How do conditionally automated cars relate to current traffic safety challenges in Finland?

Identifying target accidents for passenger cars with automated driving systems for motorways and urban areas

Fanny Malin
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Abstract

This dissertation identified the potential of passenger cars equipped with automated driving systems (SAE3) for motorways and urban areas in improving traffic safety in Finland. It includes three sub-studies which investigated the current safety situation from a i) road network, ii) single-driver, and iii) pedestrian perspective. The results were first obtained by identifying the road network on which automated driving systems (ADS) can be used based on their operational design domain (ODD). Then, the expected number of injury accidents, fatalities, and serious injuries on the respective networks was estimated with the Empirical Bayes method.

The results show that motorway ADS in passenger cars could potentially affect a maximum of 191 injury accidents, eight fatalities, and 15 serious injuries a year. Depending on severity, this corresponds to 3.1–3.3% of the national annual average. In four major Finnish cities, urban ADS in passenger cars could potentially affect 127 injury accidents, three fatalities, and 12 serious injuries annually. These correspond to 1.1–2.5% of the national and 17.1–26.8% of the selected cities’ annual average. The results also show that the current safety situation is better on the operating networks and within the operating conditions for the ADS compared to other networks and conditions not fulfilling the ODD requirements. For a single driver, the relative accident risk increases as the road weather conditions worsen and the conditions are not anymore fulfilling with the ODD requirements. This increase is largest on motorways meaning that the driver must be in control of and take over the driving task in the most dangerous conditions. Finally, the results indicate that the ADS of passenger cars in this study could have a greater effect on serious injuries than on fatalities among pedestrians.

The requirement for physical separation of driving directions currently restricts the potential to extend the network length for motorway ADS in Finland. The operating environment of ADS, and consequently their safety potential, could be substantially extended if the systems were used on high-level rural roads. Further measures should be put in place to attain traffic safety goals, since the period of transition to ADS is expected to be long. Conditionally automated cars can probably contribute to this process, especially on motorways where other highly effective traffic safety measures have already been implemented.

Keywords Automated vehicles, killed and seriously injured, single driver, pedestrian

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Doktorsavhandlingens titel
Hur motsvarar villkorligt automatiserade personbilar de nuvarande trafiksäkerhetsutmaningarna i Finland? Identifiering av målolyckor för personbilar med automatiska körsystem för motorvägar och stadsområden

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Sammandrag

Resultaten visar att automatiska körsystem för motorvägar skulle kunna påverka 191 personskadeolyckor, åtta dödsfall och 15 allvarligt skadade årligen. Beroende på svårighetsgrad motsvarar detta 3,1–3,3 % av det årliga genomsnittet i Finland. I fyra stora finska städer skulle personbilar med automatiskt körsystem för stadsområden årligen kunna påverka 127 personskadeolyckor, tre dödsfall och 12 allvarligt skadade. Detta motsvarar 1,1–2,5 % av det nationella och 17,1–26,8 % av de utvalda städernas årliga genomsnitt. Resultaten visar också att den nuvarande trafiksäkerhets situationen är bättre på vägåtverken och i förhållanden som uppfyller de automatiska körsystemens planerade driftsmiljö jämfört med de vägåtverk och förhållanden som inte gör det. För en enskild förare ökar den relativ trolldom att resa i vägar och väggåttäktens försämrar och förhållanden inte längre uppfyller de automatiska körsystemens planerade driftsmiljö. Denna ökning är störst på motorvägar vilket innebär att de automatiska körsystemens användare måste ansvara för och ta över köruppgift och de farligaste förhållanden. Slutligen tyder resultaten på att de automatiska körsystemen skulle kunna ha en större effekt på fotgängares allvarliga skador än dödsfall.

Kravet på fysisk separering av körriktningar begränsas för tillfället möjligheten att förlänga vägåtverket för automatiska körsystem för motorvägar i Finland. Vägåtverket för systemen, och följaktligen deras trafiksäkerhetspotential, skulle kunna utökas avsevärt om systemen kunde användas på landsvägar av hög standard. Övergångsperioden för automatiserade fordon förväntas bli lång så ytterligare åtgärder bör vidtas för att uppnå trafiksäkerhetsmålen. Villkorligt automatiserade personbilar kan sannolikt bidra till att uppnå trafiksäkerhetsmålen, särskilt på motorvägar där flera effektiva trafiksäkerhetsåtgärder redan har genomförts.

Nyckelord Automatiska fordon, döda och allvarligt skadade, enskild förare, fotgängare

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Helsinki, 2nd March 2023
Fanny Malin
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## List of Abbreviations

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<tbody>
<tr>
<td>ADS</td>
<td>Automated driving system</td>
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<tr>
<td>DSF</td>
<td>Driver support feature</td>
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<tr>
<td>EB</td>
<td>Empirical Bayes</td>
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<tr>
<td>KSI</td>
<td>Killed and seriously injured</td>
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<tr>
<td>MAIS</td>
<td>Maximum Abbreviated Injury Scale</td>
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<tr>
<td>ODD</td>
<td>Operational design domain</td>
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<tr>
<td>PTW</td>
<td>Powered two-wheeler</td>
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<td>SAE</td>
<td>Society of Automotive Engineering</td>
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<tr>
<td>VRU</td>
<td>Vulnerable road user</td>
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List of Publications

This doctoral dissertation consists of a summary and of the following publications which are referred to in the text by their numerals:


Author’s Contribution

**Publication 1:** Identifying crashes potentially affected by conditionally automated vehicles in Finland

Conceptualisation, FM, AS, and IS; Methodology, FM, AS, and IS: Formal analysis, FM, JM, and HP; Data curation, FM and JM; Writing – Original draft, FM; Writing – Review and Editing, FM, AS, JM, IS, and HP.

**Publication 2:** Accident risk of road and weather conditions on different road types

Conceptualisation, FM, IN, and IS; Methodology, FM, IN and IS: Formal analysis, FM, and IN; Data curation, FM and IN; Writing – Original draft, FM and IN; Writing – Review and Editing, FM, IN, and IS.

**Publication 3:** Prevalence and factors associated with pedestrian fatalities and serious injuries: case Finland

Conceptualisation, FM, AS, and MM; Methodology, FM and AS: Formal analysis, FM; Data curation, FM; Writing – Original draft, FM; Writing – Review and Editing, FM, AS, and MM.
1. Introduction

1.1 General problem setting

In Europe there is a target to halve the number of road fatalities and serious injuries from 2020 by 2030, and to have close to zero road fatalities by 2050 (EC 2020a). At the same time, there are targets to reduce transport emissions (EC 2016) and increase active transport mode use (EC 2021). Safety is a prerequisite for people to use active transport modes and, thus, is in turn a precondition for the needed systemic behavioural change (Jacobsen et al. 2009; Methorst 2007). Traffic safety has improved of late, especially for passenger-vehicle occupants and on motorways, but a similar development in safety is lacking in urban areas and for vulnerable road users (VRUs) such as cyclists, pedestrians, and powered two-wheeler (PTW) drivers (Adminaité-Fodor & Jost 2019, 2020; Elvik 2010; Olszewski et al. 2019).

Road traffic safety analysis and efforts have until now concerned mainly fatalities, even though the traffic safety targets cover also serious injuries. As a result, there is a lack of information on serious injuries both in terms of their characteristics and effective countermeasures. This knowledge gap is hindering transport policy and planning from emphasising those elements and challenges that are related to other accident consequences than fatalities (Shen et al. 2014).

The focus on fatalities results primarily from a paucity of mutual definitions and compilation of reliable accident statistics for other severities. Consequently also, safety rankings are generally performed using fatalities, but the results can change when including serious injuries (Kukić et al. 2016; Shen et al. 2014). The importance of serious injuries is also evidenced when considering the overall monetary costs of accidents, since their unit cost is considerably larger than slight injuries and accounts for 14–77% of all costs related to road casualties (Wijnen et al. 2019). A common challenge in European countries is underreporting of accidents leading to personal injury (Yannis et al. 2014). The EU recommends defining serious injuries based on the Maximum Abbreviated Injury Scale (MAIS) 3+ criteria and to record them by connecting hospital and police data (EC 2013). Nonetheless, most EU countries do not abide by these recommendations (Auerbach et al. 2016); Finland is one of the few that do, having done so since 2014. Similarly to other countries, Finnish data on traffic accidents with serious injuries has been found to be subject to underreporting, especially for accidents involving cyclists (Peltola et al. 2018; Short & Caulfield 2014; Wegman et al. 2012).
In Finland, the European traffic safety objective (EC 2020a) aspires to a target of 112 fatalities and 204 serious injuries by 2030. Still, annually 227 people have died and 430 been seriously injured in road transport during the last 5 years (Figure 1). Furthermore, in terms of traffic safety development, Finland is performing less well than other, similar, European countries (Adminaité-Fodor et al. 2021; Peltola & Luoma 2017; Utriainen et al. 2018). If the fatality risk (number of fatalities/kilometres travelled) in Finland were the same as in Sweden, almost 40% of fatalities could be avoided (Peltola & Luoma 2017). This potential is especially notable in relation to head-on and single-vehicle accidents.

A national traffic safety strategy was recently launched for the years 2022–2026 with 103 actions (Rekola et al. 2022). According to the ex-ante assessment of 53 actions which could be evaluated, some 20 fatalities (no assessment for serious injuries) could be prevented between now and 2026. This indicates that the actions set are not sufficient to achieve the traffic safety policy objectives.

