules are not obeyed, e.g. due to the driver's failure to recognise the cyclist (Räsänen & Summala 2000; Silvano et al. 2016). In addition, cyclists do not always yield to drivers, even though they should yield according to the formal rules (Räsänen et al. 1999). Drivers do not always exercise their right of way, as they sometimes yield to cyclists even when the cyclist should have yielded (van Haperen et al. 2018). Priority rules seem not to be the most important factor for the yielding behaviour (Sakshaug et al. 2010). Drivers' yielding behaviour is typically affected by vehicle speed and the proximity of the cyclist (Silvano et al. 2016).

Formal yielding rules should be the basis for the interaction, but the rules are not always obeyed (Silvano et al. 2016). As drivers do not always recognise cyclists at intersections, a capability to recognise cyclists in different situations would be the most important feature of HAVs, which would likely enhance cycling safety. In addition, HAVs should consistently follow yielding rules, which would make the rules a cornerstone of the interaction between HAVs and cyclists. From the cyclist's perspective, it is sometimes difficult to find signals in the behaviour of the driver or the vehicle that it is safe to cross the street. For instance, a vehicle's deceleration does not necessarily mean that the driver has recognised the cyclist (Kovácsová et al. 2018). Because cyclists and pedestrians cannot be sure they have been recognised by the HAV without clear messages, external light or text signals may be needed to ensure safe interaction (Merat et al. 2018).

The high hopes regarding the potential safety impacts of HAVs for pedestrians and cyclists have not yet been explicitly addressed. So far, only a few studies have evaluated the potential of HAVs to prevent pedestrian and cyclist crashes. The low number of studies is probably due to uncertainties related to interaction and the operational capability of HAVs in these encounters. As road users are not yet used to HAVs, it is possible that people behave with caution when interacting with them. For instance, cyclists were not more confident of being noticed by the HAVs compared to drivers of conventional vehicles in bicycle-car encounters, which was studied in a photo experiment by Hagenzieker et al. (2020). In a simulation study by Tafidis et al. (2019), HAVs were assessed to theoretically prevent 7% of all conflicts between cyclists and HAVs in the whole road network in a medium-sized city in Belgium. The number of conflicts at intersections would have been reduced by 26%. Previously, Zhao et al. (2019) evaluated that AEB could have avoided 15–50% of the studied 40 cyclist-car crashes, and Jeppsson and Lubbe (2020) found a crash reduction potential of 41–59% in simulated cyclist-car crashes. The range was due to the applied sensor's field of view. Even though crash reduction potential is not totally comparable to conflict reduction potential, a reduction of 7% in the number of conflicts by HAVs seems to be minor compared to AEB systems' potential to prevent crashes with cyclists.

According to Detwiller and Gabler (2017), HAVs could potentially have prevented 95% of the studied pedestrian injury crashes in the United States. Crashes were evaluated as preventable if a driver violation was identified or the pedestrian was visible one second or more before the impact. Combs et al. (2019) evaluated that 36–98% of fatal crashes involving pedestrians could theoretically have been avoided by HAVs. The range is due to the applied sensor technology, i.e. whether a camera, lidar, or radar sensors were used. Compared to the possibilities of AEB systems to reduce the pedestrian fatality risk by 36–87% (Haus et al. 2019) and road crash casualty costs by 25–26% in pedestrian crashes (Lubbe & Kullgren 2015), the potential of HAVs to prevent pedestrian crashes could be better, but the range is wide in the existing research, which presents uncertainty.

2.5 Road safety and vehicle automation systems

The introduction of safer vehicles among other safety promotion actions is important to make the crash reduction target by 2030 achievable. Previous studies presented in section 2.2 have indicated that ADASs are able to reduce the number of crashes substantially, i.e. vehicles equipped with LKA, AEB and ACC systems (SAE level 2), can potentially decrease the number of crashes by about 30–40%. However, successful crash prevention requires the high market penetration rate of these systems, which is yet to be achieved in Finland and other countries. In addition, the operational design domain (ODD) is limited, which means the systems cannot operate in all conditions. As another factor, it is important to ensure that drivers utilise these systems as much as possible and recognise the limitations of the systems (Figure 3). Even though a driver is responsible for the driving tasks, driver assistance (SAE level 1) or partial automation systems (level 2) improve road safety compared to vehicles without automation (level 0). Level 0 vehicles cannot influence lateral or longitudinal vehicle motion control tasks without the driver's input (SAE 2018). Systems that can only warn the driver (e.g. LDW) are examples of the systems on level 0.

		Publications 1 and 2 without last scenarios		Publications 3 and 4, and lasts scenarios in publications 1 and 2
Levels of driving automation:	Level 0: No automation	Level 1-2: Driver assistance and partial automation	Level 3: Conditional automation	Level 4-5: High and full automation
Description:	-No automation	-Driver is responsible for driving tasks -Assisted driving -Limited ODD	-System is responsible for driving tasks -Driver should be fallback ready -Limited ODD	-System is responsible for driving tasks -Driver is not needed -Limited ODD in level 4
Crash reduction potential:	-Warning systems may help the driver to make an earlier evasive action	-About 30-40% in level 2	-Automated driving function can potentially prevent more crashes than in level 2	-High potential with great uncertainty -Driver-related risks and human errors can be excluded
Safety threats:	-False warnings reduce system's reliability	-Systems' limitations are not recognised -Systems are not turned on	-Role of the driver may be unclear -Safety risks in fallback situations	-Interaction with other road users -High market penetration only from 2050s?

Figure 3. Description of the levels of driving automation (SAE 2018), including information on crash reduction potential and safety threats. The data on crash reduction potential and safety threats are based on literature and discussions in sections 2.2–2.5.

In the higher levels of driving automation, starting from SAE level 3, automated driving becomes a topic of discussion. Especially at level 3, the driver should be constantly ready for handover transition from the system to the driver (Bellet et al. 2019). Some car manufacturers have announced their intention to ignore level 3 vehicles, because the handover transition is a great safety concern due to humans' poor supervision skills (Noy et al. 2018; Parasuraman 1987). However, the higher levels of driving automation (especially levels 4 and 5) can potentially provide better safety impacts than the lower levels, because the driver is not necessarily needed at all. If the driver is no longer responsible for the driving tasks, this theoretically enables the elimination of crashes related to alcohol or drug use, speeding, and drivers falling ill or aiming to commit suicide while operating the vehicle.

In terms of safety threats at the higher levels of driving automation, interaction is one essential threat from the perspective of pedestrians and cyclists. The threat is that HAVs may not be able to properly assess the forthcoming trajectories of pedestrians and cyclists (Botello et al. 2019; Rasouli and Tsotsos 2019), which makes safe encounters more difficult. Weather and infrastructural conditions are examples of possible other threats, which can have an impact on the safe operation of HAVs. In addition, new safety problems can appear when more evidence is provided on actual encounters between HAVs and other road users. It will probably take decades until the number of HAVs is large enough for high safety expectations concerning the whole car fleet.

According to some statements, the number of motor vehicle crashes is also predicted to decline dramatically, when conventional vehicles are replaced by HAVs. However, HAVs are not yet operated on a large scale in any part of the world, which causes great uncertainty in terms of impacts. Because it has not been possible to properly examine the actual operation of HAVs, the existing literature on the potential safety impacts is mostly based on simulations and modelling. Therefore, the results must be treated with caution. For instance, the number of conflicts could be reduced by 48–65% at signalized intersections and 64–98% at roundabouts with an HAV market penetration rate of 90–100% (Morando et al. 2018; Virdi et al. 2019). On motorways and freeways, the number of conflicts or rear-end risks could potentially be reduced by 90–95% (Jeong et al. 2017; Papadoulis et al. 2019). In urban areas, the range seems to be wider, as the number of crashes or conflicts have been evaluated to decrease by 19–84% with an HAV market penetration rate of 75–100% (Kitajima et al. 2019; Tafidis et al. 2019).

To conclude the literature review section, it can be stated that better vehicle technology – including the deployment of driver assistance and automated driving systems – has an important role to play when trying to achieve the crash reduction target. Each level of driving automation has safety-related potential and concerns, which should be assimilated by users, vehicle manufacturers, technology developers, public authorities, and decision makers. It should be noted that automated driving will not be the only solution to traffic safety problems, even if every vehicle was fully automated, because motor vehicles are not involved in all crashes.

2.6 Research gap

The potential safety effects of lower levels of driving automation have been evaluated in several studies (e.g. Rizzi et al. 2014; Sternlund et al. 2017). It has not always been possible to utilise all essential information on the operational conditions of the systems related to the driver, environment, and vehicle in the same research due to the data available. In this thesis, data on in-depth investigated fatal passenger car crashes were utilised, which enabled the consideration of several important operational requirements of ADASs in the analysis. For instance, adverse weather conditions (for the operation of LKA, AEB, and ACC), estimated vehicle speed in pre-crash events (LKA, AEB, and ACC), the visibility of lane markings (LKA), and driving under the influence of alcohol or drugs (LKA) were included in these publications when evaluating the potential safety impacts. As these are essential factors to consider for the operation of ADASs, and weather and road conditions are typically different in Finland compared to studies from other countries (e.g. Japan (Kitajima et al. 2019) and the United States (Scanlon et al. 2016)) in terms of the systems' safety potential, Publications 1 and 2 complement previous research and add new knowledge to the potential safety impacts of ADASs focusing on Finland.

HAVs without human drivers can possibly deliver greater safety potential than vehicles controlled by drivers and equipped with ADASs. Safety expectations have been confirmed by researchers (e.g. Fagnant & Kockelman 2015), companies (e.g. Waymo 2020), and authorities (e.g. U.S. Department of Transportation 2018), but the actual operation of HAVs and their integration in the road transport system are still unsure due to the lack of proper data (Kitajima et al. 2019; Morando et al. 2018). In particular, interaction with pedestrians and cyclists is a concern, because changes in interaction may cause new safety problems (Rodríguez Palmeiro et al. 2018). Possible changes in the behaviour of other road users (e.g. cyclists) in encounters with the HAVs compared to interaction with driver-managed cars could make the design of automated driving systems more difficult (Hagenzieker et al. 2020). One of the key challenges in the operation of HAVs seems to be the intention estimation of pedestrians and cyclists (Botello et al. 2019; Rasouli & Tsotsos 2019).

Thus far, studies have focused on safe encounters between HAVs and vulnerable road users such as pedestrians and cyclists. These studies have typically assessed interaction in these situations, e.g. whether and how HAVs could signal to pedestrians and cyclists that they have been seen (Ackermann et al. 2019; Merat et al. 2018). This thesis aims to increase scholarly knowledge on the potential safety impacts and required features of HAVs in encounters with pedestrians and cyclists. This is a subject that only a few studies have previously focused on (Tafidis et al. 2019). Overall, knowledge related to encounters between the HAVs and pedestrians and cyclists is deficient, and therefore Publications 3 and 4 are necessary.

3 DATA AND METHODS

3.1 Overview of data and methods

Data on in-depth investigated fatal crashes in Finland were used in each publication. The data are provided by the Finnish Crash Data Institute, and they are based on investigations made by the road accident investigation teams. The teams consist of experts from the police and the fields of medicine, vehicle technology, road maintenance, behavioural science, and other needed disciplines (Finnish Crash Data Institute 2020). The data include crash descriptions with scene photographs and variables on involved road users, vehicles, environments, and risk factors. Since 2001, investigations on fatal road crashes have been mandated by law in Finland (Finlex 2020), and hence almost all fatal crashes are investigated in-depth (Lehtonen 2020). This data set was chosen, because it includes the necessary information related to the driver, vehicle, and environment that is required when the potential of driver assistance and automated driving systems to prevent crashes is evaluated. This thesis is focused on vehicle automation systems solely in passenger cars, because passenger cars are typically involved in fatal crashes. Furthermore, concentrating on passenger cars reduces the heterogeneity of the vehicle characteristics in the analysis.

Fatal crashes for the 2014–2016 period are included in this thesis. Crash data from 2016 were the latest available for research purposes when the analysis was done. Crashes are analysed starting from 2014 so that the number of crashes is large enough for scientific approaches. In addition, the crashes are relatively new cases, which diminishes speculations involving more advanced road transport systems that could potentially have prevented some cases. The crash data from 2014–2016 were used in each publication, allowing for a better comparison of the results. In total, accident investigation teams investigated 721 fatal crashes in the period (Salenius & Sihvola 2020). In this thesis, 506 fatal crashes that involved a passenger car are focused on. The number of analysed crashes varies across the publications, as the analysed crash types were different in each publication. Although the number of analysed crashes is smaller in Publications 3 and 4 compared to Publications 1 and 2, the crashes and crash types analysed in Publications 3 and 4 are comparable to the larger sample studies, e.g. in the United States involving pedestrian crashes (Dai

2012; Kemnitzer et al. 2019) and in Sweden involving cycling crashes (Isaksson-Hellmann 2012). Table 1 summarises the analysed data and assessment principles in Publications 1–4.

Table 1. Descriptions of crash data and methods in Publications 1–4.

	Crash data	Systems focused on	Assessment principles in qualitative case-by-case analysis
Publication 1	364 head-on and single-vehicle crashes	LKA	-Lane markings' visibility -Weather conditions -Driver-related risks
Publication 2	115 rear-end, pedestrian, and intersection crashes	AEB and ACC	-Vehicle speed -Weather conditions -Driver-related risks
Publication 3	40 pedestrian crashes	Automated driving	-Time-to-collision (TTC) analysis -Driver's observations -Driver-related risks
Publication 4	24 rear-end and intersection crashes with cyclists	Automated driving	-TTC analysis -Priority rules -Visual obstacles -Driver-related risks

All publications are retrospective cross-sectional studies of fatal road crashes. In each publication, a qualitative case-by-case study was made to evaluate the potential of ADASs or HAVs to prevent crashes. In this methodology, each crash is analysed individually considering the crash characteristics, such as pre-crash events, driver-related risks, weather and road conditions, and information on vehicles, which are based on the reports from the accident investigation teams. This method was chosen for the thesis because data on in-depth crash investigations were available concerning almost all fatal crashes in a single country, which is uncommon in scientific research. In addition, previous studies have not typically used a case-by-case analysis to evaluate safety potential. Methods applying simulations (e.g. Kitajima et al. 2019) or induced exposures (e.g. Sternlund et al. 2017) have been more common in previous studies involving ADASs. The potential safety effects of HAVs on pedestrian or cyclist crashes have been studied by a method comparable to case-by-case analysis (Detwiller & Gabler 2017), but the number of studies is small; thus, more research is needed. Sections 3.2–3.5 present main information on methods, but the detailed description of a case-by-case analysis is presented in publications.

3.2 Potential safety effects of LKA (Publication 1)

A case-by-case analysis was made to evaluate the current and future LKA systems' potential to prevent lane departure crashes. Consequently, fatal head-on (n=192) and single-vehicle crashes (n=172) involving a passenger car from 2014–2016 were included in the publication. In the data set, there was only one car equipped with LKA, but the car with the system was a secondary party, and hence LKA was not designed to prevent the case. Firstly, the user manuals of four different car models were studied in order to assess the operational conditions of the current LKA systems. Secondly, each crash was analysed individually with a what-if frame, i.e. what if the cars involved in the crashes without LKA systems had been LKA-equipped with the LKA continuously on? The LKA system was assessed to potentially prevent the crash if three conditions were favourable. If at least one of the conditions was unfavourable, LKA was assessed as not being able to prevent the crash. The favourable conditions were:

- Fully visible lane markings (a centre and an edge line clearly visible),
- Normal weather conditions (snowfall, wet snow, or fog are not allowed)
- No driver-related risks (intentionally caused crashes, driver suffers an illness, and overtaking are not allowed).

To evaluate the more advanced LKA system's safety potential, four other scenarios were formed. These scenarios consider potential future LKA systems taking into account theoretical advancements in the infrastructure and system. In the first (1) scenario, the whole road network has fully visible lane markings, but the system is similar to the current LKA. In the second scenario (2), LKA is able to follow digital lane markings (e.g. high definition maps), which are hypothetically available on the whole road network. In the third scenario (3), the driver is not allowed to bypass the system, eliminating intentionally caused and overtaking crashes. The other requirements are as in the second scenario. In the fourth scenario (4), LKA is also able to park the car safely in the case the driver's sudden illness attack. The crashes were analysed similarly as with the current LKA system (e.g. each car is equipped with LKA, and LKA is always on) considering advancements in each scenario.

3.3 Potential safety effects of AEB and ACC (Publication 2)

A case-by-case study was conducted to evaluate the AEB and ACC systems' potential to prevent relevant crash types. Fatal rear-end (n=33), pedestrian (n=29), and intersection (n=53) crashes involving a passenger car between 2014 and 2016 were included in the study. None of the vehicles involved in the crashes were AEB- or ACC-equipped. The user manuals of four different car models were examined and considered as guidelines for the operational conditions of the AEB and ACC systems. Publication 2 addresses whether fatal crashes could have been avoided if the vehicles involved had been equipped with AEB and ACC systems. Each vehicle involved in the crash was assumed to be equipped with the systems, and the systems were assumed to be always turned on. The AEB and ACC systems were evaluated to potentially prevent the crash if each operational condition was favourable. If at least one of the conditions was unfavourable, the crash was deemed to not be prevented by the systems. The favourable conditions were:

- The vehicle speed is 60 km/h or less in pedestrian and intersection crashes or the speed difference between the involved vehicles is 60 km/h or less in rear-end crashes,
- Normal weather and road conditions (snowfall, wet snow, fog, or icy road surface are not allowed),
- No intentionally caused crash.

The possibilities to increase the safety potential of vehicles equipped with AEB and ACC were also assessed, as was done in Publication 1 involving the LKA system. The crash data were re-analysed by using three additional scenarios related to hypothetical advancements in vehicle and infrastructure requirements, as well as the inclusion of intelligent speed assistance (ISA) to evaluate the possibly increased safety potential. In the first scenario (1), vehicles are also equipped with ISA, which would theoretically prevent exceeding the speed limit. In the second scenario (2), communication technology between the motor vehicles and specific intersection AEB systems would potentially prevent a greater number of intersection and rear-end crashes. In the third scenario (3), the hypothetical possibilities of HAVs in preventing crashes were evaluated. In this scenario, the driver is replaced by an automated driving system and the driver is unable to bypass the system.

3.4 HAVs' potential to prevent pedestrian crashes (Publication 3)

In Publication 3, the hypothetical possibilities of HAVs in preventing fatal pedestrian crashes involving a passenger car were evaluated. HAVs are considered to perform all dynamic driving tasks and the user or passenger is not expected to respond to requests to intervene in the driving tasks. Data on in-depth investigated crashes consisting of 40 fatal pedestrian crashes between 2014 and 2016 were used in this publication. Each crash was analysed qualitatively by considering two different approaches, i.e. prioritising pedestrian safety or efficient traffic flow in HAV operation. These two approaches were selected for the analysis, because the road transport system is a compromise of the optimisation of safety, traffic flow, travel time, etc., which may have an impact on HAV operation. Since these two ambitions are considered key factors, they were compared in this publication. Previous studies (Botello et al. 2019; Rasouli & Tsotsos 2019) have indicated that HAVs may have difficulties in estimating the intentions of pedestrians, and thus it could be necessary to note that the expected safety impacts of HAVs may not be realised if safety is not prioritised over other ambitions.

The evaluation of HAVs' potential for crash avoidance is made with two different ambitions, namely prioritising pedestrian safety (1) or efficient traffic flow (2) in the HAVs' operation. In both approaches, it is assumed that even if HAVs are able to identify the presence of nearby pedestrians, they are not able to assess pedestrians' intentions to, e.g. cross a street. In the pedestrian safety approach, HAVs would always slow down or stop when pedestrians are identified near the vehicle even if the trajectories do not intersect, because the system cannot evaluate the pedestrians' intentions. This approach would likely cause unnecessary decelerations and would influence the flow of traffic. In the efficient traffic flow approach, HAVs slow down only when a pedestrian is identified as being on a collision course, i.e. stepping onto a pedestrian crossing that the HAV is about to cross. In this approach, it is unsure whether there is always enough time to avoid the collision with the pedestrian, even though unnecessary decelerations could be avoided.

Crashes were evaluated for both approaches (i.e. two evaluation rounds), and three outcomes of the potential crash avoidance were possible in each evaluation: (A) the crash would likely be preventable, (B) unpreventable, or (C) unclear. The analysis is divided into three parts according to the crash types: 13 pedestrian crossing crashes, 13 crashes outside a pedestrian crossing, and 14 other pedestrian crashes. The difference between pedestrian crossing crashes and crashes outside pedestrian crossings is the priority rule (e.g. whether the HAV or pedestrian is obligated to yield). In situations outside pedestrian crossings, the HAVs may be designed to assume that the pedestrian at the roadside is not intending to cross the street without yielding. In addition, the third category (other pedestrian crashes) includes crashes in which a pedestrian did not cross the street (e.g. crashes in parking areas).

The assessment principles of crash avoidance vary in different crash types and approaches that are applied in the evaluation (Table 2). As a general guideline in the approach prioritising pedestrian safety, HAVs are assumed to be able to detect pedestrians and decelerate early as a precaution, which would enable crash avoidance in several cases. In the prioritising efficient traffic flow approach, time-to-collision (TTC) analysis is applied to evaluate crash avoidance potential when possible.

Table 2. The assessment principles of crash avoidance in different crash types, when prioritising 1) pedestrian safety and 2) efficient traffic flow in HAV operation.

<table>
<tr><th colspan="2">Crash Type</th><th>Prioritising Pedestrian Safety</th><th>Prioritising Efficient Traffic Flow</th></tr>
<tr><td rowspan="2">Pedestrian crossing crashes</td><td>Crashes related to driver's behavior</td><td colspan="2">HAV maintains safe behavior and obeys the law</td></tr>
<tr><td>Crashes related to driver's wrong observations</td><td>HAV is assumed to be able to detect pedestrians in all circumstances and it decelerates early as a precaution</td><td>Crash avoidance is based on TTC analysis</td></tr>
<tr><td colspan="2">Pedestrian crashes outside pedestrian crossings</td><td>HAV is assumed to be able to detect pedestrians in all circumstances and it decelerates early as a precaution</td><td>Crash avoidance is based on TTC analysis</td></tr>
<tr><td colspan="2">Other pedestrian crashes</td><td colspan="2">HAV maintains safe operation and avoids e.g., unintended lane departures, running off the road and parking area cases. TTC analysis also applied when possible and needed depending on the case.</td></tr>
</table>

TTC analysis refers to time-to-collision analysis, in which the crash is assessed as likely preventable if TTC > 1.5 s, unlikely preventable if TTC < 1.5 s, and crash avoidance is unclear if TTC = 1.5 s.

TTC values are calculated by considering the assumed pedestrian speed and the distance between the point in which the pedestrian stepped onto the roadway and the collision point. The crash is assessed as unlikely to be preventable if TTC is less than 1.5 s. This value represents a high collision risk and the braking systems should apply the brakes at the latest when TTC is 1.5 s (Papadoulis et al. 2019; Yang et al. 2019).

3.5 HAVs' required features to prevent crashes with cyclists (Publication 4)

In Publication 4, fatal crashes between cyclists and passenger cars (n=24) in 2014–2016 were qualitatively analysed to assess what features would allow HAVs' safe operation and crash avoidance in these encounters. HAVs are defined as in Publication 3, i.e. a passenger is not expected to respond to requests to intervene in the driving tasks. In the analysis, it is assumed that driver-managed passenger cars would be replaced by HAVs and HAVs would assumedly not have operated in the same manner as the human prior to the crash. Firstly, five features related to HAVs' design and operation were described based on findings from previous research involving interaction between cyclists and drivers, and between cyclists and HAVs. In addition, a preliminary analysis of the crashes (by analysing crash types, crash descriptions and other variables) was made to understand the occurrence of crashes and key factors that HAVs should be able to address. Based on the literature review and the preliminary analysis of the crash data following features were formed:

- Feature 1 (recognise): HAVs should always recognise all road users that may end up on a collision course.
- Feature 2 (follow rules): HAVs' yielding behaviour should be based on formal priority rules, and HAVs should accurately obey the obligation to yield in all traffic situations and different types of intersections.
- Feature 3 (indicate intentions): HAVs should indicate their intentions to cyclists in a clear and consistent manner.
- Feature 4 (safe driving patterns and situational awareness): HAVs should select a safe speed and maintain safe driving patterns by considering the traffic situation.
- Feature 5 (assess cyclist's intention): Even if the priority rules state that the cyclist should yield, HAVs should assess cyclists' intentions and choose a speed so the HAVs are prepared for cyclists not yielding.

Three questions related to pre-crash events were used to evaluate the features needed by HAVs for crash avoidance. First, it was assessed whether a passenger car or a cyclist had the obligation to yield. Second, it was evaluated whether there was a visual obstacle blocking the visibility of the cyclist. Third, if the car had the obligation to yield, it was also studied whether the driver behaved dangerously by violating some other rules than the obligation to yield. In addition, TTC analysis was conducted to evaluate the potential to avoid collisions by HAVs. TTC values are based on the estimated or assumed cyclist's speed and the distance between the collision point and the trigger point. The trigger point is the location in which the cyclist turns into the car's trajectory from the side of the roadway in rear-end crashes or the cyclist enters the roadway from a cycle path at cycle crossings. This complements the qualitative evaluation of crash avoidance, because some of the crashes are difficult to avoid despite the features due to a short time margin for when the cyclist could be first recognised as being on a collision course.

4 RESULTS

4.1 Potential safety effects of LKA (Publication 1)

According to the case-by-case study, the LKA system could potentially have avoided 99 (27%) of 364 head-on and single-vehicle crashes, because lane markings were fully visible, the weather conditions were favourable, and driver-related risks were not identified in the studied cases. This constitutes 20% (99 of 506) of the total amount of fatal passenger car crashes in Finland in 2014–2016.

Lane markings were partially visible or invisible in 161 (44%) of 364 cases, which was typically due to incomplete markings, a lack of markings, or snow or ice covering the markings. Weather conditions were unfavourable in 23 (6%) cases. Driver-related risks appeared in 170 (47%) cases, of which 88 were intentionally caused, 61 were due to the driver suffering an acute illness, and 21 were overtaking crashes. In many cases, two unfavourable factors (e.g. invisible lane markings and a driver-related risk) would have prevented the proper operation of LKA. In addition, if exceeding the speed limit by 10 km/h or more and driving under the influence of alcohol or drugs would have an impact on the LKA system's proper operation – only 47 (13%) crashes could have been avoided instead of 99 (27%).

An advanced LKA system and infrastructure improvements could possibly increase the safety potential. If the entire road network had fully visible lane markings, LKA could hypothetically have prevented 46% of crashes (Scenario 1). Had LKA been able to follow digital lane markings, 52% of the crashes would theoretically have been avoided (Scenario 2). Intentionally caused crashes could also be avoided if the ability to override advanced LKA were removed (Scenario 3). Consequently, 82% of the crashes could potentially have been avoided. Eliminating also the crashes due to acute illness (Scenario 4), 99% of the crashes could potentially have been avoided. Three head-on collisions with a motorbike and two crashes due to a passenger car's technical failure would theoretically have remained unavoidable.

4.2 Potential safety effects of AEB and ACC (Publication 2)

AEB and ACC systems would potentially have avoided 47 (41%) of 115 rear-end, intersection, and pedestrian crashes. In these cases, the vehicle speed or speed difference was 60 km/h or less, the weather conditions were favourable, and the crashes were not intentional. The number of potentially preventable cases is 9% (47 of 506) of the total amount of fatal passenger car crashes in Finland in 2014–2016.