Traffic safety can be analysed from different perspectives. From a transport system perspective, the number of fatalities and injuries in road accidents relates to exposure, accident rate, and consequence (Nilsson 2004). Exposure depicts the amount of activity at the place where accidents can happen, accident rate depicts the accident risk per exposure unit, and consequence depicts the accident severity. A change in any of these dimensions thus affects traffic safety.

Traffic safety measures can relate to different components of the transport system (Figure 2) and the impacts can be direct and indirect. Direct impacts are those that result from changes in the targeted factor, whereas indirect impacts are unintended and generally follow behavioural adaptation (Kulmala 2010). New methods, such as Palm probability (Norros et al. 2016), allow examining the accident risk from a single-driver perspective.

![Figure 1. Number of fatalities and serious injuries per transport mode in 2016–2021 in Finland, and target for 2030 (Statistics Finland 2022).](image-url)
One recent safety measure related to vehicles has been vehicle automation, made possible by technological advancements in sensor, communication, and computation capabilities. There are different automation levels which are classified according to the Society of Automotive Engineering’s (SAE) International Classification (SAE International 2021). The classification has six levels which depend on how much the human is involved in the driving task:

- no driving automation (SAE0)
- driver assistance (SAE1)
- partial driving automation (SAE2)
- conditional driving automation (SAE3)
- high driving automation (SAE4)
- full driving automation (SAE5).

Systems related to the first three levels (SAE0–2) are called driver support features (DSF), and systems related to the higher levels (SAE3–5) refer to automated driving systems (ADS) (Fisher et al. 2020). DSF have been found to reduce traffic accidents and are predicted to improve traffic safety also in the future (Furlan et al. 2020; Scholliers et al. 2020). Many DSF are available today, some of which have become obligatory in the EU for new vehicles from 2022 onwards (Scholliers et al. 2020). Some studies have concluded that ADS can improve traffic safety, but these studies relate generally to high driving automation systems (SAE4–5) (Fagnant & Kockelman 2015; Milakis et al., 2017; Noy et al. 2018). Fewer research results are available on the traffic safety impacts of conditional automation (SAE3). Conditionally automated cars are passenger cars with SAE level 3 ADS for different driving tasks (such as parking) or environments (such as motorways) (ERTRAC 2022). In conditional driving automation, the driver can engage in secondary non-driving related tasks when driving in automated mode, but they must immediately take charge of the driving task when requested by the system (Bishop 2020). Additionally, ADS can function
only in conditions inside their operational design domain (ODD). The ODD requirements can concern infrastructure, such as availability of lane markings, road type and quality of infrastructure, and prevailing conditions such as weather and traffic. Several safety challenges have been linked to conditional automation, mainly in relation to human factors (e.g., driver’s situational awareness, take-over requests) and limitations of the ODD (e.g., bad weather conditions).

In order to know the overall potential of a measure for improving traffic safety, it is imperative to know the scope of impact in addition to its effectiveness (Elvik et al. 2009; Kulmala 2010). Even though ADS are estimated to be effective in a certain driving situation, the overall effect is minor if the scope is limited (i.e., targets only a small number of accidents). The targeted impact of an ADS is restricted by the ODD requirements for its operating environment and conditions, especially in countries where wintry road conditions, which are generally challenging for ADS, are common. Previous studies (Norros et al. 2016) have suggested an elevated accident risk for single drivers in bad weather. Thus, weather is a relevant aspect of conditional automation, as the system only works when the vehicle is driving in conditions matching the ODD requirements.

Studies identifying the traffic safety potential of ADS have been based on accident statistics, which tend to suffer primarily from underreporting and random variation (Elvik et al. 2009; Yannis et al. 2014). The safety situation of a place is best described with the expected number of accidents. The expected number of accidents is the average number of accidents expected to occur in the long term with unchanged exposure and accident rate, and it is calculated with the Empirical bayes (EB) method (Elvik 2008, Elvik et al. 2009; Hauer et al. 2002). Unlike the recorded number of accidents, the expected number controls for random variation in accident records (Elvik 2008, Elvik et al. 2009; Hauer et al. 2002). Using the expected number of accidents is especially important for analysing accident severities separately, since it requires splitting accident records further.

The European and national targets to reduce road fatalities and serious injuries are ambitious. There is, however, a knowledge gap on serious injuries, which is hampering transport policy and planning from emphasising elements related to other accident consequences than fatalities. Introduction of ADS is one measure for improving traffic safety. It is, however, unknown to what extent the technology can contribute to the set traffic safety targets and how ADS correspond to current traffic safety challenges. As a result, the first step towards establishing the safety effects of conditionally automated cars is to find out their scope of impact. This information is important for knowing to what extent conditionally automated cars can contribute to reaching the traffic safety objectives.

1.2 Objectives of the dissertation

The main objective is to identify conditionally automated passenger cars’ potential for improving road traffic safety in Finland. The analysis is limited to ADS (SAE3) for motorway and urban environments. This dissertation, based on
three sub-studies, identified the safety potential based on the current road traffic safety situation, which was investigated from a road-network, single-driver, and pedestrian perspective. The methodological focus is on identifying the systems’ scope of impact in terms of their target accidents (number of accidents that could be affected). The scope of impact of ADS is reflected in the current safety situation and challenges.

The main objective was examined through four research questions:

1. What are the current road traffic safety challenges from a network, single-driver, and pedestrian perspective?
2. How many accidents can motorway ADS potentially affect?
3. How many accidents can urban ADS potentially affect?
4. How do motorway and urban ADS relate to the identified safety challenges?

1.3 Structure of the dissertation

The second section presents a literature review of road traffic safety, specifically its quantification and development in Finland, and the effects of vehicle automation on traffic safety. The third section outlines the methods for calculating the current safety situation and the number of accidents potentially affected by ADS. Section 4 summarises the results relating to each research question. Section 5 discusses the results and limitations of the dissertation. The sixth and final section presents the overall conclusions and implications of the dissertation and future research suggestions.
2. Literature review

2.1 Traffic safety development in Finland

The main Finnish actors in the traffic safety area are shown in Figure 3, along with available accident statistics from various stakeholders on which descriptions of the traffic safety situation depend. The official statistics on traffic accidents (traffic fatalities, serious injuries (MAIS3+), and injury accidents) are compiled by Statistics Finland and are based on police reports. Other statistics are compiled by the Finnish Transport Infrastructure Agency (fatal, injury, and property damage accidents, based on official statistics), the Finnish Crash Data Institute (in-depth investigations of fatal accidents), and the Motor Insurers’ Centre (self-reported insurance claims). Comparisons of road accident statistics show that the statistics by these other organisations report a higher number of cases, especially those with slighter outcomes, than the official statistics do (Lehtonen 2020). Furthermore, the Finnish Institute for Health and Welfare compiles statistics of hospital records that include information on whether the injury is caused by a traffic accident. This information is used by Statistics Finland to classify the severity of injuries and hence distinguish serious from slight injuries.
Figure 3. Main Finnish actors in the traffic safety area.
Up until 2018, the Finnish Transport Infrastructure Agency published an annual report with detailed analysis of the safety situation on the main road network. Currently, Statistics Finland publishes transport-related statistics through their web interface. Also, the Finnish Transport and Communications Agency publishes information on the traffic safety situation and its development on their homepage, but on a more general level. There is currently no publication regularly synthesising the traffic safety situation and its development. Recent national publications (Finnish Transport and Communications Agency Traficom 2020; Ministry of Transport and Communications 2021; Rekola et al. 2022) describe the traffic safety situation mainly based on overall statistics and do not distinguish between injury severities or different road types.

During the last half-century, the number of traffic fatalities has decreased in Finland, but this improvement has stagnated over the past decade. The annual vehicle mileage has, however, stayed at a similar level on all road types except for motorways and dual carriageways, which have seen an increase of around 15% (FTA 2012, 2014, 2016, 2018a). This indicates that the main safety improvement is due to a reduction in fatality risk.

Information is especially lacking on serious injuries, which have only been included in official statistics as a separate class since 2014. Previous studies (Airaksinen 2018; Airaksinen & Kokkonen 2014; Peltola et al. 2018; Utriainen et al. 2018) indicate that there are different traffic safety challenges in relation to fatalities and serious injuries. These studies also state that only around half of all serious injuries are covered in the official statistics, which skews the situation even further. Most of the cases missing from the official statistics relate to cyclists and the single accidents involving them (Airaksinen 2018; Peltola et al. 2018; Utriainen et al. 2018).

Peltola et al. (2018) investigated all motor vehicle injury accidents (except those occurring on private roads) during 2014–2015. They compared e.g., the most common accident types based on severity and road type, and found that on main highways and other main roads, head-on and single-vehicle accidents were the most common types leading to fatal and serious injury, whereas single-vehicle and rear-end accidents were the most common types causing slight injuries. On the street network, the most common accident types were accidents involving cyclists and pedestrians for all severities, and single-vehicle accidents and accidents involving mopeds were most common for serious and slight injury accidents. Inspecting the accident costs (which enables analysing all severities together) revealed that the costs were evenly distributed among all accident types on motorways and dual carriageway roads, whereas the majority of costs on main highways were from head-on accidents, on other main roads from single-vehicle accidents, and in built-up areas from VRU accidents.