The speed of the studied AEB-equipped vehicles in pedestrian and intersection crashes or the speed difference between the involved vehicles in rear-end crashes were excessive for crash avoidance in 51 (44%) of the 115 cases. The weather conditions were adverse in nine (8%) cases, and an intentional crash would have prevented the AEB system's operation in four (3%) cases. In addition, motorbikes should have been AEB-equipped in 11 (10%) intersection or rear-end crashes with a passenger car to prevent the crash. However, motorbikes are not considered to be AEB-equipped.

Advancements in infrastructure and vehicle requirements would possibly have improved the safety potential. By introducing ISA with AEB and ACC systems (Scenario 1), 52% of the crashes could potentially have been avoided due to lower speed in cases where the driver exceeded the speed limit. With advanced intersection AEB systems and communication technology between vehicles (Scenario 2), 87% of the crashes would theoretically have been avoided. All the crashes could hypothetically have been avoided by replacing the driver with an automated driving system and assuming the system would have operated differently in pre-crash events compared to a human driver (Scenario 3). The crash prevention requires more proactive and safer driving behaviour in HAV operation compared to the human driver. The intentionally caused and remaining pedestrian and cyclist crashes would potentially have been prevented.

4.3 HAVs' potential to prevent pedestrian crashes (Publication 3)

Of the 40 case-by-case analysed crashes between pedestrians and driver-managed passenger cars, HAVs could potentially have prevented 37 in the prioritising pedestrian safety approach and 28 in the prioritising efficient traffic flow approach. HAVs would hypothetically have prevented all pedestrian crossing crashes (n=13) in the pedestrian safety approach, but four crashes would have been unavoidable or unclear in the traffic flow approach. In these four cases, the TTC values were 1.5 s or less, and hence the collisions were unlikely to have been avoided.

All pedestrian crashes outside pedestrian crossings (n=13) could potentially have been preventable by HAVs in the pedestrian safety approach, but five of these crashes would theoretically have been unpreventable in the traffic flow approach. The TTC values were 1.5 s or less in these five cases. A third group in the analysis includes 14 other pedestrian crashes (e.g. crashes in parking areas and crashes due to drifting), of which 11 cases would potentially have been avoidable in both studied approaches. Two of the potentially unavoidable crashes related to suicidal behaviour and one crash related to a pedestrian's unexpected behaviour.

4.4 HAVs' required features to prevent crashes with cyclists (Publication 4)

In Publication 4, 24 fatal crashes between cyclists and driver-managed cars were analysed assuming that the driver-managed cars would be replaced by HAVs. The driver had an obligation to yield in 12 cases and the cyclist in 12 cases. A visual obstacle from the driver's perspective was recognised in six cases and the driver behaved dangerously (e.g. broke some other rule than the obligation to yield) in four cases. In the most common crash type (n=10), the cyclist had the obligation to yield, the driver did not have a visual obstacle, and the driver was not identified as breaking any traffic rules.

According to the results, feature 1 (recognise) would be the most important feature in HAV operation, because it relates to all 24 cases. Feature 2 (follow rules) was identified necessary in 12 cases. Features 3 (indicate intentions), 4 (safe driving patterns and situational awareness), and 5 (assess cyclist's intention) were evaluated to be necessary in eight, eight, and ten crashes, respectively. According to the TTC analysis, the TTC values would have been less than 2.0 s in 10–14 (42–58%) of the studied cases. The range is due to uncertainty over the cyclist's speed.

5 DISCUSSION

5.1 Many factors have an impact on the potential safety effects of ADASs

This thesis and previous studies have indicated that ADASs promote road safety by preventing crashes. Publications 1 and 2 conclude that LKA, AEB, and ACC systems, which can influence lateral and longitudinal vehicle motion control tasks, could potentially have prevented 29% of the fatal passenger car crashes in Finland in 2014–2016. It should be noted that each passenger car should be equipped with these three systems and the systems should be turned on. In addition, the systems are assumed to operate faultlessly. This is relatively comparable to findings from Germany, in which 24% of severe and fatal crashes were evaluated to be theoretically preventable by these three systems (Stark et al. 2019).

A closer look at the results in Publication 1 indicates that LKA could potentially have prevented 27% of head-on and single-vehicle crashes in Finland. The result is comparable with previous studies (Logan et al. 2017; Scanlon et al. 2016; Sternlund et al. 2017), which indicated a crash reduction potential of 30–33% in other countries with different methodologies. The assessed safety potential of AEB and ACC was also in line with previous studies. In Publication 2, the AEB and ACC systems were assessed to have the potential to have prevented 45% of rear-end crashes. In previous studies (Fildes et al. 2015; Rizzi et al. 2014), the corresponding result was 35–57%. Publication 2 complements previous research related to the evaluation of AEB systems' safety potential in pedestrian and intersection crashes, as the number of previous studies is low. In addition, the range of crash reduction potential involving pedestrian crashes (25–87%) is wide in previous studies (Haus et al. 2019; Lubbe & Kullgren 2015). In this study, the corresponding number was 45%, which complements the understanding of AEB systems' potential to prevent pedestrian crashes.

The safety potential of lower levels of driving automation has been addressed in many studies. In this thesis, the safety potential of the key systems (i.e. LKA, AEB, and ACC) were evaluated considering Finnish circumstances and conditions, which partly differ from those in previous studies. In addition, it was possible to confirm whether the studied vehicles were equipped with LKA, AEB, or ACC, which supported the analysis. Only one vehicle involved in a crash in Publication 1 was LKA-equipped. In this case, the vehicle was a secondary party in the crash, and hence LKA was not able to prevent the collision. In the crash data, which was analysed in Publication 2, none of the vehicles were equipped with AEB or ACC systems.

The analyses presented in Publications 1 and 2 were based on a case-by-case study and data on in-depth investigated crashes, which enabled the inclusion of certain variables in the same analysis, something not generally possible in previous studies. Weather conditions have typically been included in the analyses for the evaluation of camera and radar sensor functionality, but each of the other essential factors – such as estimated vehicle speed, driver-related risks, and lane marking visibility – have not usually been addressed in previous research. For instance, vehicle speed has an impact on the AEB system's operation, and the presence and visibility of lane markings are required for the LKA system's proper operation. Accident investigation teams have estimated the vehicle speeds as a result of investigations, interviews, and reconstructions. The visibility of the lane markings was confirmed by using scene photographs. It is also important to be aware of driver-related risks, because the LKA system can be overridden. For example, intentionally caused crashes cannot be avoided by LKA. Using investigations, interviews, and autopsy findings, the investigation teams identified driver-related risks, such as intentionally caused crashes, drivers suffering a sudden illness, and driving under the influence of alcohol or drugs. By using data on these variables, the publications compliment previous research and rationalise the results.

As another essential factor and a difference to some previous studies, this thesis includes an evaluation of the impacts of additional policy actions and recommendations involving vehicle and infrastructure requirements. For instance, it was found that deficiencies in the visibility of lane markings (in 44% of studied cases) and some driver-related risks (47%) were typical factors that would have prevented the activation or proper operation of the LKA system. In terms of the operation of the AEB and ACC systems, excessive speed was a typical factor (44%), which would have deteriorated the systems' potential to prevent crashes. Related to these findings, evaluations were made regarding the potential to add, e.g. digital lane markings to the whole road network to enhance the safety potential of LKAs and the introduction of ISA together with AEB and ACC. These analyses found that the safety potential of the studied systems could hypothetically be increased substantially by introducing additional vehicle and infrastructure requirements.

The safety potential of lower levels of driving automation sounds almost too good to be true when considering the existing knowledge and the results in this thesis. Why have ADASs not been introduced in most cars in different countries given the safety potential? Several active safety systems will become compulsory in new cars in the EU within a few years (European Commission 2019b), but the renewal of the car fleet is slow. According to one estimation, 60% of the vehicles will be AEB-equipped in 2030 (Tan et al. 2020). In this thesis, the results are based on the maximum safety potential assuming that each vehicle would be equipped with the systems, even though this is not the current situation. However, the results encourage users, vehicle manufactures, and decision makers to expedite the use of ADASs.

It should be acknowledged that vehicles equipped with active safety systems do not guarantee the realisation of the safety potential. The systems should also be utilised safely. The vehicle manufacturers' role in making the system easy to use is essential, but the driver's responsibility in utilising these systems safely is a key factor. For instance, the sensitivity analysis in Publication 1 indicates that exceeding the speed limit or driving under the influence of alcohol or drugs are part of many fatal head-on and single-vehicle crashes. These factors would likely diminish the estimated safety potential of LKA (27%), because the driver may not be willing or able to utilise the LKA system as it has been designed. Driver behaviour and human factors are not only problematic in current road transport where only a few cars are equipped with ADASs, but they are also topical when ADASs become more common. Discussion on the safe utilisation of ADASs should also include the fact that some systems (e.g. LKA and ACC) can be turned off by the driver. When the systems are turned off, the safety potential would be equal to cars without such systems. An example from the United States revealed that LKA was turned off in 55% of LKA-equipped cars (Reagan et al. 2018). The corresponding usage level could theoretically be equal to about a 50% reduction in the maximum safety potential, which would cause a crash reduction potential of 13–14% instead of 27% in the case of the LKA system in Publication 1.

The realisation of the safety potential of different active safety systems is difficult, because many factors should be favourable for the proper operation of the systems. Driver behaviour, weather conditions, road infrastructure, and the system's operational capability should all be favourable to achieve the maximum safety potential. Consequently, the elements of a pre-crash event – such as human behaviour, vehicles and equipment, and the environment, as described in the

Haddon Matrix (WHO 2004, pp. 12–13) – should all be considered in the development of ADASs.

5.2 High safety potential of HAVs includes uncertainties

Compared to lower levels of driving automation, higher levels (i.e. HAVs) provide additional possibilities for safety promotion by preventing crashes involving motor vehicles. So far, HAVs have mainly operated under test environments and with supervisors inside the vehicles. As knowledge of operation in actual traffic situations is deficient compared, e.g. to ADASs, understanding of the crash reduction potential of the HAVs is somewhat deficient. HAVs likely change interaction procedures with other road users when compared to human drivers (Uttley et al. 2020), so high levels of driving automation generate more open questions compared to the lower levels. Publications 3 and 4 aim to increase understanding of encounters between HAVs and vulnerable road users.

Publication 3 indicates that 70–93% of fatal crashes between pedestrians and passenger cars could theoretically have been avoided had the cars been replaced by HAVs. The range is due to the applied approach, i.e. whether pedestrian safety (93%) or efficient traffic flow (70%) is prioritised. The results are in line with previous studies, which have concluded that HAVs could prevent 36–98% of pedestrian-car crashes (Combs et al. 2019; Detwiller & Gabler 2017). Publication 3 complements the previous research and brings a new outlook on the potential to prevent pedestrian crashes through HAVs, because the number of previous studies is small and the range of the potential safety impacts has been wide. Publication 4 notes that necessary features of HAVs related to operation and design would also promote safety from the perspective of cyclists when interacting with HAVs rather than human drivers. The features of HAVs have not typically been focused on in previous studies other than in relation to indicating intentions or identifying other road users. Therefore, the approach in Publication 4 of assessing potential encounters between HAVs and cyclists complements previous studies. It should be added that HAVs are assumed to operate faultlessly in this thesis, which has also typically been the assumption in previous studies. However, faultless operation may not be the case in real traffic situations.

One interesting issue to discuss is the different ambitions at play in the transport system (e.g. traffic flow, travel time, environmental effects, safety, etc.) that users, technology developers, and policy makers are interested in. How these ambitions are balanced and optimised are among the key factors related to HAVs' operation and safety impacts, which is disclosed in Publication 3 from the pedestrians' perspective. A comparison study of two different ambitions – i.e. prioritising either pedestrian safety or efficient traffic flow in HAV operation – was judged to be a novel approach in evaluating the possible encounters between HAVs and pedestrians.

The optimisation of different ambitions is connected to road safety targets set by the EU. Fatalities and serious injuries should be halved between 2020 and 2030 and cut to zero by 2050 (European Commission 2019a). Safer vehicle and infrastructure and lower speeds are listed among others as enabling factors. However, the relationship between the road safety targets and ambitions in the road transport system is somewhat inconsistent. It seems that road safety is not currently prioritised over other ambitions (e.g. traffic flow), which makes the ambitious targets difficult to meet. For instance, in a more safety-oriented transport system, speeding would be precluded, pedestrians and cyclists would not intersect with motor vehicles without raised intersections, and driving under the influence of alcohol would be prevented. Technology and transport planning already enables intervention regarding these risks. How likely is it that these risks would be eliminated when HAVs become more common when considering that drivers can override the automated driving system? Furthermore, how likely is the realisation of the high hopes for the future in terms of the safety potential of HAVs when the current risks cannot be handled? This is not to imply that HAVs would not promote road safety at all, but the ambitious targets would be difficult to meet. The realisation of Vision Zero (i.e. no fatalities or serious injuries) would also require technical and structural ways to influence driver behaviour.

The realisation of safety potential is not only about the driver's ability to override the system; it is also about the HAV's capability to operate in different situations. Publications 3 and 4 discuss the potential difficulties regarding the intention estimation of pedestrians and cyclists. A human driver is relatively capable of assessing other road users' intentions, but an HAV may not be as skilful in the initial stage of the introduction (Botello et al. 2019). According to Publication 4, HAVs should be able to assess cyclists' intentions in cases where the cyclist is obliged to yield, because HAVs and other road users expect cyclists to give way in these cases. If the cyclist does not give way, the HAV should be able to anticipate this action before the cyclist enters the intersection. HAVs could rely on the ability to come to a full stop by quickly decelerating after the cyclist enters the roadway from a cycle path in front of the HAV, but there may not always be enough time to avoid a collision.

Prioritising safety over other ambitions in HAV operation could possibly cause more decelerations and stops when pedestrians and cyclists are identified compared to a human driver's behaviour in corresponding situations. Conversely, when prioritising efficient traffic flow, the HAV would not decelerate before the pedestrian steps onto the roadway, even though an earlier deceleration would sometimes be needed to avoid a collision. The latter design approach would increase the responsibility of other road users to ensure safe interaction with HAVs, because HAVs would not be able to prevent all conflicts and collisions. Consequently, an approach that is closer to prioritising safety – as opposed to prioritising efficient traffic flow – may be needed for the public acceptance of HAVs, even though it would have an impact on the flow of traffic. The design and operation principles of HAVs should be widely discussed, because they will likely have notable impacts on the safety potential. For instance, in order for it to be possible to avoid almost all pedestrian crashes with HAVs, traffic flow would have to be compromised.

As many car manufacturers and technology companies are developing automated driving technology, difficulties involving intention estimation can probably be solved after the initial stage of HAV introduction. However, it will likely take years until fully automated vehicles (SAE level 5), which can operate on all roads and in all conditions, will be rolled out. The roads are occupied by vehicles of different levels of driving automation for a long time, which can pose additional safety threats. HAVs (level 4) can be programmed to obey yielding rules, but the drivers of conventional vehicles may not always follow the rules strictly, which should be considered in the design of the HAVs. One of the most important tasks of all is to ensure the safety of pedestrians and cyclists during the development of vehicle technology. Especially in urban environment, where walking and cycling are popular, lower speed limits (e.g. 30 km/h) would support safer encounters between different road users. Lower speeds would also enable more time for interaction and decision making.

Another aspect to consider when evaluating the potential safety impacts of HAVs is the overall impact on the transport system, including indirect effects (Kulmala 2010). For instance, it is widely acknowledged that traffic safety can be examined with dimensions of exposure, risk, and consequence (Nilsson 2004, p. 19). In addition to the risk that is focused on in this study, possible changes in exposure and consequences may affect the overall impact. Some studies have argued that driving mileage may increase when HAVs become more common, because people without a driving license have better access to the car and the time cost of travel is lower (Jones & Leibowicz 2019; Liljamo 2020, pp. 25–26). However, many countries in

Europe aim to promote sustainable transport modes (ETSC 2020), which may decrease the modal share of motor vehicles. Shared mobility as a potentially rising phenomenon may have similar effects. Based on the information currently available, it is unclear whether the number of kilometers travelled by motor vehicles will increase or decrease. The third factor, the consequences, relates to the passive safety of vehicles, where it is likely to be less important whether the vehicle is controlled by an automated driving system or a human. Based on this information, it seems that the most significant safety-related impact of HAVs relates to a reduction in crash risk.

The implementation of HAVs (level 4) is likely to be beneficial once HAVs are considered safer than driver-managed vehicles. Even though the maximum safety potential addressed in this thesis and in previous studies cannot be realised until full automation (level 5), HAVs would improve road safety by preventing many serious traffic crashes. Early warnings on the partial negligence of road safety in HAV operation arose when a pedestrian was killed after a collision with a vehicle equipped with a developmental automated driving system in the United States in 2018 (NTSB 2019). Although the crash occurred during a test drive, this illustrates that it is not easy to prevent all crashes with HAVs. At the very least, road safety should be prioritised more.

5.3 Assumptions and limitations

The lack of proper real-world data on the activation and operation of driver assistance systems in traffic situations is a typical limitation in studies involving the potential safety effects of ADASs (Sternlund 2020). This is partly due to the fact that the number of vehicles equipped with these systems is relatively small (Lähderanta 2018). Consequently, the operational requirements and limitations of the systems were based on available information in the user manuals of four different car models.

The results are based on the maximum safety potential, which assumes that every vehicle would be equipped with LKA, AEB, and ACC, and these systems would always be turned on. This is a theoretical approach to the safety potential considering that only some vehicles are equipped with these systems in the real-world and the usage rate of the systems may be low. In addition, as the data set utilised in this thesis included only fatal crashes, it is necessary to disclose that the probability of older vehicles being involved in a fatal crash is typically greater than for newer vehicles (NHTSA 2013). Even though newer vehicles are more likely to be equipped with

ADASs, which diminishes the probability of a fatal crash, the addressed safety potential in this thesis and the high usage rate of ADASs are unlikely to be easily achievable in the near future, because the number of older vehicles without ADASs is large. Older vehicles (i.e. those aged more than 5 years) without ADASs are likely to be on the road and involved in fatal crashes for a long time, because car fleet renewal is relatively slow.

In Publication 1, loss of control crashes were assumed to be preventable due to the LKA system, even though electronic stability control (ESC) instead of LKA is designed to prevent these cases (Høye 2011). However, lane departure crashes at high speeds in relation to speed limits are usually loss of control cases, and hence probable cases related to the loss of control could be controlled in the sensitivity analysis where cases involving speeding were considered. This enabled the specification of cases that ESC could potentially have prevented. The sensitivity analysis revealed that exceeding the speed limit by 10 km/h or more was associated with almost half of the crashes that were analysed to be potentially preventable by the LKA system. If excessive speed (i.e. exceeding the speed limit by 10 km/h or more) was assumed to prevent the LKA's proper operation, speeding could theoretically have prevented the LKA's proper use in 44 of the 99 cases that were analysed to be potentially preventable by the LKA system. The level of speeding that would be too much for LKA operation depends on the individual case, and hence it cannot be concluded that the number of preventable crashes would have been reduced by 44 (i.e. from 99 (27%) to 55 (15%) crashes) when adding exceeding the speed limit to the analysis. However, high speed in relation to the speed limit and traffic situation likely increases the possibility of loss of vehicle control (Laaportti & Keskinen 1998).

In Publication 2, the main assumptions about the AEB and ACC systems' operation related to speed. Intersection and pedestrian crashes were evaluated to be potentially preventable if the speed was 60 km/h or less. In rear-end crashes, the speed difference between the involved vehicles should be less than 60 km/h. The depicted speed and speed difference as threshold values for the crash avoidance were based on findings in previous studies, as was discussed in section 2.2. According to the previous studies, crash avoidance was considered unlikely if the vehicle speed was higher than 60 km/h in pre-crash events. Considering that AEB is designed to apply the brakes at the last possible moment before a potential crash situation and ACC is not able to cause a strong deceleration, the speed difference between the involved vehicles was applied as a determining factor in rear-end crashes instead of vehicle speed. A more detailed analysis of distances in pre-crash events was not applied to intersection and pedestrian crashes because the AEB system applies the brakes at the last possible moment. Consequently, the brakes are not always applied when the other involved road user is first recognised. The sensors were always assumed to recognise other road users, even though it was not always possible to guarantee the ability of the camera or radar sensors to recognise other road users.

Weather conditions heavily influence ADAS operation. Adverse weather conditions, such as snowfall, wet snow, and fog, were considered as obstacles for LKA, AEB, and ACC operation in Publications 1 and 2. In addition, an icy road surface was a limitation for the AEB and ACC systems' operation in Publication 2, because it was considered to have an impact on stopping distance. Weather conditions are well known obstacles for current ADAS systems, but it is possible that weather conditions will not be obstacles in the operation of more advanced ADAS systems. According to results, weather conditions were the sole reason or one of the many reasons preventing the systems' operation in 32 of the 479 (364+115) studied cases. Consequently, if it was possible to operate in adverse conditions, the safety potential would be greater, but the impacts would not be as effective as with some other system- or infrastructure-related improvements, as was shown in sections 4.1 and 4.2. In Publications 3 and 4, weather conditions were not assessed as factors preventing HAV operation, even though adverse weather is an obstacle for many automated driving systems currently being tested. However, technology is developing rapidly, and some companies are developing HAVs that can operate in adverse weather conditions.

In Publication 3, it was assumed that an HAV is not able to anticipate pedestrians' intentions, e.g. to cross a street, even though the HAV would be able to recognise the presence of nearby pedestrians. The assumption is based on the findings of previous studies, and it is estimated to be an essential issue in the initial stage of HAV introduction. The lack of proper intention estimation remains as an uncertain factor, e.g. in terms of how it is going to influence actual encounters with pedestrians and other road users.

Results did not consider the potential new crashes that HAVs could cause. In Publication 3, new safety risks are discussed when prioritising different ambitions in HAV operation, but without evidence on the HAV operation, it is difficult to make a more detailed evaluation on the type and number of crashes that HAVs may cause. This limitation is also central in previous studies (e.g. Combs et al. 2019; Fagnant & Kockelman 2015) that have evaluated the potential safety effects of HAVs. Some simulation studies (e.g. Tafidis et al. 2019) have provided estimations on the total number of crashes or conflicts after HAV implementation, but the defined parameters of the HAV, which cannot currently be determined precisely enough, likely have a major impact on the results.

The errors that HAVs can make are another topic that was difficult to consider. HAVs are expected to diminish or remove the presence of human factors by being responsible for dynamic driving tasks, which could possibly reduce the number of crashes. However, the removal of all human errors is difficult, because people are responsible for designing and programming HAVs. In addition, people are usually poor supervisors of automation systems (Parasuraman 1987), and hence, errors and conflicts involving HMI can cause new safety risks compared to the current situation with driver-managed vehicles. If HAVs are designed in a way that the driver's role as a supervisor is important (i.e. takeover requests from a system to a driver are common), the safety potential of HAVs is likely going to be less than has been evaluated in this thesis.

5.4 Validity and reliability

The quality of this thesis can be examined by assessing its validity and reliability (Leung 2015). The thesis mainly applies a qualitative research method, i.e. each crash is analysed individually to identify the necessary factors affecting the operation of driver assistance or automated driving systems. Although the total number of analysed cases is large and key issues and factors are measurable, which are common features in quantitative research, the characteristics of qualitative research are clearer due to the effect of the work done by the researcher on the credibility of the results (Golafshani 2003). The analysis of the cases was not only the analysis of variables defined by the accident investigation teams; the study also includes a more detailed evaluation of the cases. For instance, analyses were made by examining crash descriptions and scene photographs.

The validity and reliability of the qualitative research can be tested with different principles and tests, i.e. construct validity, internal validity, external validity, and replicability. The construct validity assesses which data should be gathered and how they should be gathered. It also refers to the degree to which the data and methods measure the studied phenomenon. Internal validity indicates the credibility of the study. It refers to the degree to which it can be concluded that an identified relationship is causal. External validity assesses the generalisability of the results. Reliability refers to the replicability of the study and the findings (Golafshani 2003; Hiltunen 2009; Johnson 1997; Leung 2015; Simon & Goes 2020).

In terms of construct validity, it can be stated that data on in-depth investigated crashes enabled the evaluation of the hypothetical operation of ADASs and HAVs in the studied cases. For the purpose of this study, the applied data source is better than other available sources in Finland, because the data include a great variety of different crash characteristics and risk factors identified by the multidisciplinary accident investigation teams. The data source is of high quality in the global context too, as, e.g. almost all fatal crashes are investigated in depth in Finland (Lehtonen 2020), so statistical methodologies to handle poor coverage of the data are not needed. The applied data and the case-by-case study enabled the aim of the study to be addressed, namely what the potential is to prevent fatal crashes in Finland by introducing passenger cars equipped with driver assistance or automated driving systems. When analysing the results, it is assumed that the characteristics of the crashes and other situations which may lead to crashes will mainly remain similar in the future, which enables the application of the findings on the potential to prevent crashes in the future.

The credibility (internal validity) of the thesis is built on the basis of the generalisation of the studied ADASs and HAVs. The results represent the best possible situation in terms of market penetration rates, i.e. each motor vehicle is expected to be equipped with the studied systems. In addition, the systems are expected to be always turned on and used appropriately. The credibility also depends on the potential behavioural adaptation of the drivers and other road users. Even when a vehicle is equipped with safety systems and the systems are turned on, the driver can override the systems with active driver input, such as a steering or an acceleration movement (Koisaari et al. 2020). In some cases, it was possible to recognise the driver input. However, it was not usually assumed that the active driver input would prevent the systems' operation, because the driver's behaviour may be different when the vehicle is equipped with an LKA, AEB, or ACC system and the systems are turned on. The driver input was solely considered when assessing the safety potential of systems related to intentionally caused and overtaking crashes, since the safety systems were not assumed to change the driver's decision, e.g. to commit suicide. However, it should be noted possible changes in the driver behaviour due to ADAS or, systems' possible inoperability or malfunction can possibly cause new crashes.

Kulmala (2010) has suggested that behavioural adaptation, e.g. while the LKA and AEB systems are turned on, could slightly diminish the direct safety impact (i.e. the engineering effect) of these systems. In this thesis, it is noted that drivers may change their behaviour when, e.g. LKA is turned on, which could possibly affect the results. As clear numerical evidence on the detailed impacts of the behavioural adaptation that could be used in the evaluation are not available, these potential impacts are difficult to include in the thesis. However, factors related to the driver's behaviour in crash situations were considered in the sensitivity analysis. For instance, driving under the influence of alcohol or drugs and at excessive speeds compared to the speed limits were considered as potential factors that could influence the LKA system's proper operation. These factors would not likely prevent the LKA's operation in each case, and hence these factors were considered in the sensitivity analysis.