Utriainen et al. (2018) analysed fatalities and serious injuries occurring in Finland during 2014–2015 and found that the main road-user groups involved in accidents differed when including only hospital-reported serious injuries in the analysis. Police-linked hospital-reported serious injuries highlighted car occupants, whereas all hospital-reported cases highlighted cyclists.
The importance of VRU safety is accentuated when considering serious injuries. Airaksinen (2018) investigated serious injuries to cyclists and PTW riders during 2004–2006 in South-Eastern Finland and found major underreporting of accidents (especially single-vehicle accidents) involving riders of bicycles, mopeds, and motorcycles. Head injuries were common among cyclists involved in accidents and helmet use was found to protect them from such injury. Furthermore, the share of alcohol-related cyclist injuries is not reflected in the official statistics; most such cases are single-vehicle accidents (falling over), resulting in head injuries more often than among sober cyclists. This indicates a need for increased helmet usage and introduction of prohibited blood alcohol content level for cyclists to reduce the number of injury accidents and their severity. Among PTW riders, single-vehicle accidents were also common, indicating a need for the wearing of proper protective gear and appropriate driving behaviour, such as an appropriate situational speed, to reduce the number of injury accidents and their severity.

There are no national studies on serious injuries to pedestrians. Previous research from other countries has found that accidents involving pedestrians are more common in urban areas compared to rural areas. As regards the severity of pedestrian accidents, fatalities occur more often in rural areas compared to other severities (Adminaitė et al. 2015; Fontaine & Gourlet 1997; Glász & Juhász 2017; Lee & Abdel-Aty 2005) and in locations with higher speed limits (Eluru et al. 2008; Kröyer 2015a, b; Sze & Wong 2007), due primarily to the relation between vehicle speed and injury severity of pedestrians (Rosén et al. 2011; Tefft 2013). Additionally, studies have found that pedestrian accident severity increases with vehicle weight (Clifton et al. 2009; Lee & Abdel-Aty 2005; Roudsari et al. 2004). Regarding weather and road conditions, injury severity is higher in accidents in poor lighting and weather conditions (Lee & Abdel-Aty 2005; Mohamed et al. 2013; Olszewski et al. 2015; Tay et al. 2011). The aforementioned studies use different definitions of severity and do not generally distinguish serious injuries.

2.2 Quantification of traffic safety

2.2.1 Network level perspective

The expected number of accidents controls for random variation in accident records and should be used for calculating a specific location’s safety situation (Elvik 2008; Elvik et al. 2009, p. 74–75; Hauer et al. 2002). It can be calculated with the EB method which entails unifying accident history with an accident prediction model. Accident prediction models are equations presenting accident numbers in a specific location as a function of different independent variables developed (e.g., Ambros et al. 2018).

In Finland, the ‘TARVA’ tool has been continually developed since 1994 for estimating the current traffic safety situation with the EB method and effects of different safety measures. Serious injuries were added in 2018 and then the ac-
cident prediction models were revised (Peltola et al. 2019). The TARVA tool includes all highways in Finland (appr. 78,000 km). The expected number of injury accidents, fatalities, and serious injuries (MAIS3+) can be estimated for any selected area, road, or road stretch.

In Finland, the municipalities manage the street network (appr. 26,000 km). The street network is not covered by the TARVA tool, mainly because there has been a lack of available traffic data and funding. In recent years, however, municipalities have started collecting and publishing data (e.g., traffic volumes) from their street networks.

### 2.2.2 Single driver perspective

Recently, a novel method was developed (Innamaa et al. 2013, 2014; Norros et al. 2016) for examining traffic safety using Palm probability. Palm probability conveys the distribution of the world from the perspective of a random point in a point process (e.g., Baccelli & Brémaud 2003). Applied to this case, it translates as the distribution of traffic and road conditions from the view of a random driver. It therefore becomes possible to examine accident risk from the view of a single driver.

The method entails calculating the distribution of conditions occurring at accidents and comparing it with the Palm distribution of the same conditions, i.e., comparing whether a certain driving condition is more or less likely in an accident situation than for a random driver. The condition has a reduced or increased relative accident risk compared to the overall average relative risk level of 1 when the two distributions are statistically significantly different.

The method originates from the concept that the overall intensity of accidents occurring to a driver is positive. The accident distribution of conditions would follow the Palm distribution of conditions if this intensity were evenly distributed, i.e., unaffected by conditions, for every driver.

### 2.2.3 Pedestrian perspective

The general traffic safety situation for pedestrians can be analysed from traffic accident data (Polders & Brijs 2018). It is then important to relate the accident numbers to the corresponding exposure. When conducting traffic safety analysis, the choice of unit of exposure is not as simple for pedestrians as for vehicle accidents. Earlier studies have, for example, used hours walked (e.g., Keall 1995; Lee & Abdel-Aty 2005), kilometres walked (e.g., Baltes 1998; Elvik & Bjørnskau 2019), roads crossed (e.g., Fontaine & Gourlet 1997; Keall 1995), and pedestrians at crosswalks (e.g., Kröyer 2015b).

### 2.3 Improving traffic safety with vehicle automation

There are still only a few results available on the safety impacts of higher automation from real-world tests. Some studies have analysed accidents on public
roads in California involving automated vehicles, and generally have small samples (n=133) where most of the reports are by Google (Favarò et al. 2017; Wang & Li 2019; Ye et al. 2021).

This knowledge gap on accidents involving AVs signifies that studies investigating the safety effects of AVs have used other methods. Kitajima et al. (2019) performed a multi-agent traffic simulation of an area in the city of Tsukuba (JPN) and found a decrease in the number of traffic accidents with different penetration rates of DSF (SAE1–2) and ADS (SAE4) compared to manual driving. Studies applying simulation-based surrogate safety measures also found a decrease in the number of conflicts with increasing penetration of highly automated vehicles (SAE4) on a motorway section in England (Papadoulis et al. 2019) and at different types of intersections (Morando et al. 2018; Virdi et al. 2019). At lower (20–25%) penetration rates there was an increase in the number of conflicts at all intersection types except for a priority-controlled intersection. Experiments based on virtual scenarios and Monte-Carlo techniques (Fahrenkrog et al. 2019; Wang et al. 2017) have found a decrease in accident risk on motorways for ADS compared to manual driving for some scenario types (approaching traffic jam: −28%...-49%, cut-in -83%, rear-end -73%) and a higher risk for others (obstacle in the lane: +28%). These studies have also found a decrease in mean velocity (-15%) at the time of accident for accidents involving ADS. Counterfactual simulation of accidents (n=72) found that ADS (SAE 4) would prevent all accidents when it is in the initiator vehicle, and that most accidents (82%) would be prevented and some (10%) would be less severe when it is in the responding vehicle (Scanlon et al., 2021).

Retrospective analysis of accident data has focused on identifying preventable accidents, mainly motor-vehicle pedestrian fatalities. Utriainen and Pöllänen (2020) found that of all fatal accidents involving motor vehicles and pedestrians during 2014–2016 in Finland (n=40), highly automated vehicles (SAE4–5) could prevent 28–37 accidents (depending on the prioritisation of pedestrian safety or traffic flow). Utriainen (2020) analysed the same data and found that highly automated vehicles (SAE4–5) could avoid 8–29 pedestrian fatalities depending on restricting conditions (e.g., weather conditions, lighting, lane markings). Combs et al. (2019) combined information on sensor technology capabilities with accident data and found that of all the pedestrian fatalities in the U.S. in 2015 (n=3,386), 30–90% could be avoided with different types of detection technologies (visible-light cameras, LiDAR, radar).

Driver-related aspects of conditional automation (SAE3) have been studied with surveys, simulators, test tracks, and field studies. Engagement in secondary tasks has been found to degrade the quality of handovers (Wan & Wu 2018; Zeeb et al. 2016), especially during tasks with a high cognitive load (e.g., typing or reading). Drivers’ take-over performance improves with better knowledge of automation limits, i.e., take-overs in expected situations (Spulber & Golembiewski 2016; Zhou et al. 2021). Users’ awareness of automation limits is also essential for context switching, which is imperative in conditional automation where the driver is expected to be capable of taking over the driving task at all times. Acquiring sufficient manual driving skills is further important for the ability to
handle conditionally automated vehicles in conditions not fulfilling the ODD requirements (Trösterer et al. 2016). Automated driving can also result in changes to the driver’s manual driving behaviour, for example in terms of headway and speed (Kaduk et al. 2021; Louw et al. 2021; Melnicuk et al. 2021), and to the surrounding traffic, for instance in terms of harmonised speed patterns (Mahdinia et al. 2021).

An additional important safety challenge with ADS is interaction with pedestrians and cyclists, which may relate to the ability of the ADS to detect them and predict their behaviour (Botello et al. 2019; Rasouli & Tsotsos 2019), as well as the communication between road users. There are studies (Markkula et al. 2020; Schieben et al. 2019) indicating a possible need for external human-machine interfaces (HMIs) to support this interaction.

Real-world pilot studies (Várhelyi et al. 2021; Weber et al. 2021) have found positive safety implications of conditional automation on driving behaviour in terms of smoother accelerations, driving speeds in adherence to speed limits and occurring traffic conditions, reduction of hazardous lane changes, and using safer headways. These studies also observed the negative implications of non-responsiveness in cut-in scenarios, longer overtaking situations, and an increase in sudden brakings, which are probably mainly related to the technical maturity of the tested systems.

Many studies lack descriptions of the system (e.g., vehicle type, SAE automation level) and ODD requirements (e.g., weather and road conditions, road type), in line with existing guidelines (ERTRAC 2022; Innamaa et al. 2018). Furthermore, most studies do not scale up the results to overall traffic safety impacts, i.e., they do not relate the impacts in a single situation to the target population or frequency of relevant situations. Studies on the scaled-up safety effects of conditional automation are underrepresented in the literature, with only two studies found to be devoted to this (Bjørvatn et al. 2021; Rösener 2021).