Behavioural adaptation and other changes in the road transport system are more difficult to account for when evaluating the safe operation of HAVs. The potential other factors that need to be considered concern other road users than drivers, because the drivers or the passengers in the HAVs do not have any responsibilities for the dynamic driving tasks in the analyses in this thesis. Publication 3 presents a comparison of two different ambitions (i.e. efficient traffic flow vs traffic safety in HAV operation) to assess some of the potential changes in the road transport system from the perspective of safety after the introduction of HAVs. One option is that HAV operation should be designed differently compared to the operation of driver-managed vehicles in current road traffic if the HAVs cannot reliably assess other road users' intentions. The consideration of the potential wider impacts and changes related to the road transport system increase the internal validity of the thesis. The internal validity could be further increased by better understanding the behavioural adaptation of drivers to ADAS and other road users' behavioural adaptation in encounters with HAVs. As the results on the potential of ADASs and HAVs to prevent crashes should be treated as the maximum safety potential, the findings must be tempered with the acceptance that some factors (e.g. behavioural adaptation or lower market penetration rates than expected) can reduce the number of preventable crashes. In addition, changes in the number of kilometers driven may have an impact on the overall safety effects, as is discussed in section 5.2. Changes in mileage are likely to be more significant at higher than lower levels of vehicle automation, because the driver is still responsible for dynamic driving tasks at the lower levels.

Generalisability (i.e. external validity) is not typically the most important object of qualitative research (Johnson 1997). Typically, the number of analysed cases is small in qualitative research, but in this thesis the number of cases was relatively large, especially in Publications 1 and 2. A qualitative case-by-case study was applied, which enabled the in-depth analysis of crash-related factors. The number of analysed cases improves the generalisability.

The comparability of results with previous studies also improves the external validity. In particular, the results involving ADASs are comparable with previous studies, although the methods used are different. Thus, the analysis made with the Finnish crash data would appear to be generalisable. So far, only a few studies have assessed the potential of HAVs in preventing crashes with pedestrians and cyclists, and thus the amount of comparable studies is small. HAV operation is also studied in the context of Finnish crash data and the road transport system. The results are mainly applicable in other European countries and countries with winter conditions (e.g. a snowy road surface). In order to make the results more generalisable, the traffic cultures in different parts of the world should be considered. In addition, the number of analysed cases is relatively small in Publications 3 and 4. Even though this is a common issue in qualitative research, it can diminish the comparability of the results. However, the crashes and crash types in the data are comparable with larger sample studies, which improves the external validity. Since HAVs are not common in any part of the world, we cannot know the exact parameters and details of automated driving systems before HAVs become widespread. Consequently, a larger data set would not necessarily provide a much better outlook on the potential safety effects, even though the results could be slightly different in other countries with other crash data and HAV features.

The replicability of the results is built on the high quality of the applied data. The crash data can be considered high quality, as they are based on investigations made by the accident investigation teams and such investigations are mandated by law in Finland. Although the members of the teams are experts in their disciplines and trained for such investigations, there may be differences in performance between the teams. The impacts of the potential differences are considered to be minor due to the long-term development of the investigation methods. The crash data can be judged as reliable and they contain several factors and essential information that are needed in the evaluation.

The researcher’s contribution may also have an impact on reliability. The assessment principles related to the potential of ADASs to prevent crashes are clear and unambiguous, and consequently, the importance of the researcher’s role in terms of the analysis and results remains small, which improves replicability. When assessing the visibility of lane markings using scene photographs, interpretations made by the researchers are needed, e.g. whether the lane markings are fully visible, partially visible, or invisible. The LKA system’s proper operation usually requires fully visible lane markings, but the results are also reported for when the system could operate by detecting partially visible lane markings.

When evaluating the assumed operation of HAVs and their potential to prevent collisions with pedestrians and cyclists, interpretations were usually needed. For instance, the distance between the collision point and the point at which the pedestrian or the cyclist entered the roadway from a pavement or a cycle path was evaluated for TTC analysis based on the available data, i.e. crash descriptions and variables. In addition, the speeds of the cyclists and the pedestrians were usually assumed speeds, because the investigation teams could not usually estimate the speeds of these road users. These factors may have an impact on the reliability of the results, but the results were considered in a way that the avoidance of the crash was determined unclear when TTC was close to 1.5 s (i.e. TTC = 1.5 s represents a high collision risk), which prevents misinterpretations of the results due to possible uncertainties in the output values.

6 CONCLUSIONS

6.1 Key findings

The results of the thesis show that the usage of lower and higher levels of driving automation instead of driver-managed vehicles could be an important road safety measure. In answer to research question 1, key systems (i.e. the combination of LKA, AEB, and ACC in all passenger cars and the systems are always on) could potentially have prevented 29% of fatal passenger car crashes in Finland in 2014–2016. Consequently, 146 fatal crashes and 163 fatalities could have been avoided in these years. The crash cost savings would have been about 450 million euros. Although the crash reduction potential reflects the best possible situation, i.e. when each vehicle is equipped with the systems and errors in the recognition of other road users do not occur, it is worthwhile promoting the use of ADASs. Making these systems more common in the car fleet would help to achieve the target of halving the number of fatalities and serious injuries by 2030.

In response to research question 2, driver-related risks (e.g. intentionally caused crashes and crashes resulting from sudden illness) and a lack or the poor visibility of lane markings were found to be essential factors preventing LKA systems from preventing fatal crashes. Excessive speed would have been a key factor in preventing the proper operation of AEB and ACC systems.

The implementation of policy actions and recommendations regarding the infrastructure and vehicle requirements would increase the number of potentially preventable crashes. The possibilities of promoting the safety potential were assessed to answer research question 3. For instance, digital lane markings that the LKA system could follow would have almost doubled the number of hypothetically preventable single-vehicle and head-on crashes (i.e. 52% of the crashes are preventable) compared to the current situation where physical lane markings (27%) are not always fully visible. By introducing ISA with AEB and ACC systems to prevent exceeding the speed limit, 52% of the rear-end, intersection, and pedestrian crashes could potentially have been avoided compared to a crash reduction potential of 41% without the ISA system. When ADASs are developed towards automated driving, the number of potentially preventable crashes could be further increased. By removing the possibility of the driver to override the studied systems and by improving the AEB system's ability to recognise other road users at intersections, intentionally caused crashes and additional collisions with pedestrians and cyclists could theoretically have been avoided. Without considering the technical difficulties and uncertainties in the introduction of such advanced systems, almost all of the studied cases could theoretically have been avoided.

Pedestrian-car and cyclist-car crashes were analysed in more detail from the point of view of HAVs, i.e. which crashes could be avoided and what kind of requirements would be needed if driver-managed vehicles were replaced by HAVs. In terms of research question 4, the results show that HAVs could potentially have prevented 70–93% of the fatal pedestrian-car crashes. The range is due to the applied design principles in HAV operation. Regarding the avoidance of cyclist-car crashes, the required features in HAV operation were formed to answer research question 5, and the features were evaluated from the perspective of crash avoidance to answer research question 6. A feature to assess cyclists' intentions was found to be important when cyclists have an obligation to yield at intersections. In situations where the HAV has an obligation to yield, the HAVs could possibly make encounters with motor vehicles more predictable compared to the current situation if HAVs obey priority rules more carefully than human drivers. However, a feature to always recognise other road users (and cyclists in this case) is the most important function. Considering the typically higher speeds of cyclists compared to pedestrians, HAVs may not be able to prevent as many car-cyclist crashes as car-pedestrian crashes if driver-managed cars were replaced by HAVs. Technology and interaction procedures are still developing, so the actual safety potential cannot be evaluated without uncertainties. Prioritising safe encounters with pedestrians and cyclists – i.e. the HAV decelerates for safety's sake when approaching a pedestrian crossing – to the detriment of efficient traffic flow is a key factor that this thesis notes as a potential solution to enhance the safe operation of HAVs.

The interaction procedures of HAVs should also be evaluated from the perspective of pedestrians and cyclists. HAVs can possibly make encounters more predictable compared to human drivers by obeying the rules, but non-verbal communication between humans has been found to be important (Uttley et al. 2020). Some studies (e.g. Ackermann et al. 2019) have suggested external messages, such as light or text signals, to indicate the HAV's intentions to other road users. When planning to cross a street, pedestrians could also rely on signs in HAV operation such as changes in speed and trajectory. External signals or signs do not necessary ensure a safe encounter if the pedestrian or cyclist cannot interpret the signs or does not notice the approaching HAV. In addition, the HAV does not always recognise other road users early enough. These critical situations should be further examined to guarantee safe interactions between HAVs and other road users.

In the future, it should be easier to analyse the actual operation data of active safety systems, because ADASs are becoming more common in new vehicles. It is recommended that more evidence on the usage and operation of the systems is analysed to evaluate whether the systems have prevented potential crashes and operated as they have been designed. Cooperation with car manufacturers is also called for so that traffic safety experts and crash investigation authorities can analyse existing pre-crash data on vehicles that are involved in (fatal) crashes. The amount of fatal crashes in which a passenger car equipped with LKA, AEB, or ACC was involved was small in Finland in 2014–2016. Although these systems are expected to prevent crashes, more crashes involving SAE level 2 vehicles are expected to occur when the systems become more common. It should be acknowledged that vehicles equipped with these systems may also be secondary parties in crashes. The operation of the systems should also be investigated from this perspective. When more data are available, it is important to examine whether the systems have been turned on and operated correctly.

This thesis provided an outlook on the potential of driver assistance and automated driving systems to promote road safety. The possibilities and needed requirements to make Vision Zero achievable are also discussed from the perspective of the increasing use of vehicle automatisation. The results are specific to Finland, but the findings can also be applied in other countries with a similar transport system. The results on the safety potential of ADASs in particular can be applied to countries with similar winter conditions. The publications indicate that the crash reduction potential is relatively great. Systems such as LKA, AEB, and ACC could potentially have prevented almost a third of the fatal crashes in Finland in 2014–2016, which is a result comparable with previous studies in other countries. The results also indicate that HAVs compared to cars equipped with ADASs could potentially provide greater safety impacts in encounters with pedestrians and cyclists. However, the results on both driver assistance and the automated driving systems' safety potential reflect the best possible scenario in terms of driver behaviour, technological robustness, and market penetration rate. It is expected that the addressed results cannot be met in the near future. However, progress towards a future in which as many motor vehicles as possible are equipped with advanced driver assistance systems or replaced by HAVs is recommended from a safety standpoint.

The deployment of active safety systems is probably among the most effective road safety measures in the short-term, but ADASs do not remove the important role of human factors. In the lower levels of driving automation, factors related to driver behaviour, such as safe speed and the appropriate use of systems, have an essential impact on the proper operation of ADASs. Adverse weather conditions are also among the operational restrictions, but weather conditions would rarely have prevented the systems' proper operation in the studied cases.

6.2 Practical contribution

By considering the analyses and the findings involving the potential to prevent crashes with driver assistance systems, the role of different stakeholders in realising and improving the operation of the systems can be identified. Public authorities, policy makers, and vehicle manufacturers should promote the introduction of ADASs and consider whether the systems should be turned on by default. Drivers should identify their roles and utilise ADASs in an appropriate way and recognise the limitations of the systems. Vehicle resellers also have an important role in communicating the safe use of the systems. Lower speeds, which can be supported by introducing lower speed limits and ISA systems in new vehicles, are likely to enable the more appropriate functioning of the systems and better safety potential. To improve the operation of LKA systems and to prepare for the introduction of HAVs, road authorities should prepare high definition maps and digital lane markings and ensure the high quality of painted lane markings. High-quality road and winter maintenance are important for the operational requirements of the LKA system.

HAVs are constantly being developed, but the HAV operation may not be as proficient as driver-managed vehicles in the initial stage of introduction. To enable the safe operation of HAVs and to promote current road safety, speed limit reductions and more careful driving patterns may be needed. Safe integration of HAVs into the current transport system should be planned comprehensively. An integrative regulation may also be necessary to ensure that HAVs from different manufacturers are safe enough for road traffic. As the ambitious crash reduction targets aim to halve the number of road fatalities and serious injuries by 2030 and cut the number to zero by 2050, a holistic road safety strategy is needed to ensure that the targets are achievable, and ADASs and HAVs should be part of the strategy. Policy measures, such as lower speeds and more ambitious infrastructure requirements, would allow both HAVs and human drivers to operate more safely. Although the supporting actions would not be needed to ensure HAV operation, actions to prioritise safety are needed to make crash reduction targets achievable.

The discussed wider approach to the safe operation of HAVs would not only enable their safe operation, but would also support the safe behaviour of driver-managed vehicles. The results and arguments involving a more safety-oriented road transport system are addressed to decision makers and transport system authorities. The deployment of vehicles equipped with new active safety technology does not seem to be enough for ambitious crash reduction targets, and other measures are therefore needed. The case-by-case analysis of the crash data involving driver assistance and automated driving systems provides valuable information for technology developers and car manufacturers. The analyses indicate what kind of cases cannot be prevented or would be difficult to prevent by current ADASs and HAVs; thus, the results support the development of more advanced systems. As an outcome of this thesis and a message to politicians and public authorities, it can be concluded that vehicle automation will be an important part of a safe transport system in the future, but it cannot be the only solution in promoting road safety.

6.3 Methodological contribution

Previous studies have typically not been able to evaluate the safety potential of driver assistance systems by analysing data on in-depth investigated crashes that include almost all fatal crashes in a single country. In Finland, crash investigation is mandated by law, which has made it possible to include almost every fatal crash having occurred during the years studied. It is uncommon among scientific research that a qualitative case-by-case study can be used to indicate the potential to prevent fatal crashes on a national level without applying statistical methodologies to handle the poor coverage of the data. In addition, the data and method include several essential factors that are needed to properly assess the systems' safety potential, which rationalise the results and complement previous studies. In particular, it was possible to assess the visibility of lane markings at crash scenes by using photographs, which is an important factor to consider for the operation of LKA systems. In addition, it was possible to use information on the estimated speeds for the evaluation involving LKA, AEB, and ACC systems. The speeds were based on investigations made by the accident investigation teams. Estimated speed is more accurate for the analysis rather than using the road-specific speed limit as the assumed speed.

So far, only a few studies have provided detailed analyses on HAVs' safety potential. More knowledge is needed especially on HAVs' potential to prevent crashes with pedestrians and cyclists; thus, this thesis aimed to add novel knowledge regarding HAVs' potential encounters with pedestrians and cyclists. Analyses on pedestrian-car and cyclist-car crashes provided more understanding of HAVs' available time to react and avoid collisions with pedestrians and cyclists. In addition, the needed operational features of HAVs were evaluated in possible encounters with cyclists. The thesis also discloses fundamental ambitions in daily mobility, such as travel time, efficient traffic flow, safety, etc., and the balance between these ambitions. Considering potential incompleteness in HAV operation, it is suggested that road safety should be prioritised over other ambitions in political decisions and infrastructure requirements, because the transport system may otherwise be in conflict with the principles of Vision Zero, which has been adopted in many countries. For instance, lower speed limits and the removal of conventional intersections (i.e. other than raised crossings) in important urban streets where motor vehicles and vulnerable road users meet are examples of a road transport system that would more greatly prioritise safety.

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PUBLICATIONS

PUBLICATION
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The safety potential of lane keeping assistance and possible actions to improve the potential

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The Safety Potential of Lane Keeping Assistance and Possible Actions to Improve the Potential

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***Abstract*—Before widespread automated driving, driver assistance systems become more common and can deliver safety benefits. This study focuses on current and future lane keeping assistance (LKA) systems and their potential safety effects by analysing real-world crash data and LKA's possibilities to prevent fatal passenger car crashes. The analysed data includes in-depth analysis of 364 fatal head-on and single-vehicle crashes in Finland. According to statistical analysis, 27% of these crashes could potentially have been prevented had currently available LKA been deployed. In this study, many issues are examined related to the lane markings' visibility, infrastructure, weather, and driver-related risks, which rationalise the results, compliment previous research, and highlight possibilities to increase the safety potential of LKA. Related to the lane markings' visibility, safety potential could be improved by allocating more resources to road maintenance and to snow clearance. Advanced LKA enabling exploiting digital lane markings could hypothetically almost double the safety potential as weather conditions or the visibility of lane markings would not restrict LKA's operation. While the driver is still in charge of driving tasks, driver-related risks are difficult to manage and the crashes caused intendedly or due to driver's attack of illness are not preventable by current LKA systems.**

***Index Terms*—Digital lane markings, head-on crashes, lane keeping assistance, LKA, single-vehicle crashes.**

I. Introduction

ROAD traffic is estimated to mainly consist of driverless vehicles instead of conventional vehicles after a few decades [1]. Before the era of automated driving, vehicles with advanced driver assistance systems (ADAS) become more common. With these systems assisting, the human driver is still responsible of driving tasks. ADAS promote road safety by decreasing the amount or mitigating the consequences of crashes [2]. In the European Union, most of the fatal car crashes are single-vehicle or head-on crashes caused by e.g., drift-out-of-lane cases in which preventive ADAS could have an effect [3]. Particularly, the lane keeping assistance (LKA) system is suitable for preventing aforementioned crashes [4]. To decrease the amount of fatalities and seriously injured on roads, European Commission [5] has proposed that new vehicles should be equipped with assistance systems including LKA.

By detecting lane markings and steering the vehicle, LKA is able to prevent single-vehicle and head on-crashes [4]. As an example, Volvo [6] describes the principle of its LKA solution to be based on camera, which reads the side lines of the road or lane, and if the car is about to cross a side line then LKA will actively steer the car back into the lane with a slight steering torque in the steering wheel. If the car reaches or crosses a side line, LKA will also alert the driver with vibration in the steering wheel [6]. As a clear difference to lane departure warning (LDW) system, which only alert the driver of an unintentional lane departure [7], LKA interferes with the course of the vehicle by steering or braking some of the wheels in the situation of unintended lane departure [8]. Potential safety effects of LKA system can be impressive, but the system requires specific conditions to operate. Currently, one of the most crucial operational requirements for the LKA system is the visibility of lane markings [8]. This is a challenge in adverse weather or on roads without proper lane markings.

Previous studies (e.g., [9] and [10]) have evaluated issues related to LKA, e.g., lane correction and lateral motion of vehicles, typically by deploying different models on driver behaviour and natural driving data as real-world collision data is hard to collect. By now, a systematic crash-by-crash analysis of the potential safety effects of LKA has not been conducted or the number of crashes studied has been limited. This study focuses on LKA's possibilities to prevent fatal passenger car crashes. The aim is to evaluate LKA's potential safety effects in single-vehicle and head-on crashes by studying each crash in relation to the deployment of LKA. The following questions are addressed:

- Which single-vehicle and head-on crashes could have been avoided had the conventional car been replaced by the LKA-equipped car?
- Why all single-vehicle and head-on crashes could not be avoided by LKA system?
- How the safety potential of LKA could be improved?

Potential safety effect is assessed as the maximum safety potential available, i.e., the theoretical best situation in terms of LKA's operation and avoided crashes, with sensitivity analysis related to assumptions made in the study. Furthermore, issues affecting LKA's operation are discussed, including reasons, why LKA could not prevent particular crashes. By deploying advanced LKA systems, some limitations of the current LKA could be removed. In the analysis, the potential safety impacts of more advanced LKA systems are also analysed to find recommendations involving vehicle and infrastructure requirements. The contribution of this study is in enhancing the understanding of LKA's possible safety benefits in relation to current fatal crashes, and highlighting the areas where LKA is currently able to operate and how LKA could offer increased safety benefits.

LKA is not the sole ADAS capable of preventing unintended lane departure crashes, as e.g., LDW can also help to avoid these crashes. The safety potential of LKA is analysed in this study, as the focus is on systems, which are able to prevent unintended lane

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TABLE I
OPERATIONAL CONDITIONS OF CURRENT LKA SYSTEMS IN FOUR CAR MODELS ([12]–[15])

Manufacturer	**Model**	**Name of the system with LKA functionality**	**Speed when LKA can operate**
Tesla	Model S	Autosteer	8-150 km/h
Toyota	Prius	Lane departure alert with steering control	50 km/h or more
Volkswagen	Tiguan	Lane assist	60 km/h or more
Volvo	XC 60	Lane keeping aid	65-200 km/h

departure crashes without driver's instant input. Consequently, warning systems (e.g., LDW) are out of the scope of this study. Electronic stability control (ESC) is another system, which complements the effects of LKA. ESC, particularly, prevents loss of control crashes [11] and hence is not comparable to LKA system, and is not analysed in this study. A comparative analysis on the operation of different ADAS, which are able to prevent unintended lane departure crashes, is presented in Table VII.

In Section II, operational conditions of LKA and previous studies are presented. Section III describes the data and method of the analysis. Results on the safety potential of current and advanced LKA systems are presented in Section IV. The last three sections include discussion, limitations and conclusions.

II. THE OPERATIONAL CONDITIONS AND SAFETY EFFECTS OF LKA

A. Operational Conditions

In this section, the typical operational conditions of currently available LKA systems are described based on user manuals of four different car models to understand the real-world restrictions of current LKA systems. Operational conditions mean preconditions and circumstances when LKA is able to be activated, operate, and related to our analysis, possibly prevent single-vehicle and head-on crashes. The studied car models described in Table I were selected as they are from different car manufacturers including carmakers from Europe, North America and Asia. These car models are also mainly from different car segments representing smaller and bigger cars.

According to the studied user manuals of the four car models, the driver needs to active the LKA system after starting the vehicle. In real-life circumstances, drivers do not always activate LKA or other ADAS. In a study, in which the systems' on-off status was recorded at one point in Washington, D.C., in the USA, LKA was turned on in 55% of the vehicles equipped with LKA [16]. Flannagan *et al.* [17] analysed vehicle data of about 2 000 vehicles in the USA and concluded that LDW was turned on about 50% of the driving time.

The user manuals depict that LKA participates in the dynamic driving tasks by steering the vehicle, but the human driver is always in charge of the vehicle and driving. Consequently, the system requires the driver to keep hands on the steering wheel to make sure the driver is alert. If the driver does not keep the hands on the steering wheel, the system warns by a message on the display and by a voice signal to get the driver's attention. Human-machine interaction (HMI) is an important issue affecting the possible safety effects, which can be gained by LKA, e.g., how does the driver react to steering or warnings made by the system. For instance, Winkler *et al.* [18] have found that different warning types (e.g., visual presentation) have an impact on drivers' brake reactions and warning readability. Drivers can focus on non-driving related secondary tasks, which steal drivers' attention and interfere with monitoring the environment [19], [20].

The user manuals of the four studied car models highlight the visibility of the lane markings as a crucial requirement for LKA. By camera sensors, the system detects the lane markings to keep the vehicle inside the lane. LKA may not operate properly if the traffic lines are only partially visible (e.g., worn-out or partially covered by snow). LKA cannot operate if lane markings do not exist or the markings are not visible (e.g., covered by snow or dirt). Adverse weather, such as snowfall or fog, may also prevent the camera sensors from detecting the lane markings leading to non-operating LKA [21].

Based on the studied user manuals, LKA works best on high-quality roads (e.g., highways and freeways) with gentle curves (e.g., a radius of more than about 150m [13]). LKA may not function in an appropriate way if driving in urban areas, on narrow lanes, in construction zones or at intersections. Required minimum speed for successful activation of LKA varies from eight [12] to 65 km/h [15]. If an adaptive cruise control system is also in use with LKA in Volvo, LKA assists in steering in lower speed than 65 km/h. The maximum activation speed of LKA is not stated for two of the studied car models, and for the two others it varies between 150 and 200 km/h.

B. Safety Effects

The analysis in this study focuses on LKA, but in this section previous studies on the effects of LDW are presented, as LKA and LDW have often been studied together. There is a relatively small amount of studies focusing solely on LKA's safety effects, and overall the studies have used different methodologies to assess the safety effects or the potential safety effects. When comparing LKA with LDW, Høye [22] states that LKA is likely to be more effective than LDW.

Sternlund *et al.* [23] used an induced exposure method to compare driver injury crashes with and without LKA- or LDW-equipped passenger cars from a single manufacturer and found that cars with LKA and LDW reduced head-on and single-vehicle crashes by 53% in Sweden when speed limit was 70–120 km/h and road surface was not icy or snowy. In all conditions and with all speed limits reduction of head-on and single-vehicle crashes was estimated to be 30%. The number of crashes involving a vehicle with LKA was only 11. By using in-depth crash data including crashes with at least one hospitalised occupant, Logan *et al.* [4] stated based on expert estimates that LKA would potentially reduce aforementioned crash types by 33% (range 26–41%) in Australia and New Zealand. The range was presented because of random selection of crashes and thus the data was not necessarily representative. The number of analysed crashes was 27. Scanlon *et al.* [8] simulated 478 real-world road departure crashes with and without LKA system and concluded that LKA could theoretically prevent road departure crashes by 32% and seriously injured drivers by 28% without road infrastructure improvements in the USA. The reductions with LDW system would be 28% and 21%, respectively. In the analysis, the existence of lane markings was determined by using scene photographs, but no evaluation of lane markings clarity nor visibility was made. If all roads had lane markings and wide shoulders (i.e., a roadway area outside of the lane markings) LKA could theoretically prevent 78% of studied crashes and 65% of seriously injured drivers.

By classifying real-world passenger car crashes in different crash types and subgroups, Jermakian [24] estimated that LDW could potentially prevent or mitigate 17–31% of fatal single-vehicle crashes and 40–46% of fatal head-on crashes in the USA. The range depends on whether speeding is included or excluded in the analysis. In the study, it was assumed that lane markings exist on roads with speed limits of 40 mph (about 65 km/h) or more, but actual visibility of lane markings was not taken into account in the evaluation. Furthermore, LDW requires driver action to prevent the crash, but the impact of driver's input (e.g., drowsiness) was not assessed. Sternlund [25] studied possible effects of LDW and stated that 33–38% of 100 analysed fatal head-on and single-vehicle crashes could possibly have been prevented by LDW in Sweden in 2010. The range depends on whether excessive speeding is included or excluded in the analysis. Speeding of 30 km/h or more was thought to affect the function of LDW due to insufficient reaction times of the drivers. LDW was assumed to prevent the crash, if a vehicle was drifting, lane markings were visible and speed limit was 70 km/h or more. Cicchino [7] found positive safety effects of LDW as involvement rate of vehicles with LDW was 18% lower than of vehicles without LDW in all head-on, single-vehicle and sideswipe crashes and 86% lower in the same type of fatal crashes in the United States in 2009–2015 when studying specific car models. Vehicles with LDW were equipped with other ADAS more often than vehicles without LDW, which may affect the results.

Results from previous studies indicate that LKA could prevent 26–53% of single-vehicle and head-on crashes. The research method and specific conditions of different countries affect the results, but safety potential of LKA is considerable. It can be concluded that while the importance of lane markings' visibility for LKA has been acknowledged, it has not been comprehensively quantified in the previous studies.

C. Advanced LKA

Currently available LKA systems have operational restrictions e.g., related to the visibility of lane markings. In the future, when driving automation systems are more advanced, the potential safety effects could be enhanced compared to the current LKA [26]. As cars (and LKA) in future may be able to follow digital lane markings, creating high definition (HD) maps (described by Kühn *et al.* [27]) including the exact location of lanes, the need of physical lane markings could be removed from the perspective of LKA. In addition, adverse weather conditions would not be a problem since the camera sensors would not need to follow the physical lane markings. Albeit the digital lane markings could not be provided and followed, measures related to infrastructure would also enhance LKA's operational conditions. For instance, better maintenance and coverage of the lane markings in the whole road network including edge and centre lines would increase the use range of LKA systems.

Advanced LKA systems do not eliminate possibilities for human errors or risky behaviour as long as the driver is allowed to bypass LKA and the driver is not willing to utilise the system. Consequently, advanced LKA doesn't remove all risks.

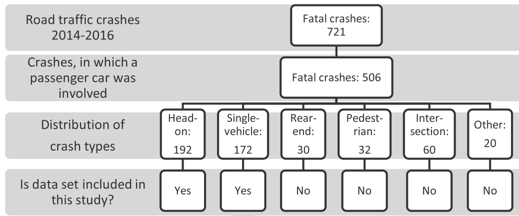

Fig. 1. Data set included in this study.

III. Method and Data

A. Overview of the Analysis

The safety potential of LKA is analysed with data on fatal passenger car crashes in 2014–2016 in Finland. The analysis is based on detailed crash data and the hypothetical functionality of LKA in each crash by considering LKA's operational requirements. LKA's possible safety potential is analysed with a what-if frame, i.e., what if the vehicles involved in the fatal passenger car crashes had been LKA-equipped and LKA continuously on. With the crash-by-crash analysis, real-world conditions, including road and weather conditions and driver's input, are considered when assessing LKA's safety potential. The crash-by-crash analysis, described e.g., Sternlund [25], includes the analysis of each individual crashes, in which the operational conditions of LKA and actual conditions in the crash site are considered. Firstly, the analysed crashes are determined. Secondly, the method and assumptions are described. Finally, the method to analyse the safety potential of advanced LKA is presented.

B. Data

In Finland, the average age of passenger cars was 11.8 years in 2019 [28]. With a relatively old car fleet, the adoption of LKA-equipped cars is likely to happen at a slower pace in Finland than in countries, where car fleet renewal is faster, and proportionally more new cars, more likely to be LKA-equipped, enter the car fleet. According to an estimation by Lähderanta [29], LKA was in 1–11% and LDW in 2–24% of passenger cars in Finland in 2018. In the crash data set of this study, there was only one LKA-equipped car involved. In this particular case, the LKA system was not able to prevent the crash as the other involved vehicle was in the wrong lane.

For the LKA systems, winter conditions (e.g., snow) bring on difficulties, and thus it is important to consider LKA's operation in the four seasons. The crash data from Finland is comprehensive and advanced due to long-term development work in accident investigations, and includes crashes with varying weather conditions (e.g., wintertime). The data is provided by the Finnish Crash Data Institute [30], and the data includes all fatal crashes in Finland in 2014–2016. The data is based on the findings from in-depth case studies made by the road accident investigation teams. The data includes crash description with crash site photographs and a list of more than one hundred attributes on crashes e.g., road and weather conditions, driver's input, background risks etc. Fig. 1 presents the crashes that are included in this study from the original data set. From the different crash types, LKA is able to prevent single-vehicle and

TABLE II
FACTORS, WHICH HAVE AN IMPACT ON LKA'S OPERATION. IN FAVOURABLE CONDITIONS, LKA MAY HAVE A POSITIVE INFLUENCE ON THE CRASH. IF AT LEAST ONE OF THE FACTORS IS UNFAVOURABLE, LKA IS NOT ABLE TO INFLUENCE ON THE CRASH

LKA may have a positive influence on the crash (favourable conditions)	**LKA is not able to influence on the crash (unfavourable conditions)**
Fully visible lane markings (a centre and an edge line clearly visible)	Lane markings partially visible or lane markings invisible
Normal weather conditions (none of the conditions described right)	Snowfall, wet snow or fog
No driver-related risks (none of the risks described right)	Intendedly caused crashes, driver's attack of illness or overtaking

head-on crashes. In the data, there are 364 relevant crashes of which 192 head-on and 172 single-vehicle crashes. Of the total 721 fatal crashes, 357 are not included in the analysis as these either do not include a passenger car (215 crashes) or are in crash types, which LKA is not able to prevent, i.e., rear-end (30), pedestrian (32), intersection (60) and other (20) crashes.

This study focuses on fatal passenger car crashes as these crashes represent a major road safety problem. In Finland, 57% of road fatalities were in a passenger car in 2014–2016 [31] and in the EU, 46% of road fatalities were in cars or taxis in 2015 [32]. LKA's safety effects are an actual topic as LKA is becoming more common in cars and may become mandatory as European Commission [5] has proposed because LKA is seen able to contribute to reaching the challenging safety targets.

As we limit our study to fatal crashes where a passenger car is involved, crashes with cyclists and other motor vehicles are included only if a passenger car is involved and the crash type is either a head-on or a single-vehicle crash. In addition to passenger cars, also other motor vehicles e.g., trucks, vans and buses involved are considered to be LKA-equipped and benefit from this system in the studied head-on passenger car crashes. For instance, in a head-on crash between a passenger car and another motor vehicle (e.g., a truck), the other motor vehicle may have drifted out of a lane and have hit to the passenger car. In this case, LKA in the other motor vehicle may be able to prevent the crash. LKA can be seen as a justified next step for heavy vehicles as LDW for new heavy vehicles has been a mandatory system in the EU since November 2015 [33]. In this study, motorbikes and mopeds are not considered to be LKA-equipped and thus crashes are not considered to be preventable by LKA in these vehicle types.

C. Method – Current LKA

The data set is analysed crash-by-crash to assess, if LKA vehicles would have been able to prevent the crash. Individual conditions and driver-related risks are analysed in each crash, as LKA's operation requires favourable conditions. LKA's proper function requires fully visible lane markings, favourable weather conditions, and driver's input should enable function of LKA. Consequently, driver-related risks (e.g., attack of illness) hinder LKA from preventing the crash. If all of factors (presented in Table II) are favourable, LKA is considered to be able to prevent a crash. If at least one of the factors is unfavourable, LKA is not able to prevent the crash. Similar factors have been evaluated in previous studies on LKA's safety potential, but all of these factors (e.g., driver-related risks and lane markings' visibility) have not typically been included in the same analysis.

D. Assumptions

In our analysis, we assume that LKA is continuously on, i.e., the LKA system is activated whenever and wherever possible, which is similar to the assumption made by Logan *et al.* [4]. Additionally, we assume that LKA is able to operate in any speed of the vehicle, in all curves (despite the radius) and in urban areas. We assume that LKA could not prevent crashes, which were caused by a technical failure in the car. The implications of these assumptions to the results of this study are discussed and sensitivity analysis related to speeding's effects on LKA are presented.

In this study's analysis, two outcomes are possible. The crash A) can be prevented by LKA (LKA has a positive influence), or B) due to unfavourable conditions LKA is not able to prevent the crash (LKA has no influence). Unfavourable conditions, when LKA has no influence (presented in Table II), are:

- *Visibility of lane markings:* visibility of lane markings is categorized in two classes:
  - *Partially visible:* the centre and edge lines are partly worn or partly covered by snow or dirt, or there is solely a centre line and the edge line is missing or vice versa.
  - *Invisible:* lane markings do not exist or lane markings are covered by snow or dirt.
- *Weather conditions: Snowfall, wet snow or fog:* Camera sensors require clear visibility [21] and hence these conditions are assessed to result in poor visibility and LKA not being able to operate.
- *Driver-related risks:* Driver-related risks are categorized in three classes:
  - *Intendedly caused crash (e.g., suicide):* LKA is not able to prevent intendedly caused crashes because the driver can bypass the LKA system.
  - *Driver's attack of illness (e.g., unconsciousness):* It is assumed that even if LKA could prevent the car from drifting out of the lane, it is not able to park the car safely, and the crash due to attack of illness would happen eventually.
  - *Overtaking:* LKA cannot prevent head-on crashes due to overtaking. Additionally, LKA cannot prevent single-vehicle crashes before or after the overtaking due to loss of control of the vehicle. In these crashes, the driver makes a strong steering input where after LKA cannot restore the control.

E. Method – Advanced LKA

The safety potential of LKA is additionally analysed in four other scenarios. The methodology is similar as presented in Sections III-B and III-C for current LKA in existing road infrastructure, but in each four additional analyses LKA is considered more advanced system compared to current LKA or the infrastructure advancements enhance system's operation. These advancements in the infrastructure or the system elude some of the unfavourable conditions presented in Table II.

In the first (1) scenario, LKA is similar to the current LKA, but the whole road network would hypothetically have fully visible lane markings. In the second (2) scenario, accurate digital lane markings are available on the whole road network and LKA is able to follow these. In this scenario, poor weather conditions or the lack of lane markings would not restrict the operation of LKA. The third (3) scenario includes additionally (compared to the second scenario) that driver cannot bypass the system. Thus,

TABLE III
VISIBILITY OF LANE MARKINGS IN RELATION TO DRIVER-RELATED RISKS AND WEATHER CONDITIONS IN CRASHES. THE NUMBERS PRESENT THE AMOUNT OF CRASHES AND THE SHARE OF CRASHES STUDIED

Visibility of lane markings	No driver-related risks and favourable weather	A driver-related risk and/or unfavourable weather	Crashes caused by a motorbike or a technical failure	**Total**
Fully	99 (27%)	99 (27%)	-	**198 (54%)**
Partially	45 (12%)	34 (9%)	-	**79 (22%)**
Invisible	28 (8%)	54 (15%)	-	**82 (23%)**
Not relevant	-	-	5 (1%)	**5 (1%)**
Total	**172 (47%)**	**187 (51%)**	**5 (1%)**	**364 (100%)**

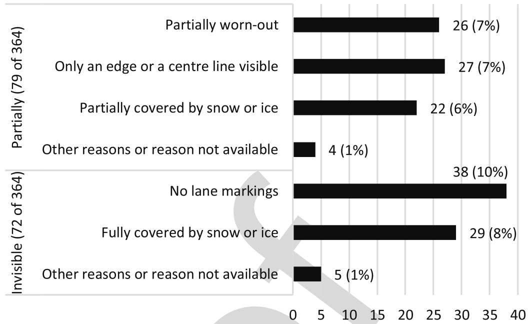

Fig. 2. Reasons for partially visible and invisible lane markings.

crashes cannot be caused intendedly and overtaking crashes are also ruled out. In the fourth (4) scenario, LKA is additionally capable of safe parking in case of driver's attack of illness.

IV. RESULTS

A. *LKA's Potential to Prevent Crashes*

364 fatal crashes (192 head-on and 172 single-vehicle crashes) were analysed to study potential safety effects of LKA. In these crashes, the number of fatalities was 415 and most of the fatalities (404) were passenger car occupants as the data includes solely crashes, where passenger car is one of the involved parties. Based on the analysis, LKA could potentially have prevented 99 (27%) of 364 fatal crashes and 115 (28%) of 415 fatalities. Concerning the different crash types, LKA could potentially have prevented 52 (30%) of 172 single-vehicle and 47 (24%) of 192 head-on crashes. In these crashes, which LKA was assessed to potentially prevent, lane markings were fully visible, and weather and driver's input were favourable for the operation of LKA. Of the total number of fatal passenger car crashes in 2014–2016, LKA could potentially have prevented 20% (99 of 506). The potential reduction in fatalities would have been 20% (115 of 568). The resulting crash cost savings from 99 prevented crashes would be 307 million euros, as the unit value of a fatal crash is 3.1 million euros in Finland [34]. As these crashes and savings are calculated based on three year's data, the theoretical annual crash cost saving would be 102 million euros, which is 14% of the crash costs of all fatal crashes (745 million euros).

B. *Visibility of Lane Markings*

In 144 (40%) crashes lane markings were fully (99 crashes) or partially visible (45 crashes) and other conditions were favourable (Table III). According the analysis, the crash was preventable, if the lane markings were fully visible. If occasional detrition is allowed or existence of an edge or a centre line would be enough for proper operation of LKA, the system could have prevented 144 crashes. Even if the weather was favourable and driver-related risks did not appear in 28 (8%) crashes, LKA would not have been able to prevent the crash because of invisible lane markings. Of 364 crashes, lane markings were fully visible in 198 (54%) crashes. In five crashes, in which the crash was caused by a motorbike or a technical failure, analysing the lane markings' visibility is not meaningful.

Detrition of lane markings in 26 of 364 (7%) and incomplete lane markings in 27 (7%) crashes were the most notable reasons for partially visible lane markings (Fig. 2). For invisible lane markings, the lack of lines in 38 (10%) crashes was the most common reason. Altogether, in 51 crashes snow or ice coverage was a reason for partially visible or invisible lane markings.

C. *Weather Conditions*

Unfavourable weather was a sole reason in 3 (1%) and one of the reasons to prevent LKA's operation in 23 (6%) crashes. When unfavourable weather was the sole reason, lane markings were fully visible and driver-related risks did not appear. Although the weather was not a common reason to prevent LKA's operation, we could note a difference between wintertime and summertime crashes. LKA could potentially have prevented 20% of the crashes, which occurred between October and April when there are wintry circumstances at least in the northern parts of Finland, while potential crash reduction would have been 37% between May and September.

Poor weather conditions may have been a sole reason in more than 3 crashes, as e.g., continuous snowfall causes partially or fully snow covered road surfaces. In our study, partially visible or invisible lane markings are recorded as the reason preventing LKA's operation, if e.g., snowfall has already ended when the crash occurred. Visibility of lane markings is considered separately as an own issue affecting LKA's operation as depicted in Section B.

D. *Driver-Related Risks*

As described in Section III, intendedly caused (suicides), driver's attack of illness and overtaking crashes are assessed to be crashes LKA is not able to prevent due to driver's input. These driver-related risks appeared in 170 (47%) crashes (Table IV). When a driver-related risk was the sole reason (94 crashes, 26%) preventing LKA's operation, intendedly caused crash (63 of 94 crashes) was the most common cause. In all, intendedly caused crash was the sole reason or one of the reasons preventing LKA's operation in 88 (24%), attack of illness in 61 (17%) and overtaking in 21 (6%) crashes.

There are notable differences when comparing reasons for LKA not to operate in head-on and single-vehicle crashes with solely a driver-related risk. Intended cause appeared in 40%

TABLE IV
DIFFERENT DRIVER-RELATED RISKS IN RELATION TO LANE MARKINGS' VISIBILITY, WEATHER, AND OTHER REASONS INFLUENCING LKA'S OPERATION. THE NUMBERS PRESENT THE AMOUNT OF CRASHES AND THE SHARE OF CRASHES STUDIED

Conditions	Intendedly caused	Attack of illness	Overtaking	Total
Fully visible lane markings, favourable weather	63 (17%)	19 (5%)	12 (3%)	94 (26%)
Partially visible or invisible lane markings, favourable weather	22 (6%)	36 (10%)	6 (2%)	64 (18%)
Unfavourable weather or other reasons	3 (1%)	6 (2%)	3 (1%)	12 (3%)
Total	**88 of 364 (24%)**	**61 of 364 (17%)**	**21 of 364 (6%)**	**170 of 364 (47%)**

of head-on crashes, but only in 6% of single-vehicle crashes. Conversely, driver's attack of illness appeared in 5% of head-on crashes and in 31% of single-vehicle crashes. These results are expected as one typical crash type within intendedly caused traffic collisions is a crash with an oncoming heavy vehicle [35]. Instead, driver's attack of illness may take place anywhere and results usually in a single-vehicle crash.

Driving under the influence of alcohol or drugs and speeding increase crash risk (e.g., [36], [37]). We present the potential effects of these factors as a sensitivity analysis related to LKA's possibility to prevent crashes.

1) Speeding: As excessive speeding makes it difficult to keep the vehicle on the road even with LKA, there is the need to analyse how speeding could affect the studied crashes. As presented in the earlier sections, LKA could potentially have prevented 99 crashes. Of these, only 55–67 crashes could have been avoided if speeding is considered as a disturbing factor (Table VIII). The range is based on considering the level of speeding. If exceeding the speed limit with 10 km/h or more has an impact on LKA's operation, only 55 crashes could have been prevented. Correspondingly, if speeding of 30 km/h or more is considered to be too much for LKA's operation, 67 crashes could have been avoided. These speeding crashes may include driving under the influence of alcohol or drugs.

2) Driving Under the Influence of Alcohol or Drugs: As depicted in Table VIII, the number of crashes LKA could potentially prevent would be 62 instead of 99, if driving under the influence (DUI) of alcohol or drugs were considered to prevent LKA's operation. DUI crashes may also include exceeding the speed limit. Considering DUI and speeding separately or the combination of these in the same crash to prevent LKA's operation, only 47–53 crashes would potentially be prevented. The range is dependent on the level of speeding. If LKA is able to be operational on roads with partially visible lane markings, the number of potentially avoided crashes reduces from 144 to 67–75 (fully or partially visible lane markings) if DUI or speeding are considered as disturbing factors.

E. Advanced LKA

LKA without additional safety measures could potentially have prevented 27% of fatal crashes. By implementing progressive policy actions and recommendations involving vehicle and infrastructure requirements, potential safety effects could be improved (Table V). By having fully visible lane markings

TABLE V
POTENTIAL OF CURRENT LKA AND FOUR SCENARIOS RELATED TO ADVANCED LKA'S POTENTIAL TO REDUCE FATAL HEAD-ON AND SINGLE-VEHICLE CRASHES, AND THE REQUIREMENTS RELATED TO ROAD NETWORK AND INFRASTRUCTURE, THE DRIVER AND THE VEHICLE

Requirements on road network and infrastructure	**Requirements on the driver**	**Requirements on the vehicle**	**Potential crash reduction**
No extra requirements, current road network	LKA is always turned on	All vehicles fitted with current type of LKA.	27% (99 of 364)
Scenario 1: Fully visible lane markings on all roads	LKA is always turned on	All vehicles fitted with current type of LKA.	46% (168 of 364)
Scenario 2: HD maps, digital lane markings	LKA is always turned on	All vehicles fitted with LKA enabling exploiting HD maps.	52% (189 of 364)
Scenario 3: HD maps, digital lane markings	None (LKA is always on)	All vehicles fitted with LKA enabling exploiting HD maps, the driver cannot bypass LKA.	82% (298 of 364)
Scenario 4: HD maps, digital lane markings	None (LKA is always on)	All vehicles fitted with LKA enabling exploiting HD maps, the driver cannot bypass the system, LKA is capable of safe parking in case of driver's attack of illness.	99% (359 of 364)

TABLE VI
STAKEHOLDERS AND THEIR POSSIBILITIES TO REALISE AND IMPROVE THE SAFETY POTENTIAL OF LKA

Stakeholder	**Possibilities to improve the safety potential of LKA**
Vehicle manufacturers	Equip all vehicles with LKA of highest standard. Make the use of LKA as safe and comfortable as possible. Develop LKA to be able to use HD maps and digital lane markings. Consider having LKA system by default always turned on.
Vehicle resellers	Make sure the vehicle purchasers and users know the LKA and appreciate its value, and are able to adopt safe use of LKA, recognising the limitations of the system.
Road authorities	Make sure lane markings are of high quality through to road network, prioritising especially roads with high traffic volume and high crash rate. Prepare for HD maps and digital lane markings.
Vehicle purchasers and drivers	Choose vehicles equipped with LKA. Utilise LKA safely and as much as possible, yet recognising its limitations.
Public authorities and policy makers	Set LKA as a mandatory equipment in vehicles and consider whether it should be turned on by default. Promote and communicate the safety potential of new vehicle technologies and their safe adoption.
All stakeholders	To support LKA's safety potential, promote the development and use of other supporting advanced vehicle technologies and driver assistance systems, e.g. intelligent speed assist (ISA).

on the entire road network in Finland, LKA could theoretically have prevented 46% of the crashes (Scenario 1). With advanced LKA systems (Scenario 2), which allow the vehicle to follow digital lane markings, 52% of the crashes could potentially be avoided. Removing the possibility for the driver to override the advanced LKA system (Scenario 3), intentionally caused crashes could also be avoided, resulting in a theoretical 82% crash reduction. Finally, eliminating also the risks related to attack of illness (Scenario 4), crash reduction of 99% could potentially be achieved. The five (1%) crashes, which could not be avoided in this theoretical analysis, consist of three crashes with a motorbike and two crashes due to a technical failure in an involved vehicle.

TABLE VII
FUNCTIONALITY OF LKA SYSTEM IN COMPARISON TO OTHER SYSTEMS CAPABLE OF PREVENTING OR WARNING UNINTENDED LANE DEPARTURES

Driver assistance system	Comparison to LKA system
Lane departure warning (LDW) [7]	LDW only alerts the driver, when the vehicle is above or near the lane markings. In these cases, LKA steers the vehicle to avoid lane departure.
Curve speed warning (CSW) [38]	CSW alerts the driver of impending lane departure when approaching a curve. LKA does not anticipate the lane departure, but without excessive speed, LKA may avoid the lane departure by steering the vehicle.
Control loss warning (CLW) [39]	CLW sends a warning message of a potential loss of control of a host vehicle to nearby connected vehicles. LKA does not send messages to other vehicles.
Electronic stability control (ESC) [11]	ESC prevents loss of control of the vehicle. LKA may not prevent lane departures due to loss of control. LKA and ESC are together more efficient to prevent lane departures.

TABLE VIII
THE NUMBER OF POTENTIALLY PREVENTED CRASHES AND SHARE OF ALL STUDIED CRASHES (N=364), IF SPEEDING AND DRIVING UNDER THE INFLUENCE (DUI) OF ALCOHOL OR DRUGS ARE CONSIDERED TO PREVENT LKA'S OPERATION

	No driver-related risks, favourable weather		
Factor preventing LKA's operation	Fully visible lane markings: 99 of 364 (27%)	Partially visible lane markings: 45 of 364 (13%)	Fully + partially visible lane markings: 144 of 364 (40%)
Driving under the influence (DUI) of alcohol/drugs	62 (17%)	26 (7%)	88 (24%)
Speeding ≥10 km/h	55 (15%)	25 (7%)	80 (22%)
Speeding ≥20 km/h	59 (16%)	27 (7%)	86 (23%)
Speeding ≥30 km/h	67 (18%)	33 (9%)	100 (27%)
DUI or speeding ≥10 km/h or both	47 (13%)	20 (5%)	67 (18%)
DUI or speeding ≥20 km/h or both	49 (13%)	20 (5%)	69 (19%)
DUI or speeding ≥30 km/h or both	53 (15%)	22 (6%)	75 (21%)

V. DISCUSSION

Based on our crash-by-crash analysis of passenger car crashes in 2014–2016 in Finland, 27% of single-vehicle and head-on crashes could potentially have been avoided by exploiting LKA. We find that LKA has a notable potential to promote road safety. However, the possible crash reduction this study found is relatively moderate compared to previous studies, where the results indicate a potential crash reduction of 26–53% in single-vehicle and head-on crashes. Scanlon *et al.* [8] and Logan *et al.* [4] analysed real-life crashes individually, but the number of crashes was limited or issues relevant for the operational conditions of LKA (e.g., visibility of lane markings) was not analysed similarly to this study. Including visibility of lane markings, driver-related risks, and weather conditions as determinants to the operation of LKA seems to lower the potential safety effects compared to previous studies. Furthermore, crashes caused intendedly or due to driver's attack of illness have an impact on results compared to previous studies, in which these have not typically been considered.

Driver-related risks are relatively common factors in fatal crashes in Finland. In 170 (47%) crashes, driver's input would have been a reason disabling LKA's operation. Particularly intendedly caused crashes and driver's attack of illness were highlighted within driver-related risks. We considered LKA not to be able to prevent the crash if the lane change is intentionally caused or the driver is not controlling the vehicle and driver's hands are not on the steering wheel (attack of illness).

At this early stage level of automation, in which the driver is responsible of the driving task, driver's input is crucial for safety as LKA only supports the human driver in the driving task. The high number of intendedly caused crashes as the reason preventing LKA's operation, highlights the additional safety benefits of advanced LKA systems and highly automated vehicles in comparison to current ADAS. If the driver is allowed to bypass the automated driving function, risky behaviour cannot entirely be prevented. Furthermore, more advanced systems can be able to notice changes in driver's physical conditions and stop the vehicle safely. It should be acknowledged that even the advanced systems would not prevent all fatalities caused by attack of illness in road traffic as driver's health issues may be the actual cause of death. However, advanced LKA systems could prevent head-on crashes resulting from attack of illness and thus avoid serious consequences for possible other parties involved.

Related to the visibility of lane markings, new technology may help to enhance the operation of LKA. HD maps and digital lane markings would allow LKA to keep vehicle on the lane without physical lane markings, i.e., paintings. Digital lane markings would increase the safety benefits, as physical lane markings' visibility is restricted in many cases. To be able to follow digital lane markings, current LKA systems are needed to be updated and potentially even replaced. Additionally, the development and maintenance of the digital lane markings is expensive, which probably delays the implementation of the digital markings. As current LKA, which require physical markings, is becoming prevalent, we may need to wait before advanced LKA is common. In the short term, improvement of physical lane markings should be prioritised instead of HD maps, as LKA systems of today are based on detecting the markings by camera sensors. In our study, snow or ice on roads made it difficult to follow lane markings in 51 of the 151 crashes with low visibility of lane markings. Allocating more resources to road (e.g., roads with full coverage lane markings) and winter maintenance, LKA's safety potential can be enhanced.

We studied LKA's possible safety impacts in relation to three driver-related risks, i.e., intentional cause, attack of illness, and overtaking. In addition, other typical risks, such as speeding or driving under the influence of alcohol or drugs, may affect the possible safety benefits of LKA. For instance, speeding in curves has an impact on the function of LKA, as it is harder to maintain the driving course. Speeding on straight roadway may also affect LKA's operation as safe vehicle speed set by the road administration is not used. As it is difficult to determine, which vehicle speed would be too excessive for LKA both in curves and on straight roadways, the different levels (10, 20, and 30 km/h) of speeding were presented as a sensitivity analysis (Table VIII). Results indicate that differences between these values are minor and if there is speeding, the speed of vehicle is typically much higher than the speed limit. In order to study this deeper, the effects of speeding on LKA should be researched more in future.

If alcohol or drug use and speeding at the same time or only one of these factors are assumed to prevent LKA's operation, LKA's possibility to reduce crashes decreases from 27% to 13%. At worst, potential safety benefits are halved because of these factors. The results indicate that alcohol, drugs and speeding are frequently involved in fatal crashes and these may greatly influence LKA's safety benefits. In order to enhance the safety potential, LKA should be complemented with other systems that reduce driver-related risks, e.g., intelligent speed assist (ISA) and alcohol ignition interlock devices.

In our study, we found several issues, which have an effect on LKA's safety potential. By considering these issues, we can identify ways to realise and further improve LKA's operation. We can also recognise the role of different stakeholders as presented in Table VI. First of all, vehicle manufactures, public authorities and policy makers should strive for new vehicles to be equipped with LKA operating with the highest standard. When operational reliability in different conditions has been confirmed, it should be considered, whether LKA should be by default always on. Secondly, vehicle purchasers and drivers should be aware of LKA and its operation and appreciate its value when choosing the vehicle and while driving. In addition to LKA's operation, the limitations of the system should be acknowledged, too. Vehicle resellers have a great role in communicating about LKA to the vehicle purchasers. Finally, road authorities should ensure high quality of lane markings and prepare for HD maps and digital lane markings for advanced LKA systems.

VI. Limitations

We recognise that many issues may have an impact on the function of LKA and LKA's possibility to prevent crashes and all these issues cannot be analysed in detail. As one example, in this study we considered LKA to be able to prevent loss of control crashes, but in reality, ESC could prevent these crashes instead of LKA (or together with LKA). However, loss of control cases typically include excessive speeds, which we considered in sensitivity analysis. By doing this, we were able to exclude cases, in which ESC could potentially have avoided the crash instead of LKA. In addition, the driver's steering manoeuvre could have an impact on LKA's operation, because the system can be bypassed, when the driver actively steers the car. The driver's behaviour during the operation of LKA should be studied further to better understand interaction between the system and the driver.