Rösener (2021) assessed the impacts of ADS on traffic safety in Germany by combining traffic simulations, re-simulations of accidents, and accident statistics. The study included two systems: Motorway Chauffeur and Urban Robo-Taxi. Motorway Chauffeur entailed a passenger car (SAE3) that can operate on motorways and on physically separated roads at speeds of max. 130 km/h but not in conditions with heavy snowfall or rainfall, icy conditions, fog, or construction sites. Urban Robo-Taxi entailed a passenger car (SAE4) that can operate on all streets in urban areas at speeds of max. 50 km/h. Of all the injury accidents in Germany in 2016, Motorway Chauffeur could potentially affect 3% and Urban Robo-Taxi 46% of them. The number of injury accidents in Germany was estimated to be reduced by 2% by Motorway Chauffeur and 17% by Urban Robo-Taxi when the penetration of ADS in use was 50%.

Bjørvatn et al. (2021) assessed the safety impacts of ADS at EU27+3 (UK, NO & CH) level by combining traffic simulations, re-simulations of accidents, and accident data. The safety impact assessment included two systems: motorway ADS and urban ADS. Motorway ADS entailed a passenger car (SAE3) that can operate on motorways and dual-carriageway roads at speeds of max. 130 km/h but not in conditions with heavy precipitation (snow/rain), fog, or ice. Urban
ADS entailed a passenger car (SAE3) operating on major streets in urban areas at speeds of max. 50 km/h but not in conditions with heavy precipitation (snow/rain), fog, ice, or construction sites. Of all injury accidents in the EU27+3 in 2018, motorway ADS could possibly affect at most 4% and urban ADS around 40%. When considering the systems’ estimated effectiveness and selected rates of penetration (5–30%), they concluded that motorway ADS can cause a reduction of 0.1–1.2%, and urban ADS 0.8–10.2%, of all injury accidents in the EU27+3. Furthermore, they found that motorway ADS can reduce i) all accidents on European motorways by 2.0–19.0% and ii) those accidents happening in conditions fulfilling the ODD requirements by 3.8–27.6% in the EU27+3.
3. Methodology

This dissertation, based on three sub-studies, identified how ADS relate to the current road traffic safety situation and challenges from a road network (study 1), single-driver (study 2), and pedestrian (study 3) perspective (Figure 4). The potentially affected accidents were determined by first identifying the networks on which the ADS work. Then, the expected number of injury accidents, fatalities, and serious injuries on the respective networks was calculated with the EB method and combined with the limitations from the condition related ODD requirements.

Figure 4. Overview of sub-studies and research questions.

3.1 Current safety situation and challenges

3.1.1 Empirical Bayes

The current road traffic safety situation was calculated with the EB method for five networks (Table 1) in study 1. The highway network was divided into three: (1) motorway/dual carriageway roads, (2) Level I main roads, and (3) other main roads. The first network covered all motorway and dual-carriageway road sections (FTIA, 2020). The network for Level I main roads was comparable to motorways in terms of maintenance, speed limits of min. 80 km/h, regular possibilities for overtaking, and infrequent intersections, but there was no physical
separation of driving directions (FTIA 2019). The third network covered the remaining stretches on the highway network managed by the national road authority.

In urban areas there were two networks: a (4) main street and (5) other street network in the Helsinki metropolitan area (population approx. 1.2 M), which constitutes the cities of Helsinki, Espoo, and Vantaa, and in the city of Turku (population approx. 193,000). These cities were chosen since they are the major ones in Finland (around a quarter of the country’s population) and their street network is extensive. The cities’ street network hierarchies were used to identify the main streets in each city. The other street network consists of collector and local streets in the corresponding cities.

Table 1. Overview of considered networks.

<table>
<thead>
<tr>
<th>Network</th>
<th>Description</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Motorway/dual carriageway roads</td>
<td>All motorway and dual carriageway roads (driving lanes totally separated)</td>
<td>1,104</td>
</tr>
<tr>
<td>2. Level I main roads</td>
<td>Remaining main highway stretches (Level I).</td>
<td>2,519</td>
</tr>
<tr>
<td>3. Other main roads</td>
<td>Main highways (Level II) and other main roads.</td>
<td>9,829</td>
</tr>
<tr>
<td>4. Main street network in the major cities</td>
<td>Main streets in the Helsinki metropolitan area and the city of Turku.</td>
<td>292</td>
</tr>
<tr>
<td>5. Other street network in the major cities</td>
<td>Collector and local streets in corresponding cities.</td>
<td>597</td>
</tr>
</tbody>
</table>

The networks current traffic safety situation was calculated in accordance with Peltola et al. (2013, 2019) by computing the expected number of injury accidents (IAe) with the EB method, i.e., combining the injury accident record (IAr = average number of injury accidents) and the injury accident prediction model (IAM):

\[
IA_e = A \times IAM + (1 - A) \times IAR \tag{1}
\]

The injury accident prediction model is calculated as follows:

\[
IAM = e^C \times ADT^B \times Mileage \tag{2}
\]

where C is a constant depending on accident type (head-on collision, VRU, other accidents). B is a coefficient depending on road type for computing the traffic volume-dependent coefficient.

A is a weight factor calculated as follows:

\[
A = \frac{K}{K + IAM} \tag{3}
\]

1 Unanswered data request to the city of Tampere, scarce traffic volume data from the city of Oulu.
where K is the inverse value of the over-dispersion parameter and is estimated with generalised linear models.

The expected number of fatalities and serious injuries is computed based on the expected number of injury accidents with average severities (calculated per road type). The expected number of injury accidents, fatalities, and serious injuries is calculated for each road section and intersection for each accident type\(^2\) (head-on collision, VRU, other accidents).

The calculations for the highway networks were done with the TARVA tool. As the tool does not include streets, the method of Peltola et al. (2013, 2019) was tailored to urban areas in order to apply the same approach to all networks. Average daily traffic volume data from city streets was used to first compute homogeneous street line sections. This was done by merging similar links (e.g., functional class and street name) and calculating a weighted mileage (vehicle kilometres driven) for each street line section. The next step was to link (based on coordinates) 5-year (2014–2018) accident data (Statistics Finland 2022) to the homogeneous street line sections. Then, the data required for the calculations (length, mileage, injury accident record (IAr)) could be compiled for each street line section according to speed limit zones of \(\leq 40\) km/h and \(\geq 50\) km/h. The compiled data was then used to calculate (i) the accident prediction model (IAm) with Equation 2, and (ii) the expected number of accidents (IAe) with Equations 1 and 3. The calculations were done with SPSS software for individual street sections and per accident type according to speed limit zone.

### 3.1.2 Palm probability

Study 2 applied the methodology introduced by Innamaa (2014) and Norros et al. (2016) and further developed by Norros et al. (2015) for assessing accident risk from the point of view of a single driver with Palm probability. The methodology entails calculating the distribution of conditions occurring at accidents and comparing it with the Palm distribution of different conditions (random driver viewpoint). When there is a statistically significant difference in the probabilities, the condition has an increased or reduced relative accident risk compared to the overall average risk level 1.

Study 2 was limited to the Finnish highway network and included 43 roads for which weather data was available. The accident data included all police-reported accidents including a motor vehicle (\(n = 10,464\)) that occurred during the period 2014–2016. Data on weather and road conditions (15 min intervals) was acquired from Foreca Ltd. for the same period. Hourly traffic volume was computed for each segment (FTA, no date) and combined with speed limits at the time to get the traffic density (i.e., time spent on the section) for the same time period.

The analysis in this dissertation focused on comparing the relative accident risks for road weather condition classes (normal, poor, hazardous) and precipitation types (no precipitation, rain, sleet, snow) based on road types (two-lane road, multiple-lane road, motorway).

\(^2\) Originating from development work of the TARVA tool
3.1.3 Accident analysis

Study 3 described the frequency of pedestrian fatalities and serious injuries and identified characteristics related to them. The study included all police-reported pedestrian fatalities and serious injuries (MAIS3+) in accidents where the other party was a motor vehicle during the period 2014–2017 in Finland (Statistics Finland 2022). In all there were 281 accidents involving 287 drivers and vehicles, resulting in 285 killed or seriously injured (KSI) pedestrians.

The frequency of pedestrian KSI was analysed with the pedestrian KSI rate as follows:

\[
Pedestrian\ KSI\ rate = \frac{Annual\ average\ number\ of\ KSI\ pedestrians\ by\ a\ motor\ vehicle}{Annual\ million\ kilometers\ walked}\]

Exposure was based on the National Travel Survey (FTA 2018b). Kilometres walked was used as the exposure in study 3, as it has been found to be a good measure of pedestrian safety (Polders & Brijs 2018) and trip length is less underreported than the number of short trips in travel surveys (Sammer et al. 2018).

The analysis of characteristics related to pedestrian fatalities and serious injuries included the following factors: pedestrian (age, gender), driver (age, gender, age of driving licence), vehicle (age, type), accident location (place of occurrence, speed limit, type of municipality, area type), road and weather conditions (road surface, lighting, weather and temperature) and time of occurrence (time of day, day of the week, season). The Chi-Square test of independence (Sheskin 2000) was applied to identify differences between the severities.

3.2 Identifying accidents potentially affected by ADS

Study 1 identified the accidents potentially affected by ADS in four steps, which are described below.

3.2.1 Description of systems under assessment

The ADS descriptions were derived from mature system descriptions developed by Metz et al. (2019, pp. 22–25) (Table 2). The descriptions are expert views of future systems. They were developed in collaboration with true ADS developers and can be assumed to portray the current view of a mature system. The ADS maintains a safe headway to other vehicles and keeps the car in the lane. At the end of the ODD, the driver receives a take-over request and has to resume control of the driving task. The occurring speed limit (maximum 130 km/h on motorways) is the target speed of the ADS.
### Table 2. Description of systems under assessment.