In this study, we assumed all crash-involved motor vehicles (except of motorbikes and mopeds) to be LKA-equipped, LKA to be activated whenever and wherever possible and to operate in the defined conditions, which do not reflect the current conditions in real-world vehicle fleet or traffic. The assumptions in this study were made to analyse the maximum crash reduction potential of LKA. If we would assume that LKA is activated e.g., by 50% of the drivers and that would straightforward lead to 50% of possible (maximum) crash reduction, the safety potential of LKA this study indicates would be 50% lower. To get closer to the situation, where the assumptions of this study would correspond to real-life circumstances, LKA should be a mandatory equipment and always turned on by default. However, development towards this situation takes a long time as the decision-making processes are slow related to vehicle technologies and vehicle fleet evolves slowly. The progress also requires that the LKA technologies are reliable. In this study, LKA is assumed to operate without technical problems. Related to LKA's reliability and robustness, we analysed the effects of lane markings' visibility and weather conditions, but other aspects, such as LKA system's possible inoperability, malfunction, or even intentional hacking or cyber-attacks are not included in the analysis. The potential negative effects of the system should be studied further.

VII. Conclusion

To improve the operational conditions and achievable safety effects of LKA, the LKA systems should be developed so that these can operate reliably with low visibility or even with invisible lane markings. Additionally, the visibility of lane markings should be improved e.g., by allocating more resources to road maintenance and to snow clearance. When advanced LKA systems or highly automated vehicles, which are able to utilise HD maps, will become more common, the visibility of physical lane markings may not be a requirement anymore.

Driver-related risks, which cannot be defeated by ADAS, are major problems for road safety. Measures to improve cooperation between police, health care and social services are further needed to prevent intendedly caused and driver's attack of illness crashes. Technology will not entirely solve these problems until the era of fully automated driving.

When LKA-equipped vehicles and the use of LKA become more common, the amount of single-vehicle and head-on crashes can decrease. The results and discussion of this study enable assessing the safety potential of LKA in relation to actual conditions in passenger car crashes and identifying the factors to focus on to increase the possible safety effects. Results indicated, with some limitations, that LKA is able to deliver notable road safety benefits. LKA can therefore be recommended as a mandatory system in new vehicles as the European Commission has proposed.

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PUBLICATION
II

The safety potential of automatic emergency braking and adaptive cruise control and actions to improve the potential

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The safety potential of automatic emergency braking and adaptive cruise control and actions to improve the potential

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Abstract: The study investigates the potential of automatic emergency braking (AEB) and adaptive cruise control (ACC) systems to prevent fatal rear-end, intersection and pedestrian crashes in Finland. The systems' possibilities to prevent crashes were assessed using data on 115 in-depth investigated fatal crashes. The data includes all fatal crashes in the three studied crash types in 2014-2016. This study considers the impact of estimated speed, weather conditions and intentionality on the systems' operation. AEB and ACC could potentially have prevented 41% of the crashes. The highest safety potential in terms of share of hypothetically prevented crashes was recognised in rear-end (45%) and pedestrian crashes (45%) and the lowest in intersection crashes (36%). This study complements previous research, which amount is low especially considering the potential to reduce pedestrian and intersection crashes, and which has typically been limited in the aspects that are considered in analysing the safety potential. Additionally, issues related to systems' operational conditions are discussed and the possibilities to further increase the safety potential are assessed.

Keywords: Automatic emergency braking; AEB; adaptive cruise control; ACC; safety potential; crash analysis, rear-end crashes; pedestrian crashes; intersection crashes.

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1. Introduction

Advanced driver assistance systems are becoming more common in car fleet delivering positive effects on road safety (Sander, 2017). Recently, automatic emergency braking (AEB) systems have gathered attention as AEB will be a mandatory system in new passenger cars from 2022 in the European Union (European Commission, 2019) and Euro NCAP (2018a) has started to test AEB with cyclist detection. The benefits of the AEB system have been recognized since long, and e.g., in the EU, AEB has been a compulsory safety feature in new trucks since 2015 (European Commission, 2018). The AEB system is one of the most potential driver assistance systems as the system is able to prevent both collisions between motor vehicles and collisions between motor vehicles and vulnerable road users (e.g., pedestrians and cyclists). Especially, actions to improve safety of vulnerable road users are desirable as fatalities and serious injuries among these road users have increased during the last years (Tiwari, 2018). Furthermore, adaptive cruise control (ACC) can function effectively together with AEB to prevent rear-end crashes. Although these new safety features enhance road safety by supporting the driver, road accidents remain as a major health problem as the driver is still in charge of the driving tasks (Noy et al., 2018).

By using radar or camera sensors, AEB system is able to detect potential objects in front of the vehicle and avoid hitting the objects. Firstly, the system warns the driver and if the driver does not brake, the system applies the brakes to avoid the collision or to mitigate the consequences (Euro NCAP, 2018b). ACC controls vehicle speed to maintain a certain time distance to the leading vehicle (Isaksson-Hellman & Lindman, 2016). The driver's input has a notable impact on ACC's safe operation as the time distance to the leading vehicle is set by the driver. Vehicle speed also affects the possibilities of AEB and ACC to prevent crashes or mitigate consequences as excessive speed with a short safety margin reduces systems' possibilities to prevent collisions (Rizzi et al., 2014). The deployment of intelligent speed assistance (ISA) with these systems could enhance the operation of AEB and ACC as ISA advises drivers of the current speed limit and automatically limits the speed of the vehicle as needed.

Previous studies have indicated promising safety potential of AEB and ACC. According to Cicchino (2017), the crash involvement rate of vehicles equipped with AEB and forward collision warning (FCW) was 50% lower in all rear-end crashes and 56% lower in rear-end injury crashes compared to same models' vehicles without these systems in the United States. The study by Fildes et al. (2015) indicated that low-speed AEB system could reduce rear-end injury crashes by 38% (range 25-55%) when comparing police reported crashes from six countries. In the analysed crashes, vehicles with and without AEB were compared. The range is due to differences in the studied countries. Furthermore, Rizzi et al. (2014) compared crashes, in which cars with and without of low-speed AEB were involved, and concluded that the system could prevent rear-end injury crashes by 54-57% at speed limits of 50 km/h or less, 35-42% at speed limits of 60-70 km/h and 12-25% at speed limits of 80 km/h or more in Sweden. The range is due to varied effects in different car models.

Advanced AEB systems may also be effective in preventing intersection crashes. According to Sander & Lubbe (2018), intersection AEB system with field-of-view of 180 degrees could prevent 79% of straight crossing crashes between cars and 90% of serious injuries and fatalities in these crashes. The corresponding reductions with field-of-view of 120 degrees would be 66% and 81%. According to Lubbe & Kullgren (2015), pedestrian AEB system could decrease road crash casualty costs by 25-26% by reducing car-to-pedestrian injury crashes, when pedestrians are hit by vehicle fronts. The range (25-26%) depends on whether the pedestrian is able to avoid the collision or solely the driver's evasive action could help to avoid the collision. Results are based on test scenarios and simulations with pedestrian dummies crossing the road in front of the vehicle. Haus et al. (2019) modelled AEB system's operation in the actual crashes between pedestrians and motor vehicles in the United States and found that the AEB system with pedestrian detection could potentially decrease pedestrians' fatality risk by 84-87% depending on the applied deceleration force. Also Silla et al. (2017) evaluated driver assistance systems' safety effects on vulnerable road users. AEB with pedestrian and cyclist detection and with 100% penetration rate could potentially have decreased the number of all road fatalities in EU28 in 2012 by 1%.

Some studies have evaluated AEB system's possibilities to prevent crashes considering a realistic development in the market penetration. Kitajima et al. (2019) simulated the operation of AEB-equipped vehicles in an urban area in Japan to evaluate the crash reduction potential. The number of all crashes would decrease by 28% with AEB market penetration of 50%. The reduction potential of rear-end crashes is the largest as more than half of the crashes are rear-end crashes with 0% market penetration. Tan et al. (2020) developed a model to evaluate AEB system's maximum and realistic safety potential in China. They found that the share of fatalities could potentially be reduced by 8% in the best possible scenario and 3% in the realistic scenario considering the predicted AEB system's market penetration (60%) in 2030. The realistic scenario refers to the current AEB technology. In the maximum safety potential scenario, the AEB system is able to operate in adverse weather and low-light conditions.

ACC has been estimated to prevent rear-end crashes on freeways by 34-40% with a 10% penetration rate and 68-78% with a 90% penetration rate based on a simulation model (Li et al., 2017). Isaksson-Hellman & Lindman (2016) concluded that the combination of ACC and collision warning and brake support prevented 37% of rear-end crashes in Sweden when comparing crashes in which a certain car model was involved with and without the aforementioned systems. NHTSA (2011) estimated the potential safety effects of AEB and ACC by using simulations of one car model, simulator drives and test drives, and concluded that 8% of all fatal crashes could be avoided by preventing rear-end, pedestrian and intersection crashes in the United States.

Albeit the potential safety effects of AEB and ACC systems have been studied within different crash types, most of the previous studies have not considered essential crash characteristics (e.g., estimated vehicle speed) comprehensively in the evaluations. For instance, crash scene analyses have typically considered speed limit, but if the vehicle exceeds the speed limit, the speed limit as a determining factor may not be relevant for the analysis.

2. Aim

This study aims to evaluate AEB and ACC systems' possibilities to prevent relevant crash types, i.e. rear-end, intersection and pedestrian crashes. The key question addressed is could fatal passenger car crashes have been avoided, if vehicles involved in rear-end, intersection and pedestrian crashes had been AEB- and ACC-equipped. The systems' possibilities and potential safety effects are evaluated as the maximum safety potential, which is the hypothetical best possible situation in terms of AEB and ACC's safety potential. This means that the motor vehicles, which are involved in the crash, are assumed to be equipped with AEB and ACC and the systems are assumed to be always turned on. It is worth to note that this hypothetical setting is not comparable with the current state or the current car fleet, but as the aim is to study the maximum potential, these assumptions are set. Issues affecting the systems' operation are discussed, e.g., why crashes could be avoided by AEB and ACC, as well as vehicle requirements to further increase the safety potential.

3. Method and data

The theoretical safety potential of AEB and ACC systems are evaluated by analysing Finnish crash data on fatal passenger car crashes in 2014-2016. The study analyses if the fatal passenger car crashes could have been prevented had the vehicles involved been AEB- and ACC-equipped. In this analysis, crash specific conditions, including e.g., estimated vehicle speed, weather conditions and intendedly caused crashes (suicidal actions and hitting other road users on purpose), are considered when assessing the systems' possibilities to prevent crashes.

Inclement weather conditions cause difficulties on the operation of AEB systems' camera and radar sensors. In the analysis of this study, Finnish crash data is used, which enables considering winter conditions' (e.g., snowfall and slippery road surface) effects on the systems' hypothetical operation. This crash data also enables taking into account the estimated vehicle speed and intendedly caused cases in the analysis as the crashes are in-depth investigated by the road accident investigation teams. In Finland, the accident investigation teams estimate the vehicle speed based on crash scene investigations, reconstructions and interviews. Event data recorder information was not available, but this could be one option to estimate speeds (see e.g., Kusano & Gabler, 2011). The Finnish Crash Data Institute provided the data, consisting of all fatal crashes in Finland in 2014-2016. The data includes crash descriptions and more than one hundred variables on each crash, crash site and all involved road users. The overall data includes 721 fatal crashes, of which 115 crashes were included in the analysis as these involved a passenger car and were in the crash types, which are considered possibly preventable by the AEB or ACC systems. Of the 115 studied crashes with total 123 fatalities, 33 were rear-end, 29 pedestrian and 53 intersection crashes with 36, 29 and 58 fatalities, respectively. None of the vehicles involved in the studied crashes were equipped with AEB or ACC.

Albeit the analysed data solely includes crashes in which a passenger car was involved, heavy vehicles may also be involved in rear-end and intersection crashes with passenger cars. The focus is on AEB and ACC systems in passenger cars, but heavy vehicles (e.g., trucks and busses) are also considered to be AEB- and ACC-equipped, when analysing the hypothetical potential of these systems to prevent crashes. In some rear-end and intersection crashes, a heavy vehicle equipped with AEB and ACC could have prevented the crash with a passenger car. The AEB system is also a viable system in the heavy vehicles, as e.g., Glassbrenner et al. (2017) have stated. The AEB system has been a mandatory equipment in new trucks in EU since 2015 (European Commission 2018).

The systems possibilities to prevent fatal crashes are evaluated by a crash-by-crash method. Each crash is analysed individually to consider AEB and ACC systems' operational conditions. The systems' operational conditions have an impact on the final decision in the analysis, whether the AEB or ACC system could potentially have prevented the crash. In this analysis, two possible outcomes are considered. Either the fatal crash is prevented by AEB and ACC, or due to unfavourable conditions, the systems cannot prevent the crash. In reality, mitigation of the consequences (e.g., a fatal crash turns to a crash with a serious injury) would be one option, but this is not considered in the analysis as it is difficult to assess the hypothetical mitigation of consequences. This means that in the analysis, the crashes that are not fully avoided are counted as non-avoided fatal crashes.

AEB and ACC systems' operational conditions and other requirements considered in the analysis (Table 1) are formed by studying user manuals of four different car models (Tesla Model S, Toyota Prius, Volkswagen Tiguan and Volvo XC

60). These conditions are also comparable with previous studies' assumptions excluding estimated vehicle speed, which has typically been displaced by speed limit in the previous studies.

Table 1 AEB and ACC systems' operational conditions. If all conditions are favourable, the systems can operate and prevent the crash. If at least one of the conditions are unfavourable, the systems cannot prevent the crash. The favourable and unfavourable conditions were defined by studying systems' restrictions in user manuals of four different passenger car models (Tesla Model S, Toyota Prius, Volkswagen Tiguan and Volvo XC 60).

System	Crash type	Favourable conditions for system's operation	Unfavourable conditions for system's operation
AEB (with pedestrian and cyclist detection)	-Pedestrian -Intersection	-Vehicle speed ≤ 60 km/h	-Vehicle speed > 60 km/h
		-Favourable weather and road conditions	-Snowfall, wet snow, fog or icy road surface
		-No intendedly caused crash	-Intendedly caused crash
AEB+ACC	-Rear-end	-Speed difference between vehicles ≤ 60 km/h	-Speed difference between vehicles > 60 km/h
		-Favourable weather and road conditions	-Snowfall, wet snow, fog or icy road surface
		-No intendedly caused crash	-Intendedly caused crash

In this study, AEB is considered to include a pedestrian and cyclist detection system. As depicted in Table 1, AEB can prevent pedestrian and intersection crashes if the AEB-equipped vehicle's speed is 60 km/h or lower, weather is favourable, and the crash is not intentionally caused. If any of these three conditions would be unfavourable, AEB cannot prevent the crash. In rear-end crashes, speed difference between the two vehicles is a determining factor instead of the vehicle speeds. In rear-end crashes, speed difference should be 60 km/h or less. Threshold value of 60 km/h has been determined by reviewing previous studies. For instance, Sander (2017) indicated that crash avoidance was very unlikely in intersection crashes, when speed of straight going vehicle was more than 60 km/h. Rizzi et al. (2014) stated that low-speed AEB system's probability to prevent rear-end crashes is clearly better at speed limit areas of 50 km/h or less compared to higher speed limit areas. In addition, Lubbe & Kullgren (2015) used maximum vehicle speed of 50-60 km/h, when they evaluated pedestrian AEB system's safety effects. Due to the determined 60 km/h threshold speed adopted in this study, AEB system is not considered to be able to prevent head-on crashes as the speed of both vehicles is typically high in these crashes (more than 60 km/h). Therefore, the prevention of head-on crashes is not considered in this study. Head-on crashes are also excluded in previous studies (e.g., Fildes et al., 2015; Rizzi et al., 2014), which have considered the safety potential of AEB systems.

At intersections, the AEB system can solely recognize other motor vehicles in front of the vehicle, but it cannot recognize them when they are approaching the possible collision point from other directions, as specific intersection AEB systems with wider field-of-view are not considered. In the analysis, intersection crashes can be avoided if the AEB-equipped vehicle is going straight through the intersection and other operational conditions of AEB are favourable. If the vehicle is turning, AEB cannot prevent the crash unless the other involved vehicle is going straight and is AEB-equipped. I.e., if both vehicles are turning vehicles, the AEB systems in the vehicles are not considered to be able to assist avoiding the crash. All intersection crashes are included in the data and the analysis. In the analysis, the effects of different approaching angles or collision angles were not considered in the possible crash prevention. In some intersection crashes, the straight going vehicle may be a motorcycle, which is not considered to be AEB-equipped in this study as AEB for motorcycles is not available (Savino, 2016).

Inclement weather conditions may also prevent the systems' operation. In this study, snowfall, wet snow and foggy conditions are considered as factors preventing the camera and radar sensors' operation. In addition, slipperiness on road due to icy conditions is considered as a factor preventing AEB system's proper operation. As AEB typically activates at the last moment to prevent the collision, icy road conditions would markedly decrease the ability to decelerate or to stop. Hence, the possibilities to prevent crashes in these circumstances are lower.

Intendedly caused crashes are also not considered to be preventable crashes by AEB and ACC systems, as the driver can turn off the systems. In most of the studied car models, the systems can be turned off by the driver, which enables intendedly caused crashes. In addition, the possibilities of AEB to prevent intendedly caused crashes is small, because vehicle speed is typically excessive in these cases (Dávideková and Greguš, 2017). Even though hitting other road users on purpose is not common in Finland, the analysed crashes included a couple of cases where the driver had intendedly hit another road user.

In addition to analysis of AEB and ACC systems' potential safety effects, a hypothetical path to increase the amount of potentially preventable crashes is also presented by evaluating other systems' safety potential with AEB and ACC. The analysis considers the potential effects of ISA, which prevents exceeding the speed limit. Additionally, intersection AEB systems and communication between vehicles allow AEB to recognize threats in potential intersection and rear-end crashes earlier. Finally, fully or highly automated vehicles would theoretically prevent crashes, which are not preventable by driver assistance systems (e.g., some pedestrian crashes).

4. Results

According to the analysis, 47 (41%) of 115 studied rear-end, intersection and pedestrian crashes could potentially have been avoided, if AEB and ACC systems had been deployed (Table 2). Forty-eight (39%) of 123 fatalities in these crashes could have been avoided (Table 3). The crash cost savings involving 47 prevented fatal crashes in three years would have been 146 million euros with the 3.1 million euros unit value of a fatal crash in Finland (Tervonen, 2016). The deployment of ISA systems with AEB and ACC was evaluated to prevent 13 crashes more (overall 60 of 115) as ISA would prevent exceeding the speed limit.

Table 2 The number and share of potentially preventable crashes in different crash types and vehicle speeds (intersection and pedestrian crashes) and speed differences (rear-end crashes).

Crash type	**The amount and share of preventable crashes, if AEB and ACC can prevent crashes in circumstances where the vehicle speed (VS) or speed difference (SD) is equal or less than…**		
	SD max 40 km/h	**SD max 50 km/h**	**SD max 60 km/h**
Rear-end	8 (24%) of 33	10 (30%) of 33	15 (45%) of 33
	VS max 40 km/h	**VS max 50 km/h**	**VS max 60 km/h**
Intersection	12 (23%) of 53	14 (26%) of 53	19 (36%) of 53
Pedestrian	7 (24%) of 29	10 (34%) of 29	13 (45%) of 29
Total	**27 (23%) of 115**	**34 (30%) of 115**	**47 (41%) of 115**

Considering the sensitivity analysis involving the maximum vehicle speed in intersection and pedestrian crashes or maximum speed difference in read-end crashes in which the AEB and ACC systems could prevent a crash, the number of hypothetically prevented crashes would be 27-47 (23-41%) of 115. The maximum number (47) of crashes could be avoided, if the vehicle speed or speed difference of up to 60 km/h would allow systems' proper operation. If AEB and ACC can prevent the crash, when vehicle speed is 40 km/h or less, solely 27 crashes (23%) could be avoided.

Table 3 The number and share of potentially preventable fatalities in different road user groups and vehicle speeds and speed differences.

Road user group	The amount and share of preventable fatalities, if AEB and ACC can prevent crashes in circumstances where the vehicle speed (in intersection and pedestrian crashes) or speed difference (in read-end crashes) is equal or less than…		
	max 40 km/h	**max 50 km/h**	**max 60 km/h**
Passenger car occupants	4 (7%) of 55	5 (9%) of 55	13 (24%) of 55
Pedestrians	7 (23%) of 31	10 (32%) of 31	13 (42%) of 31
Cyclists	16 (70%) of 23	19 (83%) of 23	21 (91%) of 23
Motorcycle riders	0 (0%) of 12	0 (0%) of 12	1 (8%) of 12
Others	0 (0%) of 2	0 (0%) of 2	0 (0%) of 2
Total	**27 (22%) of 123**	**34 (28%) of 123**	**48 (39%) of 123**

The best effectiveness in the terms of the highest percentage of prevented crashes was found in rear-end and pedestrian crashes. However, the amount of hypothetically preventable crashes is the largest in intersection crashes as the number of intersection crashes was the greatest in the analysed data. Regarding different road user groups, the best effectiveness is among crashes involving cyclists, as 91% of cyclists' fatalities in the studied crashes could potentially have been prevented.

Table 4 AEB and ACC systems' potential to prevent crashes and individual and combined reasons preventing the systems operation or activation. Bolded factors are reasons preventing the systems' operation and non-bolded factors allow the systems' operation. The numbers present the amount of crashes and the share of crashes studied.

Crashes AEB and ACC could have prevented	Crashes AEB and ACC could not have prevented and reasons why the crashes could not have been prevented					
Vehicle speed or speed difference 60 km/h or less	**Vehicle speed or speed difference more than 60 km/h**	Vehicle speed or speed difference 60 km/h or less	**Vehicle speed or speed difference more than 60 km/h**	Vehicle speed or speed difference 60 km/h or less	**Vehicle speed or speed difference more than 60 km/h**	**A motorcycle should have been AEB-equipped**
No intendedly caused	No intendedly caused	**Intendedly caused**	**Intendedly caused**	No intendedly caused	No intendedly caused	
Favourable road and weather conditions	Favourable road and weather conditions	Favourable road and weather conditions	Favourable road and weather conditions	**Unfavourable road and weather conditions**	**Unfavourable road and weather conditions**	
47 (41%)	44 (38%)	2 (2%)	2 (2%)	4 (3%)	5 (4%)	11 (10%)
Total amount 115 (100 %)						

As a single reason preventing AEB or ACC systems' proper operation, excessive vehicle speed was the most typical with 44 (38%) cases among the 115 crashes (Table 4). Overall, excessive speed appeared in 51 (44%) crashes as a single reason or one of the reasons. In Table 4, excessive speed is defined as the speed of more than 60 km/h in intersection and pedestrian crashes and the speed difference of more than 60 km/h in rear-end crashes. Intendedly caused crashes (4 crashes) and unfavourable weather and road conditions (e.g. snowfall in 4, wet snow in 1, fog in 1, and icy road surface in 3 crashes) were rarely the reasons to prevent AEB's operation.

By developing the vehicle and system requirements, the safety potential and crash cost savings could be further increased (Table 5). To prevent exceeding the speed limit by the introduction of ISA, 52% of the crashes in the three studied crash types could hypothetically have been avoided. In addition, specific intersection AEB systems and communication between vehicles would allow vehicles to warn the driver or stop the vehicle by the system in potential intersection and rear-end crashes. With connected systems, 87% of the crashes could potentially be avoided. Finally, we found that all of the studied crashes could potentially be avoided, if the vehicles would be highly automated (automation would replace the driver). These final advancements would hypothetically prevent the remaining pedestrian and cyclist crashes, and all intendedly caused crashes.

Table 5 AEB and ACC systems' potential to prevent fatal rear-end, intersection and pedestrian crashes with requirements on the infrastructure and the vehicle.

Infrastructure requirements	**Vehicle requirements (all vehicles equipped with current type of AEB and ACC unless otherwise mentioned)**	**Achievable crash reduction by AEB and ACC**	**Achievable annual crash cost savings**
No requirements	No extra requirements	41% (47 of 115 crashes)	49M€
No requirements	Exceeding the speed limit is prevented (Intelligent speed assistance deployed)	52% (60 of 115 crashes)	62M€
Infrastructure supports communication with vehicles	Exceeding the speed limit is prevented, connected vehicles and intersection AEB	87% (100 of 115 crashes)	103M€
Infrastructure supports communication with vehicles	Automation is responsible of driving and the driver cannot bypass it, connected vehicles, intersection AEB	100% (115 of 115 crashes)	119M€

5. Discussion

According to the analysis of fatal passenger car crashes in 2014-2016 in Finland, AEB and ACC could potentially have prevented 41% of rear-end, intersection and pedestrian crashes. This is 9% of the total number of fatal passenger car crashes. The result is based on a crash-by-crash analysis, in which estimated vehicle speed, weather and road conditions and intentionality were considered in assessing AEB and ACC systems' possibilities to prevent crashes. The crash reduction potential is not completely comparable to previous studies, which have typically studied some particular crash type. In this study, the analysed crash types were defined based on current AEB and ACC systems' operational conditions and previous studies, and all three crash types were included in the analysis to indicate the whole safety potential. In the previous studies, AEB has been found or has been estimated to prevent 35-57% of rear-end crashes, which is comparable to the results of this study (45%). Involving the potential to prevent pedestrian and intersection crashes, this study complements previous studies, which amount is low. Based on a simulation study of Lubbe & Kullgren (2015), AEB could prevent pedestrian crashes by 25-26%, which is clearly less compared to this study (45%). Overall, the safety potential of AEB in pedestrian and intersection crashes is not widely studied and there are not many publications on the issue.

Previous studies, which have evaluated AEB system's safety effects by analysing crash data, have typically utilized data on speed limits, which may differ from the actual speeds of the involved vehicles. This study utilized data on estimated vehicle speeds based on road accident investigation teams' assessment. Previous studies indicate that the probability to avoid a crash by AEB is minor, when the speed is more than 60 km/h. Consequently, 60 km/h was set as the maximum vehicle speed in pedestrian and intersection crashes and as the maximum speed difference in rear-end crashes for systems' operation. The sensitivity analysis (50 km/h and 40 km/h as threshold values instead of 60 km/h) indicates that the threshold speed is a significant factor for the potential safety effects. By developing the systems further to manage higher speeds and to handle demanding situations, the safety potential could be increased. For instance, if AEB would recognize the needs for activation earlier and ACC would recognize stagnant or lane-changing vehicles reliably, the safety potential could be higher.

Limiting vehicle speeds is also an option to increase the safety potential of AEB and ACC systems. For instance, ISA could prevent exceeding the speed limit and thus could decrease excessive speeds. According to the analysis in this study, 52% of the crashes could potentially have been avoided instead of 41% by deploying ISA with AEB and ACC. Weather conditions and intentional cause are also considered as reasons to prevent these systems operation, but according to the analysis, these were rarely obstacles for the operation. This further emphasizes the importance of low enough speed on the operation of AEB and ACC. As the low enough speed depends on the circumstances, the systems would have increased capabilities if these took into consideration e.g., the friction of the road in their operation.

As speed is a critical factor for the successful intervention of the systems, AEB can be seen as a more effective system in urban than rural environment, as speeds are typically lower on urban roads. However, stopping sight distances are greater in rural roads, which enhances the safety potential of AEB and ACC systems in these circumstances, and highlight the importance of AEB and ACC systems abilities to use sensor data from a far distance and to anticipate possible risks. Lower speeds in urban areas reflect AEB system's high safety potential in cyclist and pedestrian crashes as 91% of cyclist and 42% of pedestrian fatalities could potentially have avoided by AEB. It should be noted that the AEB system needs to be advanced enough to be able to prevent collisions with pedestrians or cyclists.

Most of the crashes between motor vehicles and cyclists are situated at intersections, where motor vehicles' speeds are typically lower than on other road sections, which enhances the possibilities of AEB and ACC systems to prevent crashes. The actual reason for the collision may have been confusion involving the traffic rules, poor visibility or inattention, but if the AEB system can detect the cyclist and if the vehicle speed is low, the system may help to avoid the collision. Low enough speed is also an important issue in pedestrian crashes. AEB's potential to prevent pedestrian crashes at intersections (e.g., crashes on pedestrian crossings) was clearly better than outside pedestrian crossings. This indicates motor vehicles' lower speeds at intersection areas compared to road sections without pedestrian crossings, where the driver is not prepared for pedestrians.

Higher speeds in motor vehicle crashes explain the system's lower potential in preventing passenger car occupants' fatalities compared to cyclists' and pedestrians' fatalities. For instance, in intersection crashes, the turning vehicle's speed is typically low, but the turning vehicle's sensors may not detect the other involved vehicle, if the other vehicle is going straight through the intersections with a high speed. As the straight going vehicle may not be at the intersection area at the time the turning begins, the AEB system's sensors of the turning vehicle cannot recognise the need for emergency breaking until it is too late. When vehicle speed of the straight going vehicle is high and there is a sudden obstacle, e.g., a turning or crossing vehicle in front of the vehicle, there may not be enough time for AEB to stop the vehicle. In comparison to cyclist crashes, which typically situate at urban streets and in which the involved vehicles' speed is typically low, the speeds in intersection crashes between motor vehicles are often too high for AEB's preventive action. The deployment and marketing of the intersection assistance system, which assists the turning vehicle to recognize potential obstacles on the driving path, would increase AEB's safety effects. Similarly, in rear-end crashes, there may not be enough time for AEB and ACC to decelerate, if the vehicle's speed is high and there is a stagnant vehicle in front, which is not recognized early enough by the driver.

To realize AEB and ACC systems' safety potential, the systems need to be turned on. The AEB system can be seen as a backup system for the driver in emergency braking situation. Hence, the utilization of the system does not require constant input of the driver and it could be turned on by default. Instead, ACC requires constant attention from the driver as the system may not always follow the leading vehicle due to different reasons, e.g., weather or the outward appearance of the leading vehicle. Drivers should not rely on the systems too much as AEB may not always activate and ACC may lose the leading vehicle.

The main assumptions and limitations of the study are discussed in Table 6. The limitations of this study depict many possible areas, in which both AEB and ACC could be developed as systems to provide increased safety benefits as well as issues, which can be addressed in future studies.

Table 6 Main assumptions and limitations in the study.

Assumptions and limitations	Explanation or comment
-AEB and ACC systems are considered to be effective in preventing three crash types: intersection, rear-end and pedestrian crashes. The systems are not considered to be able to prevent head-on crashes.	-The studied relevant crash types are defined based on operational conditions of current AEB and ACC systems and previous studies. Head-on crashes are not considered in this study as speeds in these crashes are usually high and AEB may not operate properly, when there is an oncoming vehicle.
-All motor vehicles (except of motorcycles) are assumed to be equipped with AEB and ACC and the systems are assumed to be always turned on.	-This assumption does not reflect current situation, where the vehicles involved in the crashes are rarely AEB- or ACC-equipped. Additionally, the systems are not always in use in the vehicles, which are AEB- or ACC-equipped as the driver may choose not to apply the system.
-Changes in the behaviour of the driver due to the deployment of AEB and ACC are not considered.	-The systems could affect driver behaviour, e.g., inattention could increase.
-Safety potential is analysed based on direct AEB and ACC systems' interference, e.g., warnings is not considered.	-For instance, an early warning signal of AEB could call driver's attention to apply brakes before the system makes an emergency brake action.
-The crashes are considered to be either avoided or they remain as non-avoided fatal crashes, when considering the safety potential AEB and ACC may deliver.	-The study does not consider e.g., the situations, where the crash would occur, but AEB's activation would turn fatal consequences to less serious.
-AEB and ACC systems can always recognize other road users in front of the vehicle.	-As an exception, adverse weather conditions are considered as an obstacle for systems' operation.
-In intersection crashes, the estimated speed of the straight going vehicle is critical in assessing the potential crash avoidance.	-In intersection crashes, turning vehicle's speed is typically low. The AEB system of the turning vehicle is not able to react to the straight going vehicle in order to avoid the crash.
-In rear-end crashes, the distance between vehicles was not considered. Instead, the speed difference is analysed in order to estimate the potential crash avoidance.	-AEB applies the brakes at the last possible moment and ACC cannot make a strong deceleration. Consequently, speed difference is a determining factor instead of distance in rear-end crashes.

6. Conclusions

This study analysed the potential crash reduction potential of AEB and ACC systems and discussed the reasons, which prevented the systems from operating and helping to avoid crashes. Progressive policy actions related to vehicle and infrastructure requirements were also presented to further increase the safety potential of AEB and ACC. This study supports the policy actions of making these systems mandatory in new vehicles. However, interaction between the driver and the assistance systems should be further researched and the uncertainties related to the assumptions and limitations of this study should be addressed. This study enhances the understanding of authorities and research community on the crash reduction potential of AEB and ACC systems in the three studied crash types and especially increases knowledge on the AEB system's possibilities to prevent pedestrian and intersection crashes.

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Prioritizing safety of traffic flow? Qualitative study on highly automated vehicles' potential to prevent pedestrian crashes with two different ambitions

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Prioritizing Safety or Traffic Flow? Qualitative Study on Highly Automated Vehicles' Potential to Prevent Pedestrian Crashes with Two Different Ambitions

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Abstract: Interaction between drivers and pedestrians enables pedestrians to cross the street without conflicts. When highly automated vehicles (HAVs) become prevalent, interaction will change. Although HAVs manage to identify pedestrians, they may not be able to assess pedestrians' intentions. This study discusses two different ambitions: Prioritizing pedestrian safety and prioritizing efficient traffic flow; and how these two affect the possibilities to avoid fatal crashes between pedestrians and passenger cars. HAVs' hypothetical possibilities to avoid different crash scenarios are evaluated based on 40 in-depth investigated fatal pedestrian crashes, which occurred with manually-driven cars in Finland in 2014–2016. When HAVs prioritize pedestrian safety, they decrease speed near pedestrians as a precaution which affects traffic flow due to frequent decelerations. When HAVs prioritize efficient traffic flow, they only decelerate, when pedestrians are in a collision course. The study shows that neither of these approaches can be applied in all traffic environments, and all of the studied crashes would not likely be avoidable with HAVs even when prioritizing pedestrian safety. The high expectations of HAVs' safety benefits may not be realized, and in addition to safety and traffic flow, there are many other objectives in traffic which need to be considered.

Keywords: highly automated vehicle; pedestrian; safety; safety potential; interaction

1. Introduction

Highly automated vehicles (HAVs) without human drivers are claimed to enhance traffic safety of all road users by eliminating human errors (see e.g., Fagnant and Kockelman [1]). The conversation about the safety benefits of HAVs has mostly focused on the elimination of driver errors, which may be the key factor to consider in collisions between motor vehicles. However, in the encounters between HAVs and other road users (e.g., pedestrians and cyclists), interaction between vehicle automation and humans is an important factor from the perspective of safety [2]. The elimination of driver error is also an important factor for improved safety in these encounters, but changes in interaction and behavior cause potentially new safety problems [3].

For pedestrians, eye contact with the driver is a clear message to decide to cross the street [3]. Text-based or visual messages, as e.g., Ackermann et al. [4] have described, can be options to replace eye contact when implementing HAVs. A more complicated task for HAVs is to assess pedestrians' intentions, e.g., whether they are about to cross the street. HAVs should always be cautious nearby pedestrian crossings as the pedestrians have a right of way, but all pedestrians walking or standing near a pedestrian crossing are not going to cross the street. Are HAVs able to specify these cases?

In theory, HAVs could be programmed to maximize safety in encounters with pedestrians and other road users. However, safety is not the only objective to be maximized in the transport system suggesting that HAV operation is likely a compromise between optimization of safety and other ambitions (e.g., flow of traffic, accessibility, travel time, environmental effects, etc.). Eventually, artificial intelligence may be able to understand the intentions of other road users, and at that point of development, encounters may not be as problematic as in the initial stage of HAV implementation. However, in the initial stage, traffic safety requires attention from various stakeholders to ensure the acceptance of the general public [5].

This study addresses the issue that the expected safety effects of the HAVs may not be realized if safety is not prioritized over other ambitions. As the other ambition, this study highlights the efficient flow of traffic, which can be seen to conflict with the safety ambition especially when discussing pedestrian traffic. By analyzing fatal crashes which have occurred between driver-managed passenger cars and pedestrians in Finland in 2014–2016, it is discussed whether HAVs—replacing the driver-managed cars in these crash scenes—could have avoided these collisions with pedestrians. Potential new crashes, which the HAVs could cause, are not discussed in this study. In the analysis, it is assumed that the HAVs operate faultlessly and reliably, e.g., there are no operational or programming errors. The hypothetical encounters between HAVs and pedestrians are studied qualitatively with in-depth investigated crash data, and it is analyzed whether prioritizing pedestrian safety or efficient traffic flow in HAVs operation leads to crash avoidance. This study aims to complement the discussion on highly automated vehicles and pedestrian safety and to point out issues to be considered in future.

In Section 2, encounters between HAVs and pedestrians are discussed based on previous studies. Thereafter, Section 3 describes the analyzed crash data and presents the method to analyze the data, i.e., the fatal crashes between driver-managed cars and pedestrians with the hypothetical setting in which HAVs replace the driver-managed cars. Results of the analysis are presented in Sections 4–6 for different types of pedestrian crashes. Finally, the two approaches, prioritizing pedestrian safety and efficient traffic flow are discussed in Section 7 and conclusions are presented in Section 8.

2. Interaction between Highly Automated Vehicles and Pedestrians

Human error is stated to be the main reason for traffic accidents in more than 90% of cases [6]. In an HAV, driving automation replaces the human driver and thus eliminates human error if the driver is fully removed from the driving task. This does not mean that errors would not be possible with HAVs as these are programmed by humans, and HAVs operate in various environments and interact with external objects in countless situations. Besides human error, other errors (e.g., poor roadway design), can constitute additional reasons for a crash [5]. In addition, at the initial stage of HAVs implementation, HAVs are likely to operate on roads without complex intersections and without encounters with other road users [7] and thus have a minor effect on pedestrian safety.

Even if we assume that automated vehicles' systems would not make a mistake while identifying pedestrians in any weather condition or that pedestrians' physical characteristics would not influence the identification, which may not be realistic according to Combs et al. [7], the interaction between HAVs and other road users is an important topic to discuss. Insufficient communication between drivers in conventional vehicles and pedestrians has been indicated to influence safety as pedestrians' decision to cross the street is greatly affected by the communication [8]. Even though the interaction in traffic situations is based on formal rules, the rules can be applied subconsciously and by non-verbal communication [9]. According to Dey and Terken [10], pedestrians do not usually show a clear message (e.g., a hand gesture) while interacting with drivers when they are about to cross the street, but they typically look in the direction of the approaching car. Understanding pedestrians' behavior and trajectories may be a challenge to HAVs' operation, but this should be able to be settled to guarantee safe encounters with other road users.

The safety of vulnerable road users (e.g., pedestrians and cyclists) requires specific focus while implementing driverless vehicles [11] as changes affect the traffic environment. Previous studies involving HAVs and pedestrians have investigated how HAVs could signal to pedestrians that they have been recognized. Ackermann et al. [4] indicated that pedestrians want a message from the HAV that they have been seen and can cross the street. Text-based messages were noticed as a better option compared to other light signals and symbols [4]. Lundgren et al. [12] argued that eye-contact should be replaced in one way or another to ensure safe interaction with HAVs. Especially in shared space areas, conflicting interactions between HAVs and pedestrians are likely without understandable communication [2].

Some other studies have found that safe interaction does not always need light or text signals. Rothenbücher et al. [13] studied the interaction in a field test, in which pedestrians thought that the vehicle was self-driving as the driver was hidden inside the vehicle and concluded that the pedestrians could manage an encounter with the HAV without any text or visual signals. The study noticed that pedestrians are adaptable road users as they are already used to operating without communication e.g., in dark conditions [13]. This argument is based on the observation that a vehicle's speed and distance to a pedestrian crossing are more important factors than the visual signal of HAVs would be when a pedestrian makes the decision to cross the street [3]. In addition, Tengvall [14] found that other road users (e.g., pedestrians), when interacting with an HAV, seem to be able to anticipate the HAV's operation by detecting its speed and trajectory, and changes in these factors. Consequently, simplifying the interactions (e.g., not implementing light or text signals) could lead to safer encounters as there would not be as many elements to handle during the interaction. In most encounters, pedestrians could probably rely on factors such as vehicle's speed and trajectory, while making the decision to cross the street or not. However, these factors do not always guarantee safe encounters, if e.g., a pedestrian does not recognize the approaching HAV, when the pedestrian is crossing the street. In addition, the HAV may not always recognize the pedestrian early enough. These situations, which finally determine HAVs' safety effects (e.g., cases requiring evasive action), need to be examined in more detail.

Detwiller and Gabler [15] assessed that HAVs could prevent 95% of the studied pedestrian injury crashes in the United States, if the pedestrian was visible over one second at the edge of the roadway or a driver violation caused the crash. Millard-Ball [16] found that potential risk-free operation of HAVs could enhance the status of pedestrians. Tengvall [14] focused on the interaction between a low speed driverless shuttle bus and other road users (e.g., pedestrians) and reported that clear safety benefits were not identified in these encounters compared to conventional vehicles. Some studies have evaluated the safety effects of automatic emergency braking (AEB) system with pedestrian detection, which is one area of vehicle automation. Lubbe and Kullgren [17] evaluated that the AEB system could decrease crash costs by 26% by preventing pedestrian crashes. The safety impact is not completely comparable to HAV's operation as the AEB system activates at the last possible moment before the collision, if the driver has not applied brakes. In addition, a human driver may break the law, e.g., by speeding, which has an impact on the AEB system's possibilities to avoid the collision as there is less time to stop the vehicle. Unlike the AEB system, HAVs should be able to anticipate forthcoming situations to increase the potential to avoid collisions with pedestrians and other road users.

How HAVs indicate that they have registered the pedestrian and that the pedestrian is safe to cross the street is an essential situation to be solved as e.g., Ackermann et al. [4] and Rodríguez Palmeiro et al. [3] have discussed. Before HAVs communicate to pedestrians by e.g., changes in vehicle speed or visual signals, the system needs to identify the nearby pedestrians, who are going to cross the street. It should be easy to identify pedestrians near the crossing by advanced technology, but it is challenging to analyze whether these pedestrians are actually going to cross the street or if they are just walking along the pavement next to a roadway without crossing. The latter would not demand action from the HAV, but in the first alternative, a conflict is possible without further actions. At the initial stage of implementation, HAVs may not be able to understand body language and non-verbal messages as human drivers do since the current algorithms assessing pedestrians' intentions are not good enough [18]. If the system cannot be sufficiently certain of the forthcoming location of the pedestrians some seconds before reaching the pedestrian crossing, the only way is to stop the vehicle or decrease vehicle speed to enable avoiding a potential collision, if the pedestrian would cross the street. Although these hypothetical procedures could ensure pedestrian safety, some other negative effects could be realized involving, for example, flow of traffic, travel times, and risk of rear-end crashes, when there are also conventional, driver-managed vehicles in traffic. It seems clear that a strategy or regulation should be implemented for the encounters in traffic between HAVs and other road users [2].

3. Data and Methods

This study assesses HAVs' hypothetical possibilities of crash avoidance by analyzing data of 40 in-depth investigated fatal pedestrian crashes, which took place in Finland in 2014–2016 and in which a driver-managed passenger car was involved. In these crashes, there were 41 pedestrian fatalities, i.e., in one crash two pedestrians were killed and, in the others, there was one pedestrian fatality per crash. Overall, there were 97 pedestrian fatalities in Finland in these years, when all involved vehicle types (e.g., heavy vehicles) are considered [19]. The analyzed data was provided by Finnish Crash Data Institute upon request for research purposes. By analyzing the crashes case-by-case, we discuss the impacts of two different ambitions, i.e., prioritizing pedestrian safety and efficient traffic flow in the operation of HAVs. The analysis is based on in-depth crash data and qualitative analysis methodology. In the analysis, we use crash data variables on the crash type, the pre-crash event, the immediate risk factor, the vehicle speed, the width of the roadway, the number of lanes, the location of the collision point, and the sight distance. In addition, written crash descriptions are used to have a better understanding of the pre-crash event. The variables and the crash descriptions on which the analysis is based are from the findings of the multidisciplinary crash investigations teams.

The operational capabilities of HAVs in adverse weather or low-light condition is not evaluated in this study, albeit adverse conditions are one of the main challenges in the development of HAVs. Inclement weather conditions pose a challenge to automated driving, but the technology is rapidly advancing, as e.g., the sensors of automated vehicles may already detect objects in foggy and dusty conditions, see e.g., TechCrunch [20]. In addition, dark conditions increase the risk of a pedestrian crash [21], but these conditions are not focused on in this study. However, it is important to ensure HAVs will be able to operate in dark conditions, because these conditions were identified in some of the studied 40 pedestrian crashes. In the crash analysis, the assessment is made based on the assumption that HAVs would be able to operate in all weather and light conditions. HAVs are also assumed to always follow rules and not drive through a red light, for example.

HAVs' possibilities to prevent fatal pedestrian crashes, which have occurred with driver-managed cars, are evaluated qualitatively by the authors based on the data. In the evaluation of crash avoidance possibilities, it is assumed that even if HAVs are able to identify the presence of nearby pedestrians, they are not able to assess pedestrians' intentions (e.g., intentions to cross the street). This assumption is based on the results of the literature review by Rasouli and Tsotsos [18] and the expert survey by Botello et al. [22], which state that the current algorithms cannot assess pedestrians' intentions in a way that the information could be used for automated driving. Based on the assumption, the evaluation of crash avoidance is made with two approaches related to different ambitions in traffic; could a HAV in a similar crash scene instead of the driver-managed car manage to avoid the crash, if prioritizing *(1) pedestrian safety* or *(2) efficient traffic flow*? Here, prioritizing pedestrian safety refers to the approach, in which the HAV would always take necessary safety precautions (e.g., slow down or stop depending on the situation), when there are pedestrians identified nearby the vehicle or in the proximity of the planned driving path. These precautions are taken in this prioritizing pedestrian safety approach as the HAV cannot be sure of pedestrians' intentions, e.g., whether they are going to cross the street. This is likely to cause unnecessary decelerations as all pedestrians nearby the roadway are not going to cross the street. This would consequently influence the flow of traffic, especially in urban areas with many pedestrians and vehicles.

In the second approach, in which efficient traffic flow is prioritized, the HAV slows down or stops only when a pedestrian is identified in the immediate collision course. In this approach, unnecessary decelerations can be avoided, but it is questionable if there is always enough time to brake and avoid collisions with pedestrians. Table 1 depicts the difference between the two ambitions and approaches (prioritizing pedestrian safety and efficient traffic flow) in the analyzed crashes.

Table 1. Description on the two highly automated vehicles' (HAVs') approaches used in the analysis of different crash scenes, prioritizing (1) pedestrian safety and (2) efficient traffic flow in HAVs operation.

How Would the HAV Operate in a Situation, in which ...	Prioritizing Pedestrian Safety	Prioritizing Efficient Traffic Flow
... a pedestrian was recognized to approach the roadway with an intersection trajectory, or a pedestrian was about to cross the street?	HAV decelerates to ensure avoiding the potential conflict	HAV continues to operate without actions
... a pedestrian stepped to the roadway?	HAV has decelerated in advance and hence, it only needs to apply the brakes moderately	HAV brakes strongly only just when a pedestrian is in a collision course and time to the possible collision is 1.5 s
In the following cases there is no difference between the two approaches		
... a pedestrian was recognized to be on the roadway (e.g., approaching oncoming traffic in the same lane)?	HAV decelerates strongly or moderately to avoid a collision	
... the driver had not obeyed the law, and had e.g., driven through a red light or was speeding?	HAV obeys the laws and thus can avoid the collision	
... the driver had drifted out of lane due to attack of illness?	HAV is in control of the car, and is not affected by illnesses	
... the driver had drifted out of lane due to loss of control and exceeding the speed limit?	HAV avoids exceeding the speed limit and thus manages to keep the right lane and the control of the car	
... the driver had crashed with a pedestrian during backing up or at a parking area?	HAV recognizes pedestrians during backing up and at parking area and can avoid these cases	
... the driver had intentionally caused the crash (i.e., the crash is due to suicidal act)?	The driver is considered to be able to override the automated driving system, and thus HAV is not able to avoid these crashes.	
... the pedestrian had intentionally caused the crash (i.e., the crash is due to suicidal act)?	The intentionally caused crashed by pedestrians are evaluated case-by-case.	

HAVs' possibilities to avoid the studied 40 fatal pedestrian crashes are evaluated from the perspective of the two aforementioned ambitions and approaches (pedestrian safety, efficient traffic flow) with three results on the potential outcomes of crash avoidance for each crash scene. The three possible outcomes are that (A) the crash would likely be preventable by the HAV, (B) the crash would likely be unpreventable by the HAV, or (C) the crash avoidance is unclear. The analysis of the crashes is divided to three different crash types because these differ in the way HAVs would operate according to the two ambitions. The crash types and the amount of studied crashes are: Thirteen pedestrian crossing crashes with two subtypes; crashes related to driver's behavior (four crashes) and crashes related to wrong observations (nine crashes), 13 crashes outside pedestrian crossings and 14 other pedestrian crashes. The first two crash types include crashes in which the pedestrian was crossing the street, whereas in the other pedestrian crashes the pedestrian was e.g., in a parking area. These three crash types are analyzed in Sections 4–6, respectively. As a contrast to the pedestrian crossing crashes, in which pedestrians have a right of way, the crashes outside pedestrian crossings differ from the HAV's point of view. To prevent pedestrian crossing crashes and to maintain undisturbed traffic, the HAVs should be able to identify pedestrians' intentions. Outside pedestrian crossings, HAVs could be designed not to assume that the pedestrian on a pavement or at the roadside is intending to cross the road. At least this would be the way according to the current regulation. According to the Vienna Convention [23], "pedestrians shall not step on to the carriageway without first making sure that they can do so without impeding vehicular traffic." The assessment principles of crash avoidance in the three different crash types are presented in Table 2.

Table 2. The assessment principles of crash avoidance in different crash types, when prioritizing (1) pedestrian safety and (2) efficient traffic flow in HAVs operation.

Crash Type		Prioritizing Pedestrian Safety	Prioritizing Efficient Traffic Flow
Pedestrian crossing crashes	Crashes related to driver's behavior	HAV maintains safe behavior and obeys the law	
	Crashes related to driver's wrong observations	HAV is assumed to be able to detect pedestrians in all circumstances and it decelerates early as a precaution	Crash avoidance is based on TTC analysis
Pedestrian crashes outside pedestrian crossings		HAV is assumed to be able to detect pedestrians in all circumstances and it decelerates early as a precaution	Crash avoidance is based on TTC analysis
Other pedestrian crashes		HAV maintains safe operation and avoids e.g., unintended lane departures, running off the road and parking area cases. TTC analysis also applied when possible and needed depending on the case.	

TTC analysis refer to time-to-collision analysis, in which the crash is assessed likely preventable if TTC > 1.5 s, unlikely preventable if TTC < 1.5 s, and crash avoidance is unclear if TTC = 1.5 s.

In the efficient traffic flow approach, HAVs are not assumed to decelerate when pedestrians are recognized nearby the vehicle. The HAV only decelerates when a pedestrian is identified in a collision course (e.g., when the pedestrian steps from the pavement to the roadway or is walking along the same lane where the HAV is driving). Consequently, time-to-collision (TTC) analysis is applied to evaluate whether there is enough time to decelerate and avoid the collision by the HAV, when the pedestrian steps to a roadway in pedestrian crossing crashes and crashes outside pedestrian crossings. TTC is calculated as presented in Equation (1) and rounded to the nearest 0.5 s. The crash is analyzed as unlikely preventable, if TTC is smaller than 1.5 s, because it represents a high collision risk and TTC = 1.5 s is when the system should apply the brakes at the latest [24,25]. If TTC is less than 1.5 s, there is likely too little time to avoid a collision. Cases with higher TTC than 1.5 s are assumed potentially preventable crashes. Cases, in which TTC was 1.5 s, are determined unclear cases.

$$TTC = \frac{s}{v_p} \tag{1}$$

In Equation (1), the distance (s) represents the distance between the point in which the pedestrian steps onto the roadway and the collision point in pedestrian crossing crashes or in other crashes with intersecting trajectories. The assumed pedestrian speed (v_p) is 1.2 m/s, which is based on the findings of Onelcin and Alver [26] and Rastogi et al. [27]. In some of the analyzed crashes, the pedestrian was already on the roadway or in the collision point, when the HAV could firstly have recognized the pedestrian. In these cases, the sight distance is utilized as the distance (s) and the car's speed (v_c) is used instead of pedestrian's speed. The sight distance is the distance between the point from which the collision point could firstly have been recognized by the HAV and the collision point. TTC analysis cannot be applied if the crash is situated at a parking area, the crash involved reversing, or the crash was intentionally caused. In addition, the TTC analysis is not applied if the crash took place due to loss of control of the car as in these crash scenes the crash avoidance is managed by HAV safe operation as described in Table 2.

4. Pedestrian Crossing Crashes

The studied 13 fatal pedestrian crashes in pedestrian crossings (Table 3) involved mostly human errors, e.g., the driver did not observe the pedestrian (at all or early enough) while driving through the pedestrian crossing. In addition, excessive vehicle speed or driving through a red light were reported in some cases. Two crashes involved misunderstanding as the driver expected the pedestrian to yield. For example, if a pedestrian stops before crossing the street, the driver may think that the pedestrian is yielding, although the pedestrian has a right of way. Without informal signals, e.g., waving a hand, both road users may think they may continue safely. Crashes presented in Table 3 were analyzed individually, but similar crashes in terms of the analysis and its results, if these existed, are presented together.

Table 3. The studied fatal pedestrian crashes with driver-managed passenger cars situated in pedestrian crossings and assessment of crash avoidance in two approaches, i.e., prioritizing pedestrian safety or efficient traffic flow by a HAV.