<table>
<thead>
<tr>
<th>ODD requirements</th>
<th>Motorway ADS</th>
<th>Urban ADS</th>
</tr>
</thead>
</table>
| Infrastructure         | - All motorways and other dual-carriageway roads, i.e., physically separated driving directions.  
                        | - Visible lane and road markings are needed on both sides (small gaps are manageable).  
                        | - The ODD begins when the vehicle has merged onto the motorway from the on-ramp and ends when the vehicle merges with the off-ramp or leaves the motorway.  
                        | - The ODD includes weaving areas without ramps and road works but not toll station areas. | - Urban streets with a speed limit of 50 km/h or under.  
                        | - On streets with oncoming traffic, the street width must be sufficient for two cars to pass each other.  
                        | - Lane separators such as curbs or lane markings are needed on one side (small gaps are manageable).  
                        | - The ODD includes signalised and non-signalised intersections, simple roundabouts (one driving lane and no bicycle lane) and signalised tramway/railway crossings but no roadwork areas. |
| Road and weather conditions | - The ODD covers clear, cloudy, and light rain, dry and moist road conditions, and all lighting conditions.  
                        | - It excludes all extreme weather conditions (e.g., hard rain, snowfall, slush) and road conditions (e.g., icy, snowy, slushy, and standing water). |  |

#### 3.2.2 Definition of networks

The target operating road network for both ADS was determined from their system description. The motorway ADS operating network consisted of all motorway and dual-carriageway roads (FTIA 2020). The urban ADS operating network consisted of the main streets in four major cities (see chapter 2.1.1).

#### 3.2.3 Weather and road condition limitations

The proportion of injury accidents that occur in weather and road conditions matching the ADS’s ODD requirements were retrieved from a previous project (Malin et al. 2017; Malin et al. 2019). The results stem from measured road and weather conditions at the time of the accident and not manually post-coded information as in the national accident statistics. The categories of the previous study (Malin et al. 2017) were re-classified based on the ODD requirements related to conditions (Table 2). Of all motor-vehicle injury accidents, 84.3% occur in weather conditions and 69.5% in road conditions matching the ADS’ ODD requirements.

#### 3.2.4 Calculation of accidents potentially affected

The potentially affected accidents (PAA) for motorway and urban ADS respectively were calculated as follows:

\[
PAA_{ADS,i} = \text{Current safety situation}_i \times \text{Limiting road conditions} \times \text{Limiting weather conditions}
\]  

(5)
where $s$ is severity. The current safety situation was calculated with the EB method (see chapter 3.1.1) for the operating network of the ADS in question (see chapter 3.2.2). The calculations were done per severity (injury accidents, fatalities, and serious injuries).

To calculate the scope of impact, i.e., the maximum share of potentially affected accidents for the ADS, the PAA (per severity) was proportioned to the national annual average (Statistics Finland 2022). The 6-year annual average for the period 2014–2019 was 5,816 injury accidents, 241 fatalities, and 470 serious injuries. The PAA (per severity) for urban ADS was also proportioned to the four selected cities’ annual average (Statistics Finland 2022). The 5-year annual average for the period 2014–2018 was 727 injury accidents, 15.4 fatalities, and 44.6 serious injuries.
4. Results

4.1 Current road traffic safety situation and challenges

4.1.1 Network level perspective

Table 3 presents the annual number of accidents and accident risk (No./Mkm) on different networks. The accident risks for all severities were higher on other main roads (28–52%) and Level I main roads (9–31%) than on the highway network in general. For motorway/dual-carriageway roads, the corresponding accident risks were lower for all severities (31–69%).

The accident risks for all severities were higher on other streets (22–24%) and lower on the main streets (19–21%) than on the urban network in general.

In comparison to the total on all networks, the injury accident and serious injury risks were considerably higher (two to threefold) on the street networks and the fatality risk was highest (56%) on other main roads. Furthermore, in comparison the total on all networks, the accident risks were lower for all severities on motorways/dual-carriageway roads (46–68%), for injury accidents on other main roads (14%), and for fatalities on the main street network (27%).
### Table 3: Overview of the current safety situation on the different networks.

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Accident Risk (No./km)</th>
<th>Injury Fatality (No./year)</th>
<th>Serious Inj. (No./year)</th>
<th>Fatalities (No./year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban network Total on all</td>
<td>0.0041</td>
<td>0.0034</td>
<td>0.0026</td>
<td>0.0012</td>
</tr>
<tr>
<td>Highway network</td>
<td>0.0036</td>
<td>0.0028</td>
<td>0.0022</td>
<td>0.0013</td>
</tr>
<tr>
<td>Other street network in</td>
<td>0.0027</td>
<td>0.0021</td>
<td>0.0017</td>
<td>0.0013</td>
</tr>
<tr>
<td>Major cities Level I main</td>
<td>0.0024</td>
<td>0.0019</td>
<td>0.0015</td>
<td>0.0011</td>
</tr>
<tr>
<td>Network Other main roads</td>
<td>0.0031</td>
<td>0.0025</td>
<td>0.0019</td>
<td>0.0014</td>
</tr>
<tr>
<td>Motorway / dual-car-roads</td>
<td>0.0029</td>
<td>0.0024</td>
<td>0.0019</td>
<td>0.0013</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Mileage (Mkm/y)</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban network Total on urban</td>
<td>14.341</td>
<td>14.489</td>
</tr>
<tr>
<td>network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highway network Total on</td>
<td>21.727</td>
<td>20.802</td>
</tr>
<tr>
<td>highway network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other street network in</td>
<td>17.20</td>
<td>16.35</td>
</tr>
<tr>
<td>Major cities Level I main</td>
<td>5.8</td>
<td>4.9</td>
</tr>
<tr>
<td>Network Other main roads</td>
<td>1.382</td>
<td>1.265</td>
</tr>
<tr>
<td>Motorway / dual-car-roads</td>
<td>0.227</td>
<td>0.202</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Length (km)</th>
<th>Mileage (Mkm/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban network Total on urban</td>
<td>28.250</td>
<td>14.341</td>
</tr>
<tr>
<td>network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highway network Total on</td>
<td>25.523</td>
<td>13.452</td>
</tr>
<tr>
<td>highway network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other street network in</td>
<td>2.519</td>
<td>1.489</td>
</tr>
<tr>
<td>Major cities Level I main</td>
<td>1.011</td>
<td>0.582</td>
</tr>
<tr>
<td>Network Other main roads</td>
<td>0.336</td>
<td>0.178</td>
</tr>
<tr>
<td>Motorway / dual-car-roads</td>
<td>0.255</td>
<td>0.125</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Mileage (Mkm/y)</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban network Total on urban</td>
<td>116.6</td>
<td>28.250</td>
</tr>
<tr>
<td>network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highway network Total on</td>
<td>106.3</td>
<td>25.523</td>
</tr>
<tr>
<td>highway network</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other street network in</td>
<td>4.5</td>
<td>2.519</td>
</tr>
<tr>
<td>Major cities Level I main</td>
<td>1.265</td>
<td>1.011</td>
</tr>
<tr>
<td>Network Other main roads</td>
<td>0.336</td>
<td>0.255</td>
</tr>
<tr>
<td>Motorway / dual-car-roads</td>
<td>0.227</td>
<td>0.178</td>
</tr>
</tbody>
</table>
4.1.2 Single driver perspective

A single driver has an increased or reduced relative accident risk in a certain driving condition compared to the overall average relative risk level 1 when the distribution of conditions occurring at accidents and the Palm distribution of the same condition are statistically significantly different. The corresponding relative accident risk\(^3\) was lower for motorways (0.75–0.77) compared to two-lane (0.88–1.12) and multiple-lane roads (1.14–1.55).

Table 4 presents the risk of road weather condition class compared to the overall accident risk per road type. It is seen that the relative accident risk increased as the conditions worsen. The increase was largest on motorways, where the relative accident risk for “hazardous” conditions was almost fourfold.

<table>
<thead>
<tr>
<th>Road weather condition class</th>
<th>Relative accident risk</th>
<th>Precipitation type</th>
<th>Relative accident risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>0.89</td>
<td>No precipitation</td>
<td>0.91</td>
</tr>
<tr>
<td>Poor</td>
<td>2.00</td>
<td>Rain</td>
<td>0.97</td>
</tr>
<tr>
<td>Hazardous</td>
<td>2.98</td>
<td>Sleet</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Snow</td>
<td>2.15</td>
</tr>
</tbody>
</table>

The precipitation type’s relative accident risks were also compared depending on type of road (Table 4). The relative accident risk was highest for snowfall on all types of roads. The relative accident risks were higher for all precipitation types on motorways (1.21–2.59) than on roads with two lanes (0.97–2.15) and multiple lanes (1.07–1.91).

4.1.3 Pedestrian perspective

Figure 5 presents the pedestrian KSI rate (annual number of pedestrian KSI per 100 M kilometres walked) for different area types. The pedestrian KSI rate was especially heightened in rural heartland areas\(^4\) (ca. 220% higher than the overall pedestrian KSI rate “Total”).

---

\(^3\) The risks were calculated for different regions (northern inland, southern inland and coastal area) due to the objectives of study 2.

\(^4\) Rural areas with intensive land use, with a relatively dense population and a diverse economic structure at local level.
Comparing the characteristics of pedestrian fatalities and serious injuries revealed differences in vehicle type, location of occurrence, area type, occurring speed limit, lighting and road conditions, and temperature. There were no differences in variables related to pedestrian or driver, weather conditions, and variables related to time of occurrence.