Crash Description (Number of Crashes if More than One)	HAV Prioritizing Pedestrian Safety	HAV Prioritizing Traffic Flow
Crashes related to a driver's behavior:		
The driver was speeding and dazzled by sunlight, TTC = 4.5 s	Likely preventable	Likely preventable
The driver was speeding, TTC = 4.5 s	Likely preventable	Likely preventable
The driver was speeding and drove through a red light, TTC = 10.0 s	Likely preventable	Likely preventable
The driver was speeding and competing with another driver, TTC = 1.5 s	Likely preventable	Likely preventable
Crashes related to driver's wrong observations: The driver did not recognize the pedestrian, or the driver assumed the pedestrian would yield, TTC = 2.0–4.5 s (five crashes)	Likely preventable	Likely preventable
The driver did not recognize the pedestrian, TTC = 1.5 s (three crashes)	Likely preventable	Unclear
The driver did not recognize the pedestrian, TTC = 1.0 s	Likely preventable	Unlikely preventable

The analyzed pedestrian crossing crashes are all likely preventable by HAVs prioritizing pedestrian safety. The HAVs can drive cautiously and with decreased speed nearby the pedestrian crossings as these are clearly visible in the road environment. If the HAVs prioritize efficient traffic flow, TTC has a key role when assessing the possibilities for crash avoidance related to analyzed crashes with drivers' wrong observations. In the analyzed crashes in which the driver had not obeyed the obligation to yield due to wrong observations (e.g., the driver had not recognized the pedestrian at all or early enough), the HAV is assessed to be able to recognize the crossing pedestrian. However, in the efficient traffic flow approach, there may not always be enough time to avoid the collision as the HAV does not decelerate until the pedestrian is already in front of the vehicle and has started to cross the street. Five of the nine crashes related to wrong observations are determined likely preventable based on TTC analysis in the prioritizing efficient traffic flow approach. In three crashes in which a driver had not recognized the pedestrian, TTC was 1.5 s. As described in Section 3, the avoidance of these crashes is determined as unclear, because it is difficult to evaluate whether the crash would be preventable or unpreventable. One crash, in which TTC was less than 1.5 s, is assessed as unlikely preventable. In the crashes related to wrong observations, vehicle speeds varied between 15 km/h and 50 km/h. In the crashes related to a driver's behavior, speeds were between 58 km/h and 120 km/h.

5. Pedestrian Crashes outside Pedestrian Crossings

In the analyzed data, there were 13 fatal pedestrian crashes in road areas outside pedestrian crossings (Table 4). In most of these crashes, the pedestrian was crossing the road, and the driver did not recognize the crossing pedestrian at all or early enough. In some of the crashes, the pedestrian was standing on the roadway or approaching oncoming traffic in the same lane. Again, similar crashes in terms of the analysis and its results, if these existed, are presented together in the table.

Table 4. The studied fatal pedestrian crashes with driver-managed passenger cars situated outside pedestrian crossings and assessment of crash avoidance in two approaches, i.e., prioritizing pedestrian safety or efficient traffic flow by a HAV.

Crash Description (Number of Crashes if More than One). The Driver did not Recognize . . .	HAV Prioritizing Pedestrian Safety	HAV Prioritizing Traffic Flow
. . . the pedestrian crossing the street, TTC = 4.5 s (five crashes)	Likely preventable	Likely preventable
. . . the pedestrian standing on the roadway, TTC = 4.5–10.5 s (two crashes)	Likely preventable	Likely preventable
. . . the pedestrian approaching oncoming traffic in the same lane, TTC = 5.0 s	Likely preventable	Likely preventable
. . . the pedestrian crossing the street and there was not enough time to stop, TTC = 1.5 s (four crashes)	Likely preventable	Unclear
. . . the pedestrian, who crossed the street suddenly, TTC = 0.5 s	Likely preventable	Unlikely preventable

All of the analyzed crashes on road sections without pedestrian crossings are likely preventable by HAVs in prioritizing pedestrian safety approach, as the HAVs operate cautiously and decrease speed to guarantee short stopping distance and ability to react to possible conflicts. Most of the crashes are also likely preventable in the prioritizing efficient traffic flow approach, but TTC values are at the critical threshold (1.5 s) in four crashes, in which avoidance is classified as unclear. Due to a small TTC margin, these four crashes may not be preventable, but the impact speed would likely be small. In addition, one case, in which a pedestrian crossed the street all of a sudden, is assumed likely unpreventable due to short TTC. Vehicle speeds varied from 30 km/h to 80 km/h in these 13 crashes.

6. Other Pedestrian Crashes

Besides the crashes described in Sections 4 and 5, there were 14 other types of fatal crashes between pedestrians and passenger cars in the analyzed data (Table 5). Most of these crashes were situated in parking areas or involved reversing. In some cases, the car had drifted out of the lane and hit a pedestrian. The data also included one case in which the pedestrian was hit by a car which was in a rear-end collision. In two cases there was suicidal behavior, of which one was by the driver and the other by the pedestrian. Again, similar crashes in terms of the analysis and its results, if these existed, are presented together in the table. In most of the crashes, TTC analysis is not applicable.

The crashes with reversing cars and in the parking areas, were assessed to be likely preventable by HAVs in both approaches. HAVs were also analyzed to be likely able to prevent crashes in which the car had drifted out of lane, e.g., due to a driver's attack of illness or loss of control of the vehicle, as the HAV does not drive with an excessive speed in curves or is not affected by attack of illness. The rear-end crash between two motor vehicles, in which the crashed vehicle hit a pedestrian was also analyzed to be likely preventable in both approaches, because the HAV is assumed to recognize the rear-ended vehicle earlier. In this case TTC was 10.0 s, when the sight distance and vehicle's speed is considered. The crash, in which a pedestrian was under the vehicle, when the car started to back up, was assessed to be likely unpreventable as the HAVs were not assumed to have sensors which would recognize objects under the car. The analyzed crash including suicidal action by the driver is likely unpreventable as we consider that the driver is able to bypass the automation if they choose to do that as discussed in Section 3. The crash related to pedestrian's suicidal act was also assessed likely unpreventable due to sudden act of the pedestrian. In most of the studied crashes, vehicle speeds were usually low e.g., smaller than 15 km/h. In four crashes speeds varied from 70 km/h to 125 km/h.

Table 5. The studied other fatal pedestrian crashes with driver-managed passenger cars and assessment of crash avoidance in two approaches, i.e., prioritizing pedestrian safety or efficient traffic flow by an HAV.

Crash Description (Number of Crashes if More than One)	HAV Prioritizing Pedestrian Safety	HAV Prioritizing Traffic Flow
A reversing car or parking area crash, TTC = NA (six crashes)	Likely preventable	Likely preventable
The car drifted out of lane due to a driver's attack of illness and hit a pedestrian, TTC = NA (three crashes)	Likely preventable	Likely preventable
A vehicle exceeded a speed limit by 20 km/h and drifted out of lane, and hit a pedestrian, TTC = NA	Likely preventable	Likely preventable
The driver did not recognize a stopped vehicle on the road and hit the vehicle. The vehicle involved in a rear-end collision hit a pedestrian, TTC = 10.0 s	Likely preventable	Likely preventable
A pedestrian was under the car when it started to back up, TTC = NA	Unlikely preventable	Unlikely preventable
Driver's suicidal behavior, TTC = NA	Unlikely preventable	Unlikely preventable
Pedestrian's suicidal behavior, TTC = NA	Unlikely preventable	Unlikely preventable

NA = Not Applied.

7. Discussion

Previous studies on highly automated vehicles from the perspective of pedestrians and pedestrian safety have mainly focused on the interaction and alternative ways to communicate to the pedestrians that they are seen. As one starting point for this study was the finding that HAVs may not be able to interpret pedestrians' non-verbal messages as human drivers do, and thus HAVs cannot be sure whether the pedestrian nearby the roadway is going to cross the street. We found no previous studies with a similar setting to analyze the possibilities to prevent pedestrian crashes by considering HAVs instead of driver-managed cars in actual fatal crashes, and with two approaches, prioritizing pedestrian safety or efficient traffic flow.

Although the number of analyzed crashes in this study is only 40, the crash types and crashes are comparable to larger sample studies e.g., in the United States. According to Dai [28], in 37% of the studied pedestrian injury crashes (n = 7195) in Atlanta, the trajectories of a pedestrian and a driver intersected outside pedestrian crossings and the trajectories intersected in a pedestrian crossing in 22% of the cases. In this study, the correspondent shares (33% and 33%, respectively) are relatively close to Dai's [28] study. In addition, in Kemnitzer et al.'s [21] study on pedestrian crashes (n = 11,241) in Ohio, 33% of the crashes were situated at the pedestrian crossing, which is comparable to our study. Next HAVs' possibilities and challenges in enhancing pedestrian safety are discussed in the three different types of pedestrian crashes analyzed in this study.

7.1. Pedestrian Crossing Crashes

HAVs' possibilities to prevent crashes in pedestrian crossings assessed seem promising as all 13 studied fatal crashes could potentially be preventable by the approach prioritizing pedestrian safety. In this approach, driver-related errors (e.g., driving through a red light) are assumed to be avoided by the HAV. In addition, cautious automated driving would ensure that the HAV would have enough time to stop or make an evasive action in the potential conflicts with pedestrians. The pedestrians have a right of way at the pedestrian crossings, but sometimes they may let cars go first by waving a hand or without any visual communication. These situations may be hard to interpret by the HAVs and cause even longer delays and stops in traffic, when automated driving is introduced. It is also worth noting that pedestrian crossings on urban streets are often signalized. In signalized pedestrian crossings there would be no need to evaluate pedestrians' intentions if HAVs could assume that all road users follow the signals.

Prioritizing safety over other ambitions in HAV operation by e.g., slowing down before pedestrian crossings as a precaution, when there is a pedestrian nearby the pedestrian crossing, is a potential mode on urban streets with speed limit of 30–40 km/h and relatively low amount of vehicular traffic and pedestrians. If there is a great amount of pedestrian traffic, HAVs may end up totally jammed as these would be cautious to proceed if there is a risk of pedestrians coming to a collision course. Traffic lights would help HAVs in these situations as well as a defined "safe" speed, with which the HAV would pass pedestrians even if they are close to the road. The safe speed should be defined for different traffic environments and situations, but to avoid fatal consequences, the speed must be moderate. The discussion about the safe speed relates to many stakeholders, from city dwellers and citizens to local government and state officers, from HAV developers to international organizations, such as the UN and EU.

Driving with lower speed than what is allowed by the speed limit in the prioritizing pedestrian safety approach may, however, cause other undesired impacts such as rear-end crashes in traffic with automated and driver-managed vehicles, and reduced traffic flow due to lower speeds and decelerations. Despite possible inconveniences for vehicular traffic, the pedestrians should be prioritized over vehicles on urban areas (see e.g., ETSC [29]; Toroyan et al. [30]) and hence, low speeds and cautious driving patterns are recommendable for HAVs in urban streets. In urban areas with higher speed limits, the prioritizing pedestrian safety approach may conflict with other ambitions (e.g., efficient traffic flow) and hence, this approach may be difficult to implement as such.

Low speed limits (e.g., 30 km/h) in urban areas could also allow HAVs to operate with the efficient traffic flow approach, as HAVs then could have enough time to avoid the collision, although the braking would not start until a pedestrian is in the collision course in front of the HAV. However, the crash avoidance would highly depend on the distance to a pedestrian, when the evasive action is taken. According to TTC analysis, nine of the 13 analyzed crashes would likely be preventable as the HAV would probably have enough time to avoid the collision, when the pedestrian is recognized in a collision course. The avoidance of three of the remaining four crashes was unclear, because in these cases TTC values (1.5 s) reflect a high collision risk and hence, crash avoidance could not be determined. However, if the crash would occur, impact speed would likely be low and hence fatal consequences could likely be avoided. Less than 2% of the collisions between a pedestrian and a passenger car end up with fatal consequences at impact speed of 30 km/h [31]. In addition, in some cases, only a minor change in vehicle speed could lead to crash avoidance, because the pedestrian may have passed a collision point. It should be noted that the prioritizing efficient traffic flow approach may not be desired from the perspective of pedestrians, because the HAV seem to ignore them until the last possible moment when the HAV brakes heavily to avoid the collision or mitigate its consequences. This affects the perceived safety of pedestrians. Heavy braking would also be unpleasant for HAVs' passengers, too. On roads with higher speed limits and non-signalized pedestrian crossings, the HAVs should not operate in the prioritizing efficient traffic flow mode, because all crashes could probably not be avoided, and the greater the speed is, the more likely are the serious consequences.

7.2. Crashes Outside Pedestrian Crossings

Based on the analyzed 13 crashes, HAVs would not likely be able to avoid all pedestrian crashes which are situated outside pedestrian crossings. This is because HAVs are not likely able to adopt a policy in which they would reduce speed considerably and prepare for a quick stop whenever there is a pedestrian nearby the roadway. Preparing for all possible conflicts would reduce the flow of traffic considerably. HAVs can be programmed to expect that pedestrians obey their responsibility to yield, but in theory, HAVs can also be designed to avoid collisions with pedestrians in all situations to emphasize the important role of pedestrians in (urban) traffic. If HAVs are programmed to avoid collisions in all situations, also e.g., when there are no pedestrian crossings, pedestrians may take advantage of this feature and change their behavior, increasing risk in encounters with HAVs [16]. For instance, the pedestrians could cross the road anywhere without a worry as HAVs would take evasive action in all situations. Thus, the approach of prioritizing pedestrian safety could eventually lead to undesired outcomes.

Whether HAVs are programmed to prioritize pedestrian safety or not seems to have a significant effect on the possibility of crash reduction in the crashes outside pedestrian crossings. In the prioritizing pedestrian safety approach, all 13 crashes situated on other road sections than pedestrian crossings would likely be preventable. Solely eight of 13 crashes could potentially be preventable if the efficient traffic flow approach is prioritized. However, four of the remaining five crashes were assessed as unclear as TTC was evaluated to be at the critical threshold. This could mean that fatal consequences could potentially be avoided in these cases, although the collision would still occur.

As the efficient traffic flow has been one of the key goals of traffic planning, it is possible that HAVs will be programmed to minimize anomalies in traffic flow. This could mean that the vehicles would not decelerate their speed as precaution on road sections without pedestrian crossings, although pedestrians are identified at the roadside. If a pedestrian is crossing the road and the HAV is on a collision course, the time distance defines whether there is enough time to avoid the collision. Some of the crashes, which currently happen with driver-managed cars, e.g., when the pedestrian is standing on the roadway in dark conditions or oncoming traffic is approaching in the same lane, are likely to be avoided if HAVs can identify the pedestrian earlier than the human driver currently does. Evasive action (e.g., steering the vehicle to other driving path) could be another option to avoid the collision with a pedestrian in front, but at the same time, the vehicle may hit oncoming vehicles or some other obstacles. If the HAV is able to assess different options for crash avoidance and the crash is not avoidable, ethics involving the decision-making is another challenge, as e.g., Lin [32] has discussed. However, the approach, i.e., how the HAVs are going to operate, has a notable impact on the outcomes, and thus, the operation principles should be widely discussed from various perspectives.

7.3. Other Pedestrian Crashes

The analyzed other pedestrian crashes included a wide range of different types of crash scenes (e.g., crashes, where the car drifted out of lane, reversing and parking area crashes, and suicidal acts) despite the low amount of crashes analyzed (14). The versatility of the cases makes them difficult to consider in HAV development, because there are numerous situations which could take place with pedestrians. It was assessed that 11 of 14 other pedestrian crashes were likely preventable by HAVs prioritizing pedestrian safety as well as in the prioritizing efficient traffic flow approach.

Some of the reversing and parking area crashes could already be avoided with partially automated vehicles, e.g., with parking assistance or AEB systems. However, HAVs may not be able to prevent some of the other pedestrian crashes at all or at least in the early stage of HAVs implementation. For instance, the crash in which a pedestrian was under the vehicle when the car started to back up was assessed to be likely unpreventable in this study, but such a crash scene could be preventable in a longer term as the sensors would develop and also recognize objects under the vehicle. Additionally, crashes with suicidal behavior can remain difficult to be avoided by vehicle automation. The suicidal crashes caused by the driver can be prevented only if the driver cannot bypass the driving automation system. Overall, the group of other pedestrian crashes includes a wider range of cases compared to two other groups, and hence it is possible that crashes in this group are the last remaining unavoidable crashes when HAVs develop and become prevalent.

7.4. General Discussion

In this study, the prioritizing pedestrian safety approach referred to the principle that if an HAV would not be sure about the pedestrian's intention to cross the street when the pedestrian is walking or standing nearby the roadway, the HAV would always slow down or stop as a safety precaution. Although this mode aims to maximize pedestrian safety, it can also cause unnecessary decelerations or stops, which influences the flow of traffic and may increase the risk of rear-end crashes in traffic including both automated and conventional, driver-managed vehicles. This raises the question, would the drivers be willing to decrease speed similarly as the HAV could do to maximize pedestrian safety? If adopting lower speeds, the human drivers would also have more time to react to obstacles and make an evasive action. In urban traffic, especially in residential areas, lowering the speed limit from 40 to 30 km/h has become widespread [33], which allows both current driver-managed and future automated vehicles more time to recognize nearby pedestrians and make an evasive action in different scenarios. Slowing down as precaution on the roads, which have been designed for high volume of motor vehicle traffic, may not be acceptable by drivers. Consequently, HAVs may not be able to avoid all crashes at these streets if not decreasing their speed when pedestrians are recognized.

As different modes and policies in HAVs' operation are possible, it is not certain that all HAVs by different manufacturers and in different traffic environments would be programmed to operate according to a similar policy. To avoid misunderstandings, as well as undesired and unexpected outcomes, an integrative regulation for HAVs' operation is important to implement. As HAVs would replace drivers and thus reduce driver error, errors made by pedestrians and other road users, e.g., cyclists, remain. In addition, the persons requiring special attention (e.g., visually impaired people, elderly, and children) should be taken into consideration in the operation of HAVs.

In the encounters between pedestrians and HAVs (e.g., when a pedestrian crosses a street), the possibility to avoid a collision is affected by the HAV's speed and whether the HAV decelerates as a precaution before the pedestrian steps to a roadway (e.g., pedestrian safety approach). If the HAV decelerates in advance to the reduce crash risk, the flow of traffic is affected. If we want HAVs to be able to avoid all pedestrian crashes, the flow of traffic is greatly compromised. What should be the balance between these two ambitions? What level of safety do we accept? What is the traffic flow we are not willing to compromise? The HAV could e.g., calculate its speed so that is able to make a full stop before the crash with a certain deceleration which would also be acceptable from the HAV's passenger's point of view. It could also calculate that in case of pedestrian crash the impact speed would be below a threshold value (e.g., 10 km/h), but even with a low impact speed preventing fatal consequences is not certain. By accepting some other level than zero fatalities, we are not fulfilling vision zero, which sets the target of no deaths or serious road injuries, and thus is in conflict with the vision adopted in many countries and e.g., a long-term strategic goal of the EU [34]. In addition to safety and traffic flow, there are many other objectives in traffic and the whole transport system which need to be considered and discussed to form a compromise about.

8. Conclusions

Different ambitions, e.g., prioritizing pedestrian safety and ensuring efficient traffic flow, related to automated driving are a challenge to the realization of high-pitched hopes on HAVs' safety potential. This study complements the discussion on aspects to be considered in the development of highly automated vehicles in relation to pedestrian traffic by the developers of HAVs, authorities, decision makers, and others. The 40 case-by-case analyzed fatal pedestrian crashes from 2014–2016 in Finland reveal the complexity of pedestrian safety in relation to HAV development.

Of the 40 fatal crashes analyzed in this study, 28 would likely have been avoided if HAVs had been involved instead of driver-managed cars, and the HAVs operated according to the prioritizing efficient traffic flow approach. If, instead, pedestrian safety would be prioritized, nearly all analyzed pedestrian crashes (37 of 40 crashes) would likely be avoided. The result in the pedestrian safety approach is also comparable to the study of Detwiller and Gabler [15], which evaluated that 95% of the pedestrian injury crashes could be avoided by the HAVs. Although pedestrian safety is clearly better in this approach, this is not an obvious choice to implement as such, because e.g., the flow of traffic would be affected. Traffic is a compromise of many factors and hence, safety cannot be prioritized over other ambitions without proper considerations. In different traffic environments (e.g., urban areas and rural roads), the different ambitions are likely to lead to diverse solutions, e.g., where there is a large number of pedestrians or vehicles.

The analysis is based on a relatively small number of crashes and on the hypothetical evaluation of HAVs' possibilities to prevent crashes. This presents uncertainty in the numbers presented in this analysis, but simultaneously highlights many important aspects, which affect the potential and limitations of HAVs. It should be noted that the assessment of crash avoidance is hypothetical as all factors cannot be considered and we do not know how the HAV would be able to operate in different crash scenes. For instance, in some likely unpreventable or unclear crashes, fatal consequences could potentially have been avoided due to smaller impact speed. Additionally, the assumptions made in the study, especially that the HAVs are able to operate faultlessly and reliably in all circumstances, e.g., poor weather and darkness, require developing HAV technology and should be acknowledged and studied further in future.

This study shows that the potential safety effects of highly automated vehicles are dependent on many factors, of which other road users' behavior is one of the most important. Regardless of the approach and policy that HAVs adopt, crash prevention should consider a wide array of issues. Further studies should carry on the research and discussion involving the interaction between HAVs and other road users, indicate potential challenges, and propose solutions in these encounters. A larger amount of studied crashes would probably raise more issues into awareness, and with a quantitative approach also statistical analysis could be applied. Future studies should also address other ambitions besides safety and traffic flow, which need to be considered in addition to approaches discussed in this study. Studies should also look into the wider impacts on transport systems, besides pedestrian safety.

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IV

How automated vehicles should operate to avoid fatal crashes with cyclists?

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How automated vehicles should operate to avoid fatal crashes with cyclists?

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ABSTRACT

The study assesses what kind of features would allow highly automated vehicles' (HAVs) safe operation in encounters with cyclists and allow avoiding fatal crashes between cyclists and passenger cars. Five features of HAVs' capabilities are formed based on previous studies and evaluated qualitatively using data from fatal crashes between driver-managed passenger cars and cyclist in Finland. By analysing these crashes, it is assessed which features HAVs should have in order to avoid each crash in a hypothetical setting, in which driver-managed cars would be replaced by HAVs. The necessary features of HAVs for crash avoidance are analysed crash-by-crash by considering the obligation to yield, visual obstacles at the crash scene and driver's behaviour prior to the crash. In order to avoid different types of fatal crashes with cyclists, the HAVs should be able to recognize nearby cyclists (feature 1), be aware of the priority rules in various intersections and traffic situations (2), indicate its intentions to cyclists (3), maintain safe driving patterns and anticipate future situations (4), and assess cyclists' intentions (5). Albeit the number of different features to allow crash avoidance is only five, implementing these features is a considerable challenge for HAVs' programming and design, as these should function in various and complex traffic situations. The study discloses the complexity in the encounters between HAVs and cyclists, which are to be considered in further studies and real-world implementations.

Keywords: Highly automated vehicle, HAV, cycling, safety, crash avoidance.

1 INTRODUCTION

Increased safety is one of the benefits highly automated vehicles (HAVs) are expected to deliver. Especially, safety of motor vehicle traffic would be enhanced, when human drivers are replaced by driving automation (Fagnant & Kockelman 2015). Even if the HAVs would become mainstream as forecasted e.g., by 2050 or by 2060 (Litman 2020), humans will still remain as important and visible road users as cyclists and pedestrians. In the encounters between HAVs and other road users, interaction is an essential factor to consider from safety perspective (Merat et al. 2018). However, as HAVs are mainly operated under test environments, knowledge on the encounters with other road users, and especially with cyclists, is currently deficient.

Studies on drivers' yielding behaviour have shown a great challenge in the encounters with the cyclists due to inconsistency as the drivers sometimes obey the priority rules, but in some cases, the drivers may ignore their obligation to yield to the cyclists (Räsänen & Summala 2000; Silvano et al. 2016). Even though the rules would obligate the cyclist to give way, the drivers may yield to cyclists at intersections (Silvano et al. 2016; van Haperen et al. 2018), and sometimes the drivers may not yield to cyclists, albeit the drivers should give way. HAVs are likely designed and programmed to obey formal traffic rules (e.g., the obligation to yield), which would supposedly make the encounter more predictable from cyclists' perspective. However, the cyclists may not always obey their obligation to yield (Räsänen et al. 1999), and therefore the question arises whether HAVs could and should be programmed to recognize and anticipate these situations to ensure safe encounters. In order to manage this task, the HAVs should be able to assess the cyclists' as well as other road users' intentions, which is likely to be a challenge for the HAV's operation (Botello et al. 2018).

So far, there are only a few studies, which have focused on the interaction between HAVs and cyclists. According to a photo experiment made by Hagenzieker et al. (2020), cyclists were not more confident to be noticed by HAVs compared to manually driven cars in bicycle-car interactions. Cautiousness towards HAVs was evident as the cyclists were found to be similarly sure that the driver or the HAV would stop for them. In addition, it was found that the appearance of the HAV is important for the interaction from cyclist's point of view. Merat et al. (2018) studied the interaction between cyclists and pedestrians and an automated shuttle bus (ASB) in a shared space area without lane markings and concluded that other road users thought that the ASB should yield and have an external way to communicate in the encounters. Tengvall (2018) noticed that interaction with the ASB of the same type was considered to be simpler compared to a human driver as the ASB either reacted clearly (e.g., decelerated or stopped) while in collision course with other road users or the ASB ignored others and continued moving. Tengvall's (2018) study did not recognize clear safety benefits from the perspective of cyclists or other road users in case of ASB encounters. Rodriquez et al. (2016) found that cyclists felt the interaction with the ASB at unsignalised intersections less safe compared to a driver-managed vehicle. These studies suggest that an HAV may simplify the interaction and encounters from the perspective of cyclist and other road users, but acceptable and practical procedures should be developed for the interaction.

The aim of this paper is to qualitatively assess, what features would allow HAV's safe operation in encounters with cyclists and allow avoiding fatal crashes between cyclists and passenger cars. Related to the aim, the key questions this paper aims to answer are:

1) What features should an HAV (i.e., a passenger car with an automated driving system) have in order to manage safe encounters with cyclists?

2) How would these features help to avoid crashes, which have resulted to fatalities in actual crash scenes between cyclists and driver-managed passenger cars?

2 METHODS AND DATA

Firstly, this section describes the different features related to HAVs' design and operation, which would allow HAVs' safe operation in the encounters with cyclists. The features are described based on findings from previous studies and a preliminary analysis of the crash data. Secondly, data on fatal crashes between cyclists and passenger cars are presented. Finally, the method to analyse the needed HAVs' features to avoid each studied crash is presented.

2.1 Features of HAVs to acknowledge cyclists and provide cycling safety

As the HAVs are still mostly non-existing in real traffic settings and the knowledge on the encounters between the HAVs and the cyclists is limited, this section refers mostly to studies, which discuss the interaction between driver-managed cars and cyclists. The few existing studies on interaction between HAVs and cyclist are also referred. The findings from previous studies and a preliminary analysis of the crash data are used to define the features of HAVs, which would be needed to acknowledge safety in the encounters with cyclists. The preliminary analysis of the crash data was used to gather understanding on the occurrence of crashes by analysing crash types, crash descriptions and other variables (e.g., speed, visual obstacles etc.) that enable identifying key factors associated to undesirable outcomes. Features are presented in a numerical order following a paragraph, which describes and reasons the features. The features relate to cyclist recognition (section 2.1.1), following the rules and indicating intention (section 2.1.2), and safe behaviour and situational awareness (section 2.1.3).

2.1.1 Features related to cyclist recognition

Feature 1 (recognize): HAVs should always recognise all road users which may end up on a collision course.

In order to operate safely, the HAV should be able to recognize all nearby road users, which may end up on a collision course in all situations, including also e.g., bad weather. One essential factor related to yielding behaviour is whether the driver notices the crossing cyclist (Räsänen & Summala 2000). Even if the driver should yield to the cyclist (e.g., when exiting a roundabout), the driver does not always yield as the driver may not recognize the cyclist due to the lack of attention or poor visibility (Silvano et al. 2016). For instance, when the driver is approaching an intersection, the driver may pay attention only to other motor vehicles and fail to recognize the cyclists (Räsänen & Summala 2000).