Most (64%) pedestrians were killed or seriously injured by a passenger car. A passenger car was more often involved in pedestrian serious injuries (73%) than fatalities (51%), whereas a truck was more often involved in pedestrian fatalities (21%) than serious injuries (8%).

Of the KSI pedestrians, 43% were impacted in a 40 km/h speed limit zone (Table 5). Compared to pedestrian fatalities, serious injuries happened less often in over 80 km/h speed limit zones (7% vs. 34%) and more often in speed limit zones of 40 km/h (49% vs. 35%) and 50–70 km/h (35% vs. 22%).

About 40% of the pedestrians were killed or seriously injured on pedestrian crossings and carriageways respectively. Compared to pedestrian serious injuries, fatalities occurred more often on a carriageway (52% vs. 34%) and less often on pedestrian crossings (27% vs. 49%).

Around 40% of the pedestrians were killed or seriously injured in inner urban areas. Compared to pedestrian fatalities, serious injuries happened more often in inner urban areas (25% vs. 51%) and less often in sparsely populated rural and rural heartland areas (25% vs. 13%).
Table 5. Distributions (%) of speed limit, location, and area type according to pedestrian fatality and serious injury

<table>
<thead>
<tr>
<th>Speed limit</th>
<th>Fatalities (n=116)</th>
<th>Serious injuries (n=169)</th>
<th>Total (n=285)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤30 km/h</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>40 km/h</td>
<td>35</td>
<td>49</td>
<td>43</td>
</tr>
<tr>
<td>50–70 km/h</td>
<td>22</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>≥80 km/h</td>
<td>34</td>
<td>7</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Place of accident</th>
<th>Fatalities (n=116)</th>
<th>Serious injuries (n=169)</th>
<th>Total (n=285)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carriageway</td>
<td>52</td>
<td>34</td>
<td>41</td>
</tr>
<tr>
<td>Pedestrian crossing</td>
<td>27</td>
<td>49</td>
<td>40</td>
</tr>
<tr>
<td>Car park</td>
<td>15</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Other (cycle path, bridge, bus stop)</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area type</th>
<th>Fatalities (n=116)</th>
<th>Serious injuries (n=169)</th>
<th>Total (n=285)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner urban area</td>
<td>25</td>
<td>51</td>
<td>40</td>
</tr>
<tr>
<td>Outer urban area</td>
<td>20</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td>Peri-urban area and rural area close to urban area</td>
<td>17</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Local centre in rural area</td>
<td>13</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Sparsely populated rural and rural heartland area</td>
<td>25</td>
<td>13</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

The road conditions were dry for 48% of all KSI pedestrians. Compared to pedestrian fatalities, serious injuries happened more often in wet road conditions (37% vs. 21%). On the other hand, they occurred less often than fatalities in dry road conditions (44% vs. 55%) and winter road conditions (20% vs. 24%).

Most (59%) pedestrians were killed or seriously injured in daylight. Compared to pedestrian fatalities, serious injuries occurred more often in places with streetlights lit (31% vs. 13%) and less often in daylight (53% vs. 66%).

The temperature was above 3°C for most (54%) KSI pedestrians. Compared to pedestrian fatalities, serious injuries occurred more often than fatalities in temperature conditions of -3––3°C (40% vs. 28%) and less often at temperatures below -3°C (7% vs. 16%).

4.2 Accidents potentially affected by ADS

4.2.1 Motorway ADS

The accidents potentially affected by motorway ADS were identified by multiplying the current safety situation on its operating network (motorway/dual-carriageway roads) with the percentage of limiting road and weather conditions. The motorway ADS could annually affect at maximum 191 injury accidents, eight fatalities, and 15 serious injuries (Table 6). The scope of impact, i.e., proportioning numbers to the national annual average, would be 3.3% of all injury accidents, 3.1% of all fatalities, and 3.2% of all serious injuries in Finland.
Table 6. Scope of impact (compared to the national annual average\(^1\)) of motorway ADS.

<table>
<thead>
<tr>
<th></th>
<th>Injury accidents</th>
<th>Fatalities</th>
<th>Serious injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of potentially affected accidents</td>
<td>191</td>
<td>7.6</td>
<td>14.9</td>
</tr>
<tr>
<td>Scope of impact compared to national annual average(^1)</td>
<td>3.3%</td>
<td>3.1%</td>
<td>3.2%</td>
</tr>
</tbody>
</table>

\(^1\)5,816 injury accidents; 241 fatalities; 470 serious injuries (Statistics Finland 2022)

4.2.2 Urban ADS

The accidents potentially affected by urban ADS were identified by multiplying the current safety situation on its operating network (main street network) with the percentage of limiting road and weather conditions. In four major Finnish cities, urban ADS could annually affect at maximum 127 injury accidents, three fatalities, and 12 serious injuries (Table 7). The scope of impact compared to the national annual average would be 2.2% of all injury accidents, 1.1% of all fatalities, and 2.5% of all serious injuries. The scope of impact compared to the annual average in the four cities would be 17.4% of all injury accidents, 17.2% of all fatalities, and 26.8% of all serious injuries.

Table 7. Scope of impact (compared to the national\(^1\) and selected cities\(^2\) annual average) of urban ADS.

<table>
<thead>
<tr>
<th></th>
<th>Injury accidents</th>
<th>Fatalities</th>
<th>Serious injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of potentially affected accidents</td>
<td>127</td>
<td>2.6</td>
<td>11.9</td>
</tr>
<tr>
<td>Scope of impact compared to national annual average(^1)</td>
<td>2.2%</td>
<td>1.1%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Scope of impact compared to selected cities’ annual average(^2)</td>
<td>17.4%</td>
<td>17.2%</td>
<td>26.8%</td>
</tr>
</tbody>
</table>

\(^1\)5,816 injury accidents; 241 fatalities; 470 serious injuries (Statistics Finland 2022)
\(^2\)727 injury accidents; 15.4 fatalities; 44.6 serious injuries (Statistics Finland 2022)

4.3 Relation of ADS to current safety challenges

The results indicate that the analysed ADS do not address the road networks with the worst current safety situation, i.e., with the greatest safety potential. Specifically, the current accident risk (No./Mkm) was lower on those networks where ADS could be activated (motorway/dual-carriageway roads and main streets) than on the other considered networks where ADS could not be used (study 1). Similarly, from a single-driver perspective, the relative accident risk on motorways was lower than on roads with two or multiple lanes (study 2). Furthermore, the pedestrian KSI rate was highest in rural heartland areas which do not fall within the operating environment of motorway and urban ADS (study 3).
The risks were considerately higher on the two urban networks than the total risk on all networks, highlighting the safety issues of urban areas and need for improvement, which could be addressed by urban ADS.

The accident risk for a single driver increased in weather conditions not matching the ODD requirements (hazardous conditions and snowfall) on both motorways and two- and multiple-lane roads. The increase in accident risk in worsening conditions was greatest on motorways where the corresponding risks were highest. These weather and road conditions do not fulfil the ODD requirements of the ADS, meaning that the driver must be in control of the driving task in the most dangerous conditions.

A passenger car was more often involved in pedestrian serious injuries than fatalities, whereas a truck was more often involved in pedestrian fatalities than serious injuries. The ADS in this study concern passenger cars, indicating that they target more pedestrian serious injuries than fatalities. For variables related to location of the accident, serious injuries occurred more commonly than fatalities in inner urban areas, in 40–70 km/h speed limit zones, and on pedestrian crossings. These align with the infrastructure-related ODD requirements of urban ADS of passenger cars, thus indicating that the system would target more pedestrian serious injuries than fatalities. For variables related to weather and road conditions of the accident, fatalities occurred more commonly than serious injuries at temperatures below -3°C and in winter conditions. The ADS do not operate in wintry road and weather conditions; consequently, they target more pedestrian serious injuries than fatalities.
5. Discussion

The overall objective was to identify the potential of passenger cars with motorway and urban ADS (SAE3) for improving traffic safety in Finland. This dissertation, based on three sub-studies, identified the safety potential of the ADS based on the current road traffic safety situation, which was investigated from a network, single-driver, and pedestrian perspective.

The four research questions of the dissertation were: 1) What are the current road traffic safety challenges in Finland from a network, single-driver, and pedestrian perspective; 2) how many accidents can motorway ADS potentially affect, 3) how many accidents can urban ADS potentially affect, and 4) how do motorway and urban ADS relate to the identified safety challenges? This chapter discusses each of the questions and the limitations of the dissertation.

5.1 Current road traffic safety situation and safety challenges

5.1.1 Network perspective

Study 1 calculated the current safety situation for five road networks in terms of the expected number and risk (No./Mkm) of injury accidents, fatalities, and serious injuries. In order to apply the same approach for all networks, the method of Peltola et al. (2013, 2019) was tailored to urban areas.

Compared to the highway network in general, the risk of injury accident, fatality, and serious injury was higher on other main roads (28–52%) and Level I main roads (9–31%) but lower (31–69%) on motorways/dual-carriageway roads. These results are in accordance with previous research (e.g., Elvik et al. 2009 pp. 54). The difference in risk for serious injury and the other severities was of the same magnitude for each network. The Level I main road network is similar to the motorway network (high-level maintenance, speed limits >80 km/h, limited number of intersections), except for having physical separation of driving directions. One of their main traffic safety issues is head-on and single-vehicle accidents, which are often severe at such high speeds.