2.1.2 Features related to following rules and indicating intention

Feature 2 (follow rules): The HAV's yielding behaviour should be based on formal priority rules and the HAV should accurately obey its obligation to yield in all traffic situations and different types of intersections.

Räsänen & Summala (2000) discussed three driver-related factors, which have an impact on the yielding behaviour: 1) is the cyclist noticed, 2) are the priority rules known, and 3) is the driving style (e.g., speed) safe. According to Silvano et al. (2016), drivers consider time distance to the intersection, vehicle speed and the proximity of cyclists, when making the yielding decision. Even if Räsänen & Summala (2000) mentioned the priority rules as one factor, formal yielding rules do not seem to have a major effect on the yielding behaviour, or they are not more important than some other factors. Sakshaug et al. (2010) have stated that formal rules (e.g., priorities at intersections) have only a minor effect on the yielding behaviour. The HAVs should follow formal rules, which would make the rules a stronger basis for the yielding behaviour contrary to present procedures in operations by human drivers. The accurate compliance would likely increase cyclists' trust on HAVs, because the cyclists seem not to be more confident that the HAVs would yield more often than the drivers, even if the law would obligate them to give way (Hagenzieker et al. 2020). In addition, Vlakveld et al. (2020) found based on video experiments that the less cyclists trust on HAVs, the more likely they decelerated in conflicts with the HAVs at intersections even if they had a priority.

Feature 3 (indicate intentions): The HAV should indicate its intentions to cyclists in a clear and a consistent manner.

It is also important to examine the encounter from the cyclist's point of view. At intersections, the cyclist may sometimes think that the driver has recognized them (Silvano et al. 2016), but decreasing vehicle speed as a potential clue of the recognition may not be a result of detecting the cyclist (Kovácsová et al. 2018). From the perspective of the cyclist, it is sometimes difficult to find proper signals in the behaviour of the driver or the manoeuvres of the vehicle, which would indicate to the cyclist that they can safely cross the street first. As an answer to the problem, the HAV should be designed to indicate its intention in the encounters with other road users by e.g., decreasing vehicle speed or by light or text signals, as Ackermann et al. (2019) have studied from the pedestrians' point of view. For instance, the HAV could indicate that the cyclist is recognized and whether the HAV is yielding or not.

The feature to indicate intentions has also been identified necessary in previous studies on HAVs, as Merat et al. (2018) concluded that the HAVs should have an external way to communicate in the encounters with cyclists and other road users. Lee et al. (2020) also suggested that some way to communicate is needed, when the HAVs replace the role of drivers.

2.1.3 Features related to safe behaviour and situational awareness

Feature 4 (safe driving patterns and situational awareness): The HAV should use safe speed and maintain safe driving patterns by considering the traffic situation.

Maintaining safe driving patterns and being consistent in yielding behaviour is a crucial part of HAV's operation for the cyclists to be able to anticipate the HAV's behaviour. In some occasions, where the drivers should give way, the drivers do not always yield to cyclists (Silvano et al. 2016). It has been found that high speed of the car increases the probability not to yield to cyclists (Räsänen & Summala 2000). Obeying the obligation to yield or maintaining safe speed should not be a problem in the programming and designing of HAVs. Safe speed refers to obeying the speed limit and choosing lower speed in interaction situations with cyclists (OECD 2018). Anticipation is important for safety, if the automated driving systems cannot be sure that the cyclist is going to yield.

Similarly, if a visual obstacle in the traffic environment restricts the view to potential cyclists or other road users at intersections approaching from other directions, speed should be lowered to prepare for making an evasive action, if a road user should appear behind the obstacle. Zhao et al. (2019) indicated that speed reduction by the automatic emergency braking system would typically have been small in car-cyclist collisions, when a visual obstacle restricted the view to the cyclist and hence, the visual obstacles should be able to consider in the HAV operation. HAVs should be designed in a way that they are always able to stop for any foreseeable obstruction, which sometimes means lower speed than the speed limit indicates (OECD 2018). As the HAVs should be able to consider these types of obstacle and potential conflicts in its operation, implementing situational awareness (see Endsley 1995) as a feature of HAVs may not be easy. Considering the potential conflicts is important as according to the principles of vision zero and safe system approach (OECD 2018), it should be recognised and emphasised that people will always make mistakes, but these mistakes should not lead to serious consequences.

Feature 5 (assess cyclist's intention): Even if the priority rules state that the cyclist should yield to the HAV, the HAV should assess cyclists' intentions and choose its speed so that it is prepared for the cyclist not yielding.

The safe driving patterns and situational awareness discussed related to feature 4 are probably not always enough to avoid collisions with cyclists. For instance, as the cyclist may not always obey their obligation to yield, the HAV should anticipate such behaviour of the cyclist and take evasive action to avoid a possible crash. Decreasing the speed is probably needed in most of the encounters with cyclists in the early phase of the HAV's deployment, because intention estimation is assessed to be difficult (Botello et al. 2019). Lower speed enables more time to make the evasive action and to avoid the collision.

Cyclists do not always pay attention to cars (and turn their heads towards the car) at intersections, if they can be sure that there will not be a conflict (Kovácsová et al. 2018). This suggests that HAVs cannot solely rely on cyclist's head movements when assessing the cyclists' intention. As it is not always possible to assess cyclists' intentions in various situations, HAVs should choose safe speed to anticipate the possibility that cyclists would come into collision course, e.g., by crossing the street, albeit the cyclist has the obligation to yield.

2.2 Crash data

In order to analyse HAVs' possibilities to safe operation in situations, in which fatal crashes have occurred, Finnish data from years 2014-2016 considering all 24 fatal crashes between cyclists and driver-managed passenger cars were studied. For study purposes, data on in-depth investigated crashes was received from Finnish Crash Data Institute. The data includes crash descriptions and descriptive factors on the crashes based on the investigations by multidisciplinary crash investigation teams.

In this study, the crashes between cyclists and passenger cars were chosen as the crashes to be studied in order to reduce the heterogeneity of vehicle and crash characteristics to be considered. The amount of cycling crashes is relatively low in Finland as the total number of fatal crashes in Finland in 2014-2016 was 721, of which 80 (11%) were cyclist crashes (Finnish Crash Data Institute 2019). In addition to the 24 crashes between cyclists and passenger cars, the fatal cycling crashes include 31 single-bicycle crashes, 23 collisions between cyclists and other motor vehicles than passenger cars and 2 collisions with other cyclists or with pedestrians. The analysed 24 fatal crashes between cyclists and passenger cars include 17 crashes in cycle crossings or at intersections and seven other crashes, which were rear-end crashes or crashes, in which the cyclist crossed the lane without a cycle crossing.

2.3 Case-by-case evaluation

Using the crash data, it is evaluated qualitatively, which features should the HAV have in order to be able to prevent crashes with cyclist in the hypothetical scenario that HAV would be involved vehicle instead of a driver-managed car. The crash data enables evaluation of the factors, which caused or enabled the crash and thereafter enables considering, what kind of HAV design and operation could make preventing the crashes possible. The needed HAV features and behaviour to allow crash avoidance is evaluated broadly prior to the crash instead of just assessing the possible operation in the immediate crash situation as the HAV would assumedly operate differently from driver's actions prior to the crash.

The needed HAV features for crash avoidance are evaluated qualitatively using three questions related to each crash as depicted in Figure 1. First, it is evaluated, whether the passenger car or the cyclist had the obligation to yield. Second, it is studied, whether there was a visual obstacle (e.g., a building or other vehicles), which blocked the possibility to recognize the cyclist. If the cyclist should have yielded, the required features of the HAV to avoid the crash can be recognised based on this information. If the car had the obligation to yield, it is further assessed, did the driver behave dangerously by violating some other rules than an obligation to yield (e.g., passed traffic island from wrong side as in one of the studied crashes).

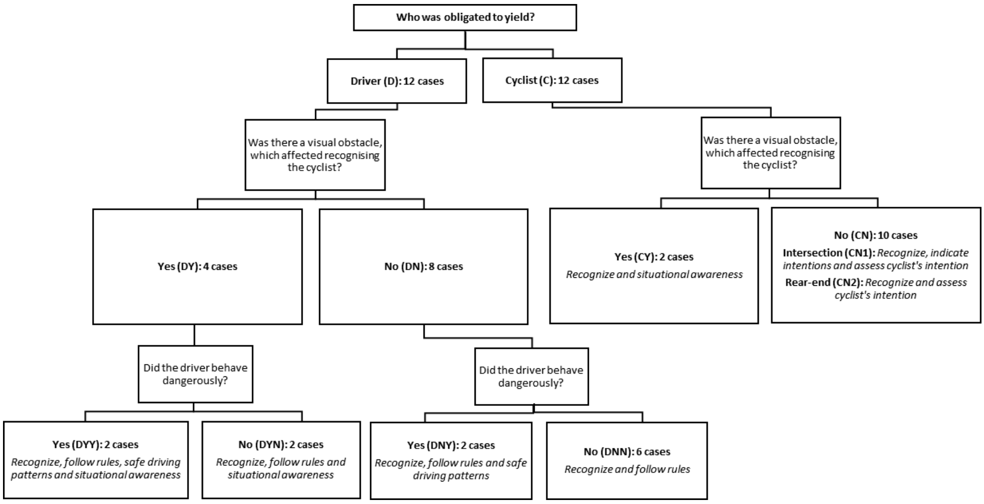

Figure 1. The questions, which were considered in evaluating crash avoidance possibilities and different HAV features. Code in the parenthesis (e.g., DYY) represents different crash types between driver-managed cars and cyclists, and the italic text presents the features, which the HAV should possess to be able to avoid the crash.

In Figure 1, cases CN1 and CN2 represent different needs in HAV's features in intersection (CN1) and rear-end or same driving direction crashes (CN2). However, in most of the cases the location of the crash had no effect on the required features. As an example, an intersection crash without any visual obstacles and when the driver had obligation to yield and drove dangerously (case DNY), could be avoided by the HAV with features 1 (recognize), 2 (follow rules) and 4 (safe driving patterns). This means that to avoid similar crashes, HAVs should recognize the cyclist, follow priority rules at intersections and maintain safe driving patterns (e.g., not violate any rules). Similarly, all crashes are evaluated case-by-case to assess the features, which the HAV should have to be able to avoid each crash.

The analysis in Figure 1 assists to evaluate the potentially needed HAV's features, but some of the cases may be difficult to avoid despite of the HAV's features due to a short time margin to the collision, when the cyclist is recognized. Therefore, we conducted a time-to-collision (TTC) analysis to evaluate HAV's possibilities to avoid the crashes assuming a similar crash scene and characteristics to the actual crash. TTC was calculated as presented in Equation 1.

$$\mathrm{TTC} = \frac{X_{CY}}{V_{CY}} \tag{1}$$

In Equation 1, X_{CY} presents a distance between a trigger point and a collision point. The trigger point is a point in which the cyclist enters the roadway from a cycle path at cycle crossings (e.g., the cyclist passes a kerb) or the cyclist turns to car's trajectory from the side of the roadway in the crash type of same running directions. In one case, the depicted distance could not be analysed, because the cyclist was already on the collision point, when the cyclist could firstly have been recognized. In this case, TTC is based on the car's speed and the sight distance, when the cyclist could be firstly recognized. V_{CY} presents cyclist's speed.

In many cases, speed of the cyclist was not available in the data as it could not be investigated by the crash investigation teams and hence, TTC was calculated by using two different cyclist's speeds as assumptions: 5 km/h and 15 km/h. Consequently, two different TTC values are presented, when the cyclist's speed is not known. The depicted TTC analysis enables to evaluate the time distance to the collision point, when it is likely that the trajectories of the car and the cyclist are going to intersect. The HAV could apply the brakes before the cyclist goes to the roadway from the cycle path (e.g., passes the trigger point), but it is not sure whether the HAV is able to anticipate that the approaching cyclist is going to cross the street, before the cyclist passes the trigger point. The TTC analysis is not applied when the driver broke the law (e.g., passed the traffic island from the wrong side), because the HAV is assumed to obey the law and it would enable avoiding these crashes.

3 RESULTS

3.1 Crashes in cycle crossings and at intersections

The analysed 17 cycle crossing or intersection crashes typically occurred as the car driver, the cyclist or both of them were not able to recognize the other involved party before the collision. This led to the situation, in which the road user, who would be obliged to give way, did not yield. In some of the studied crashes, the driver or the cyclist assumed the other road user would yield. The studied cycle crossing and intersection crashes could be divided to two groups based on the priority rules. In seven crashes, the driver had the obligation to yield and in ten crashes, the cyclist had the obligation to yield. When the passenger car was obliged to yield, features 1, 2, and 4 would be essential for crash avoidance. In the other cases, when the cyclist was obliged to yield, the range of needed features is wider (Table 1). Impact speeds of the cars varied from 12 km/h to 50 km/h in the studied crashes.

Table 1. Fatal cycling crashes in cycle crossings and at intersections, and HAV's features, which would be needed to avoid the crashes. TTC is not applied (NA), when the driver had broken the law as is depicted in section 2.3.

Code for the case as presented in Fig. 1	Amount of crashes and time-to-collision (TTC) values	Crash description	Visual obstacle	Driver's dangerous behaviour (excluding priority rules)	Road user obligated to yield according to priority rules	HAV's features needed for crash avoidance
DYY	1 TTC=NA	The car hit a cyclist when driving straight through and passing another car, which had stopped in front of cycle crossing.	Another car	Yes	Driver	1; 2; 4
DYY	1 TTC=NA	The car turned and passed the traffic island from the wrong side and hit a cyclist.	Another car	Yes	Driver	1; 2; 4
DYN	2 TTC=1.0-4.0s	The car turned and hit a cyclist. The driver did not recognize the cyclist.	Another car/ environment	No	Driver	1; 2; 4
DNN	3 TTC=0.5-1.5s	The car was exiting a roundabout or turned at intersection and hit a cyclist. The driver did not recognize the cyclist.	None	No	Driver	1; 2
CN1	8 TTC=0.5-2.5s in six cases and 2.0-6.0s in two cases	The car drove straight and hit a cyclist. The driver and/or the cyclist did not recognize the danger, or the driver assumed the cyclist to yield.	None	No	Cyclist	1; 3; 5
CY	2 TTC=0.5-1.0s in one case and 6.0s in one case	The car drove straight and hit a cyclist. The driver did not recognize the cyclist.	Environment	No	Cyclist	1; 4

3.2 Other cycling crashes

In addition to the 17 analysed cycle crossing and intersection crashes discussed in section 3.1, there were seven other crashes between cyclists and passenger cars in the dataset. The crashes presented in Table 2 had occurred, when a car and a cyclist were going to same direction and the car hit the cyclist (5 crashes), or when the cyclist crossed the lane without using a cycle crossing and was hit by a car (2 crashes). Impact speeds of the cars varied from 30 km/h to 50 km/h in four cases and from 60 km/h to 80 km/h in three cases.

Table 2. Fatal cycling crashes in other road sections than in cycle crossings or at intersections, and HAV's features, which would be needed to avoid the crashes. TTC is not applied (NA), when the driver had broken the law as is depicted in section 2.3.

Code for the case as presented in Fig. 1	Amount of crashes and time-to-collision (TTC) values	Crash description	Visual obstacle	Driver's dangerous behaviour (excluding priority rules)	Road user obligated to yield according to priority rules	HAV's features needed for crash avoidance
DNY	2 TTC=NA	The car drifted outside of the edge line due to driver's decreased alertness and hit the cyclist or the driver hit the cyclist intentionally.	None	Yes	Driver	1; 2; 4
DNN	2 TTC=NA	The car hit a cyclist, who was cycling to the same direction on the side of the roadway. The driver was distracted or a sense of sight was impaired.	None	No	Driver	1; 2
DNN	1 TTC=4.5s*	The car hit a cyclist. The driver did not recognize the cyclist, who had fallen of the bicycle.	None	No	Driver	1; 2
CN2	2 TTC=0.5-2.5s	Cyclist moved from the other side of the lane to the other. The car hit to the rear of the cyclist.	None	No	Cyclist	1; 5

*TTC analysis is based on a sight distance.

3.3 Summary on the needed features

To summarise the analysis presented in sections 3.1 and 3.2, the most important feature to allow crash avoidance was feature 1 (recognize), which relates to all 24 studied crashes, and can thus be characterised as a basic feature. Feature 2 (follow rules) is an essential requirement in all 12 cases, in which the driver had an obligation to yield. In addition, features 3, 4 and 5 were recognized necessary in eight, eight, and ten crashes, respectively. Cases with cyclist's obligation to yield at intersections (CN1) and cases with driver's obligation to yield without a visual obstacle or the driver's clear risky behaviour (DNN) cover more than half of the cases (14 crashes). Due to difference in the obligation to yield, the cases vary greatly from the perspective of required features in the HAV's operation.

4 DISCUSSION

4.1 Crashes in cycle crossings and at intersections

The realization of feature 1 is required in the first place so that the HAV could take evasive action in potential conflicts with the cyclists. Another basis for the safe operation of HAV and for the crash avoidance is the feature to obey priority rules (feature 2). If there is additionally a visual obstacle, which may delay recognising the cyclist when turning at an intersection, the HAV should anticipate taking evasive action in case the cyclist comes out behind an obstacle (feature 4). In cases, in which a driver broke the law, the HAV would be able to avoid the crashes by following the rules and maintaining safe driving patterns. For instance, the HAV would not pass a stopped car in front of the cycle crossing without stopping first, neither would the HAV pass a traffic island from the wrong side as had happened in one crash. If formal traffic rules are obeyed, an obstacle (e.g., a stopped car), which would block recognising the cyclist, would not be a problem for HAV's safe operation and crash avoidance. In addition, according to the Finnish law (Finlex 2018), road users should anticipate other road users' actions to avoid conflicts and collisions.

The crashes, when cyclist should have had yielded to the car, but the cyclist has not yielded are more demanding to be avoided by an HAV. It is important that the HAV recognizes the approaching cyclist (feature 1), but it should also be able to assess cyclist's intentions (feature 5), i.e., whether the approaching cyclist will cross the street, stop prior to crossing or perhaps turn to another direction before the crossing. To anticipate the potential conflict related to cyclists' surprising manoeuvres and cyclists not yielding, the HAV should choose safe speeds in these situations. As it may be impossible to reliably assess cyclist's intentions in every situation, the HAV should decelerate as a precaution in unclear situations (feature 5), e.g., when the cyclist is recognized near the intersection with a possible colliding course. Another solution could be that the HAV would indicate its intentions to the cyclist that it is not going to yield as it has the priority (feature 3). However, at the same time, the HAV should choose safe speed to prepare for cyclist's surprising actions, if the risk of fatal crashes is strived to be minimized. Additionally, there could be obstacles restricting recognizing the other party early enough and thus preventing assessing the intentions, too. In these circumstances, HAV should consider the traffic situation and anticipate that cyclists or other road users may come out behind nearby obstacle (feature 4).

4.2 Other cycling crashes

HAV's basic function is the feature of recognizing nearby cyclists on the roadway (feature 1). The HAV should pass the cyclist travelling on the roadway from a distance far enough or slow down, if there is not space to pass the cyclist (feature 2). Unlike cases in the crash data, the HAV would not hit cyclists intentionally and the HAV should be able to keep the vehicle between the lane markings and avoid drifting outside of an edge line (feature 4). Thus, it should be safe to cycle on road shoulders with HAVs sharing the road.

Crashes, where the cyclist neglected their obligation to yield, are challenging to avoid from the perspective of an HAV. When a cyclist travelling on the roadway moves from the other side of the lane to the other in front of the HAV, the HAV should be able to take evasive action. However, as the cyclist is travelling to the same direction at the roadway, it may be difficult to assess the cyclist's intention (feature 5) to change lane position, unless the cyclist makes a clear sign of the intention. Similarly, the cyclist cannot assess the HAV's intentions by interpreting the

HAV's external signals without a rear mirror (not required by law and rarely as an accessory in Finland) unless the cyclist would glance behind or the signal would be e.g., an audio signal. To maximise safety of HAV's operation, all signs, even minor ones, should be recognised to ensure that possible changes in cyclists' position can be anticipated and evasive actions can be taken.

4.3 General discussion

In almost all of the studied fatal crashes, either the driver or the cyclist was not able to recognize the other involved road user, which emphasizes the importance of feature 1 (recognize) for crash avoidance. However, reliable and tireless driving automation does not always guarantee recognizing the cyclist early enough, if the cyclist comes into sensor's field of view behind an object (e.g., behind other vehicles or a building) just before the HAV arrives to the possible collision point. Therefore, an important feature of HAV's operation is that it should always maintain safe speed and driving patterns and anticipate that cyclists might approach behind visual obstacles (feature 4). This feature is especially emphasized, when the HAV has the obligation to yield to other road users.

Sometimes a cyclist is recognized late and hence, even the HAV may not be able to avoid the collision. To evaluate the possibility to avoid the crashes, we also made a TTC analysis. It was found that TTC values would be less than 2.0s in 10-14 (42-58%) of the analysed crashes depending on the assumed speed of the cyclist. If it is assumed that the HAV would start decelerating after the cyclist is recognized at a trigger point by 6.0 m/s^2, which is the average of deceleration values used in the studies by Grover et al. (2008) and Strandroth et al. (2012), the crash could be avoidable with HAV's speed of 43 km/h or less with TTC of 2.0s. Considering the crash data and vehicle speeds in the actual crashes, all cases would not be avoidable with this assumption. Consequently, it is important the HAV is able to anticipate that the cyclist is going to intersect with a trajectory of the HAV before the cyclist passes the trigger point.

One of the most important factors to consider related to crash avoidance analysis is the obligation to yield as it has a great impact on the required features of the HAV. Cases, where the driver has the obligation to yield, are simpler in theory as the HAV should only be able to recognize the cyclist (feature 1) and to obey priority rules (feature 2). However, differences and exceptions in priority rules regarding the various traffic environments complicate the robust and universal implementation of these features. Although recognizing the cyclist and following rules is perhaps the simplest combination of the features, the combination would tackle some of the contemporary key challenges. Currently drivers do not always obey the obligation to yield to cyclists at intersections as the studied crash data and previous studies (e.g., Silvano et al. 2016) indicate. HAV's feature to obey priority rules carefully could make the encounters more predictable for the cyclists.

Related to feature 3, a way to make the encounters with cyclists and other road users more predictable could be an external screen sending text or visual signals (see Ackermann et al. 2019) in front of the HAV, which would help the cyclist to identify, whether the HAV is about to yield or not. The HAV would operate according to priority rules in all circumstances, but an external message could make it easier to anticipate HAV's actions from the perspective of the cyclist. In addition, as informal rules are sometimes followed instead of formal yielding rules, the HAVs should also be able to acknowledge that and communicate with the cyclist to address possible deviant yielding behaviour. A simple light signal could be a suitable solution as it may be difficult to interpret other signals or more complicated messages while cycling. A visual obstacle may also block the view from the cyclist's perspective, and thus it is possible that the cyclist does not see HAV's signal. The realization of feature 3 requires that a universally understandable communication system for these signals is developed.

The analysed crash data and previous studies (e.g., Räsänen et al. 1999) indicate that the cyclists do not always obey their obligation to yield. If the HAVs are designed and programmed to avoid all potential collisions, the cyclist and other road users may change their behaviour to a riskier one, e.g., not obeying the priority rules as they may assume that the HAV will always give way. HAV's design to maximise safety would lead to conflicts with traffic flow. If the HAVs should always slow down near cyclists as a precaution, this would cause lots of decelerations. Even if the cyclists' behaviour would not become riskier, some changes in the behaviour are possible compared to encounters with driver-managed cars (Hagenzieker et al. 2020) making the design of HAVs' features more complicated. In addition, when a visual obstacle would be restricting seeing a potentially approaching cyclist, the HAV should decelerate as a precaution in case the cyclist would appear behind the obstacle. In order to be possible to avoid all these collisions, taking into consideration the possible high speed of the cyclist, the HAV should strongly decelerate in many situations in urban traffic. This would further influence the flow of motor vehicle traffic. In mixed traffic with both driver-managed cars and HAVs, there would be non-uniform practices, which would have an effect on the total safety and traffic flow outcome.

4.4 Limitations and assumptions

In the analysis, it was not assumed that adverse weather conditions or road characteristics would have an impact on HAV's features, i.e., features were expected to operate in all conditions. Of the 24 analysed crashes, two occurred during rainfall and in one case the road surface was snowy. Four cases occurred in dark conditions. Fourteen of the 24 crashes situated on street network, seven situated on low-volume road network (such as local, connecting and private roads) and three on main roads. For instance, if dark conditions and adverse weather conditions will be obstacles for HAVs' operation, many of the analysed 24 crashes would not be preventable by the HAV.

Of the single features, assessing cyclist's intention (feature 5) may be the most difficult feature to realize in a near future. Intention estimation (e.g., whether a cyclist is about to cross the street or not) made by the HAV may not be reliable enough, as e.g., Botello et al. (2018) and Rasouli & Tsotsos (2019) have discussed regarding the current situation in the development process. The reliability of feature 1 (recognize) is the uttermost important to guarantee safe operation. Other features' reliable operation is also needed, but an HAV can compensate possible deficiencies of the other features in unclear situations by slowing down. However, continuous decelerations would eventually influence people's perceptions of the HAVs and hence, developing sensors to recognize road users' movement and algorithms to assess intensions reliably are important tasks for safe automated driving. The features' operational capability should be high-quality, because otherwise the system cannot reliably control dynamic driving tasks.

The number of the analysed crashes in this study was small, albeit the crash data included all fatal crashes between cyclists and passenger cars in 2014-2016 in Finland. Crashes between cyclists and other vehicles than cars may involve different characteristics and therefore also other features that were recognised in this study may be needed to avoid these. By analysing other crash data sets, additional other features could come up and the relative importance of the features could appear dissimilar. Therefore, further studies should include more analysis of the possible encounters between HAVs and cyclists, and also other types of situation than those, which have led to fatal consequences in current situation with human drivers.

5 CONCLUSIONS

The amount of studies related to the interaction between HAVs and cyclists is currently low. This study discloses potentially needed features of HAVs, which would allow safe encounters with cyclists and allow avoiding fatal crashes between cyclists and passenger cars. In order to fulfil the expected safety benefits of HAVs - thinking that HAVs replacing current driver-managed passenger cars would remove the fatal crashes and help to move towards vision zero - also in the encounters with cyclists, the HAVs should have at least the five features discussed in this study. The HAVs should be able to (1) recognize nearby cyclists, (2) be aware of priority rules in various intersections and traffic situations, (3) indicate its intentions to cyclists, (4) maintain safe driving patterns and anticipate the upcoming situations, and (5) assess cyclists' intentions. If all of these features are not available, HAV's capabilities for crash avoidance are clearly reduced.

The study increases knowledge on HAVs' features from the perspective of cycling safety. Albeit the number of features (five) recognised in this study is relatively low, the features include various requirements. Implementing these in real world at least in the near future, and especially assessing the intentions (feature 5), will be a great challenge, as well as anticipating future situations (feature 4). All features possess a challenge as cycling and traffic in general are a very complex and take place in varied environments. There is clearly a need to further study the interactions and encounters between cyclists and HAVs, e.g., in real world tests to examine technical requirements and best practices for safe encounters as well as from the perspective of safety and traffic flow. In this study, technical requirements of the five discussed HAV features are not assessed, e.g., what would be required to recognise cyclists in different situations or what should be considered for assessing cyclists' intentions. Therefore, these should be addressed in future studies. It should also be noted that communication systems (e.g., vehicle-to-everything, V2X) were not considered in this study.

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