Infrastructure-related measures such as physical separation of driving directions can be very costly and should be prioritised to sections with a high number of accidents, both in terms of vehicle and road km, to be cost-effective. On sections with high accident risk only per vehicle km driven (generally rural roads with small traffic volumes), emphasis should be put on low-cost safety measures (e.g., automatic speed enforcement). The advanced equipment of a car fitted
with ADS allows driver support features to be used during manual driving. This includes support to e.g., avoid drifting out of the lane on roads not fulfilling the ODD requirements, where costly infrastructural measures (such as physical separation of driving directions) are not justifiable from the road operator's viewpoint.

The risk of injury accident, fatality and serious injury was higher on other streets and lower on main streets compared to urban areas in general. The risks on the street networks were higher than the total on all networks (over twofold risk for injury accident and serious injury). Previous studies have also found that urban areas pose one of the main traffic safety challenges, and that the safety situation there has not improved at the same pace as on motorways (Adminainté-Fodor & Jost 2019; Elvik 2010). Furthermore, consistent with the literature (e.g., Adminainté-Fodor & Jost 2019; Malin et al. 2020), the findings emphasise the importance of urban areas when targeting the objective to decrease the number of serious injuries. The findings also indicate that including serious injuries in traffic safety work places greater responsibility on municipalities, which in turn calls for collaboration among different stakeholders to achieve the traffic safety objectives.

5.1.2 Single-driver perspective

Study 2 analysed accident risk from the point of view of a single driver with Palm probability. Similarly to the network-level results (study 1), motorways had a lower relative accident risk compared to roads with two and multiple lanes. In line with previous research (e.g., Malmivuo & Kärki 2002; Salli et al. 2008), the accident risk increased in bad or worsening weather conditions. This increase was the greatest on motorways, where the corresponding risks were also the highest.

5.1.3 Pedestrian perspective

Study 3 analysed the frequency of pedestrian KSI and identified differences between the severities. Comparison of pedestrian KSI rates per area type found that they are very frequent in rural heartland areas.

There were differences in the characteristics of pedestrian fatalities and serious injuries for the following factors: vehicle type, place of occurrence, area type, occurring speed limit, lighting and road conditions, and temperature.

A passenger car was involved more often in serious injuries to pedestrians than fatalities, whereas a truck was more often involved in pedestrian fatalities than serious injuries. This is supported by other studies, which also found that accidents involving heavier vehicles result in higher pedestrian injury severity (e.g., Clifton et al. 2009; Lee & Abdel-Aty 2005; Roudsari et al. 2004).

A large majority of pedestrians were killed or seriously injured in areas with 40 km/h speed limits. In speed limit zones of 80 km/h or more, pedestrian serious injuries occurred less often than fatalities (7% vs. 34%). Compared to pedestrian fatalities, serious injuries occurred more often in speed limit zones of 40 km/h (49% vs. 35%) and 50–70 km/h (35% vs. 22%). Comparable results
have been found in other studies (Eluru et al. 2008; Kröyer 2015; Sze & Wong 2007).

With regard to area type, most pedestrians were killed or seriously injured in areas categorised as inner and outer urban areas. Compared to pedestrian fatalities, serious injuries occurred more often in inner urban areas and less often in rural heartland and sparsely populated rural areas. Previous studies have also found a higher severity of pedestrian accidents in sparsely populated areas and villages than in other areas (Adminaité et al. 2015; Gláš & Juhász 2017; Lee & Abdel-Aty 2005). This finding could be related to the safety-in-numbers phenomenon, where the number of accidents involving pedestrians and cyclists increases disproportionally compared to the number of pedestrians and cyclists (e.g., Elvik & Bjørnskau 2017). It can also be related to the street environment being safer overall or to different engineering measures reducing vehicle speeds (e.g., Retting et al. 2003). These findings suggest that pedestrian traffic safety measures need to be tailored to the location in question.

Compared to pedestrian serious injuries, fatalities occurred less often on pedestrian crossings (27% vs. 49%) and more often on a carriageway (52% vs. 34%). The results are supported by previous studies (Clifton et al. 2009; Gitelman et al. 2012) and by the findings described above, since the location of pedestrian crossings is often in urban areas and in areas with lower speed limits.

Serious injuries to pedestrians happened more often than fatalities in wet road conditions (less often in winter road conditions and on dry roads) and in temperature conditions of -3–3°C (less often at temperatures below -3°C). This is supported by previous research which has found that adverse weather conditions increase injury severity (Lee & Abdel-Aty 2005; Olszewski et al. 2015).

5.2 Accidents potentially affected by ADS

Study 1 identified the potentially affected accidents for motorway and urban ADS based on the current safety situation of their operating road networks. The motorway ADS of passenger cars can annually affect a maximum of 3.3% of all injury accidents, 3.1% of all fatalities, and 3.2% of all serious injuries in Finland. This finding is comparable to those of Rösener (2021), who found that 3% of all injury accidents in Germany could potentially be affected by a similar system, and Bjørvatn et al. (2021), who found that 4.4% of slight injury accidents, 4.1% of fatalities, and 3.1% of serious injury accidents in the EU27+3 could potentially be affected by the same system as in this dissertation.

In four major Finnish cities, urban ADS of passenger cars could potentially affect at most 2.2% of all injury accidents, 1.1% of all fatalities, and 2.5% of all serious injuries in Finland. Compared to these cities’ annual average, the scope of impact corresponds to 17.4% of all injury accidents, 17.2% of all fatalities, and 26.8% of all serious injuries. These findings are far more modest than those of Rösener (2020) and Bjørvatn et al. (2021). Rösener (2020) found that 46% of all injury accidents in Germany could potentially be affected by an Urban Robo-Taxi. Bjørvatn et al. (2021) found that in the EU27+3 the same system as in this dissertation could potentially affect at most 43% of slight injury accidents, 18%
of fatalities, and 33% of serious injury accidents. The disparities in the findings could interrelate to Rösener’s system being more advanced (higher SAE level and no ODD restrictions for operating conditions). Furthermore, the results of both studies were based on all accidents occurring in urban areas (regardless of e.g., size of the urban area) and thus the assessment included all urban areas in Germany and the EU27+3 area.

This dissertation did not take into account the effectiveness of ADS in preventing or reducing the severity of potentially affected accidents. Previous studies have found that similar ADS effectively avoid accidents in single-driving circumstances such as cut-in and rear-end situations (Bjørvatn et al. 2021; Fahrenkrog et al. 2019; Wang et al. 2017). Furthermore, modifications in accident causation, e.g., accident severity and type, could occur instead of preventing accidents. The system’s effectiveness also depends, however, on the occurrence of specific situations; even though the system is effective in preventing accidents related to a certain situation, the overall effect is minor if the scenario is rare. As indicated by Bjørvatn et al. (2021), although equipping passenger cars with motorway ADS effectively improves traffic safety in conditions fulfilling the ODD requirements, the effect on all European road accidents is small, since there is a limited number of motorways and their safety situation is already relatively good.

5.3 Relation of ADS to current safety challenges

The results from the three studies are reflected in the answer to RQ4. The operating environment of the analysed passenger cars’ ADS does not correspond to environments and conditions where the current safety situation (accident risk, relative accident risk from a single-driver perspective, pedestrian KSI rate) is the worst. Thus, there is a lot of safety potential if the operating environments and conditions of ADS could be extended to e.g., high-level rural roads. For networks in urban areas, the accident risks were considerably higher than the total risk on all networks, indicating that there is considerable safety potential for urban ADS.

The increase in relative accident risk with worsening conditions was greatest on motorways, showing that the driver must handle the driving task in the most dangerous conditions. Previous studies (e.g., Kaduk et al. 2021) have found that there can be a deterioration in driving performance following an automation phase, adding further strain to a driver who is required to drive manually in road and weather conditions not matching the ODD requirements. This also means that take-over requests, which in themselves are already challenging from the driver’s point of view (e.g., Wan & Wu 2018; Zeeb et al. 2016), can occur in dangerous conditions due to sudden changes in weather conditions. This further emphasises the need for users of conditionally automated vehicles to acquire sufficient experience of manual driving, since previous research (e.g., Trösterer et al. 2016) highlight initial skilling as a prerequisite for maintaining driving skills after long periods of driving inactivity.
From a pedestrian perspective, the ADS in this study seem to address pedestrian serious injuries more than fatalities since the ADS concern passenger cars and do not work in wintery road and weather conditions. Furthermore, serious injuries happened more often than fatalities in locations within the ODD of urban ADS, indicating that the system would again target more pedestrian serious injuries than fatalities.

These results link the characteristics of current accidents to the operating environment of the ADS but do not assess the effectiveness of ADS for preventing the target accidents. The interaction between pedestrians and ADS has been recognised as a foremost safety challenge and possible hindrance to the deployment of ADS (Botello et al. 2019; Rasouli & Tsotsos 2019). In the case of urban ADS working only on main streets, the interaction can be expected to occur at crosswalks. Some studies suggest that there is a need for external HMIs to support the interaction (Markkula et al. 2020; Schieben et al. 2019).

5.4 Limitations

This dissertation has several limitations to be considered when interpreting the results:

- As a result of different data availability, the street networks included in the estimation of the current safety situation in study 1 were limited to the cities of Helsinki, Espoo, Vantaa, and Turku, thus excluding two major cities in Finland: Tampere (unanswered data request) and Oulu (scarce traffic volume data) and all the smaller towns. Nevertheless, the analysis included the major cities in Finland, which make up a quarter of the Finnish population.
- Extending the method of Peltola et al. (2013, 2019) developed for main roads to urban areas poses some uncertainties. For example, the utilised accident category division (head-on, VRU, other) is not as well suited to urban areas as to rural roads, but the method was nevertheless applied to urban areas, as it has been found to better predict the safety situation than relying on accident history alone (Peltola et al. 2013).
- The national travel survey used to calculate the pedestrian KSI rate expresses reported behaviour and does not therefore correspond to revealed behaviour. Underreporting is frequent in travel surveys, more so for the number of short trips than for trip length (Sammer et al. 2018), which is why the latter variable was chosen to be used in the analyses conducted in study 3. Pedestrian KSI rate could not be compared based on location and conditions, since there was no corresponding exposure information.
- Uncertainties arise from accident data due to underreporting of accidents. The utilised accident data cover all fatal traffic accidents involving a motor vehicle, but injury accidents and accidents with serious injuries are still underreported (Peltola et al. 2018).
• Using urban ADS of passenger cars would be possible also in other cities than those included in the calculations and, as a result, the safety potential could be larger. This was acknowledged by proportioning the potentially affected accidents by urban ADS to the annual average of the whole country and selected cities. Nevertheless, the analysis includes four major cities that have an extended street network and are therefore places where urban ADS of passenger cars can be anticipated to be used.

• The road and weather condition limitations which were used to calculate the accidents potentially affected by ADS originated from a previous project (Malin et al. 2017, 2019) analysing the highway network. Hence, some uncertainties arise from using these results for all the road networks included in this dissertation. They were still used, however, since they are based on measured conditions and not on post-coded information as in the accident statistics. These results also distinguished between more detailed categories for road and weather conditions than those used in the national accident statistics, which in turn detailed the estimated share of accidents which occurred in conditions fulfilling the ODD requirements. Even without considering road and weather condition limitations, passenger car ADS could potentially affect 2–5% of all injury accidents, fatalities, and serious injuries in Finland.

• The dissertation did not account for passenger car ADS usage or deployment scenarios. Thus, the results of the thesis only indicate the maximum potential scope of impact of the ADS studied in the current situation. With introduction of ADS, new types of risk factors that are associated with accidents could occur (e.g., sensor failure, minimum risk maneuver).
6. Conclusions

6.1 Summary of findings

The main objective was to identify the potential of passenger cars with motorway and urban ADS (SAE3) in improving traffic safety in Finland. The results showed that the current safety situation is better on operating networks of ADS and conditions fulfilling ODD requirements than other networks and conditions not fulfilling them.

All in all, motorway ADS of passenger cars can annually potentially affect at maximum 191 injury accidents, eight fatalities, and 15 serious injuries. Depending on severity, this corresponds to 3.1–3.3% of the national annual average. In four major Finnish cities, urban ADS of passenger cars can annually potentially affect 127 injury accidents, three fatalities, and 12 serious injuries. These correspond to 1.1–2.5% of the national and 17.1–26.8% of the selected cities’ annual average.

In terms of scope of impact, urban ADS seem to have greater potential than motorway ADS. The total maximum number of potentially affected accidents is nevertheless smaller for urban ADS, since this study included only four major cities in the country. However, it is important to note that the development and introduction of ADS in urban environments is not as advanced as systems designed for motorways, since the operating environment is far more complex in urban areas.

Despite the more developed ADS for motorway environments, improving traffic safety on motorways is challenging, since generally the most effective measures have already been carried out. Hence, motorway ADS can be seen as one relevant vehicle technology development with the potential to improve traffic safety on motorways.

The requirement for physical separation of driving directions currently restricts the potential to extend the network length for motorway ADS in Finland (there is physical separation on about 1.5% of the highway network length). The operating environment of ADS, and consequently the scope of impact, could be substantially extended if the development work moved towards including high-level rural roads in the ODD, especially since these roads have a high share of fatal and severe head-on and single-vehicle accidents, which are the accident types effectively prevented by ADS.

For a single driver, the relative accident risk for road and weather conditions not fulfilling the ODD requirements was especially high on motorways, meaning
that in a conditionally automated vehicle, the driver must take over and handle the driving task in the most dangerous conditions. This emphasises the safety aspects of take-over requests and the need for harmonised and well-designed take-over requests and HMIs supporting users’ awareness of the system’s capabilities and limitations (e.g., Spulber & Golembiewski 2016, Zhou et al. 2021). Incorporating meteorological information or services into ADS would also enable the systems to take into account local and sudden changes in road and weather conditions. Furthermore, efforts to ensure a novice driver’s initial driving skills are important (Trösterer et al. 2016) to ensure that drivers have the required capabilities to handle the driving task in adverse road and weather conditions. Future driver education and training might have to include practising take-over request situations.

There are differences in the characteristics of pedestrian fatalities and serious injuries in terms of vehicle type, accident location, area type, current speed limit, temperature, and lighting and road conditions. The results indicate that the passenger car ADS in this study could target more pedestrian serious injuries than fatalities. The prerequisites for the interaction between pedestrians and ADS are subject to different recommendations, highlighting the need for further research to introduce well-designed systems both in terms of driving behaviour (e.g., speed and yielding) and external appearance (incl. HMIs).

### 6.2 Contributions

This dissertation identified the road network on which the analysed ADS can be operated and estimated the current number of injury accidents, fatalities, and serious injuries on each network with the EB method. It provided information on the scope of impact of conditionally automated passenger cars (SAE3) in terms of clearly defined ADS for motorway and urban environments. Furthermore, the dissertation contributed to the knowledge gap on serious injuries by 1) comparing the accident risk for different severities (injury accident, fatality, and serious injury) on different types of road networks and 2) showing that there are differences in accident characteristics related to killed and seriously injured pedestrians in accidents with motor vehicles.

From a methodological perspective, this dissertation extended the method of Peltola et al. (2013, 2019) to urban areas, enabling calculation of the expected number of injury accidents, fatalities, and serious injuries with the EB method in the selected cities. Applying EB is very important when analysing accident severities separately, as the accident data must be divided into even smaller categories. Thus, the EB method enables a detailed and methodologically sound analysis (Elvik 2008) per accident severity. This also entailed identifying the maximum number of accidents potentially affected by passenger car ADS per severity.

Furthermore, this dissertation presented a new approach to identifying the safety potential of ADS. The results derive from identifying the road network where ADS can be operated and calculates its current safety situation with the EB method as compared to previous research (Rösener 2020; Bjørvatn et al.
identifying accidents potentially affected by ADS from accident databases.

### 6.3 Future research recommendations

This dissertation only assessed the scope of impact in terms of maximum number of potentially affected accidents in the current situation. Further studies are needed to estimate the traffic safety impacts of ADS. Direct and indirect impacts should be considered when assessing the overall effectiveness of ADS for improving safety. This can be done by e.g., applying the safety assessment framework originally developed for ITS (Kulmala 2010; Rämä & Innamaa 2021) and further developed for AVs (Innamaa et al. 2018), which covers both the engineering effect and behavioural adaptation for all traffic safety dimensions (exposure, risk, and consequence). The framework consists of impact mechanisms for user and non-user modification of behaviour in both the short and long term.

The traffic safety work has until recently focused mainly on fatalities. With better knowledge on serious injuries, it should be altered to include both fatalities and serious injuries. The results of this dissertation indicate that with the inclusion of serious injuries in traffic safety work, the responsibility shifts from the national road and traffic administration to the municipalities, creating a need for collaboration between different stakeholders at different levels (local, regional, national, and European). Regarding the definition of serious injuries and data collection procedures, there is a need for further harmonisation between the Member States to diminish the related knowledge gap.

Although ADS (SAE3) for passenger cars have been released (e.g., Mercedes Benz 2022), deployment is expected to be slow especially in Finland, where vehicle fleet renewal is among the slowest in Europe (ACEA 2022). Since the transition period is expected to be long (Bishop 2020), it is necessary to plan how ADS can safely be introduced and integrated into traffic (EC 2020b; Papadimitriou et al. 2022). This also indicates that additional measures are needed to reach the traffic safety goals, preferably with a systematic approach (Várhelyi 2016). Additional measures could be related to a reduction in accident risk (e.g., physical separation of driving directions and road user groups, improved crossing facilities, speed limit reductions, increased automatic enforcement, introduction of speed reducing devices), exposure (e.g. reduction in kilometres travelled, shift to modes with lower accident risk), or accident severity (e.g., improved emergency services, forgiving roadsides, increased use of safety equipment). On the other hand, conditionally automated cars are likely to be able to contribute to reaching the traffic safety goals—especially in terms of improving traffic safety on motorways, where the most effective traffic safety measures have already largely been implemented.
References


References


FTA. (2020). Road register. [Cited 1 Feb 2021]. Available at: https://extranet.vayla.fi/web/extranet/

FTIA. (2019). Pääteiden palvelutaso ja tulevaisuuden tarpeet. [Service level and future needs of main public highways]. Helsinki. Finnish Transport Infrastructure Agency. Available at: https://vayla.fi/documents/25230764/0/%C3%A4%C3%A4teiden+palvelutaso+ja+tulevaisuuden+tarpeet_Raportti_05.11.2019.pdf/16d2427b-34cb-4a93-be78-bc6f49a7a1ed


References


Milakis, D., van Arem, B., & Vanwee, B. (2017). Policy and society related implications of automated driving: A review of literature and directions for future re-


References


Schieben, A., Wilbrink, M., Kettrwich, C., Madigan, R., Louw, T., & Merat, N. (2019). Designing the interaction of automated vehicles with other traffic participants:
design considerations based on human needs and expectations. *Cognition, Technology and Work*, 21(1), 69–85. [https://doi.org/10.1007/s10111-018-0521-z](https://doi.org/10.1007/s10111-018-0521-z)


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