

How Passenger Cars Protect their Drivers and Should Cars be Protected from their Drivers: from Airbags to Automated Driving

Tapio Koisaari



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This thesis examined not only the effectiveness of the currently available safety devices for passenger cars (introduced by 2018) but also crashes that cannot be prevented by current safety technology.

The research was carried out as a statistical analysis using Finnish databases as material. The material of the Finnish Crash Data Institute (OTI) was used exclusively as the crash data. In the publications, this crash data was combined with appropriate Finnish databases as needed.

All four publications were quantitative observational studies. The first three studies were retrospective cross-sectional studies regarding passenger car safety technology, but the first one also included a case-control part. The last of these studies was a prospective cohort study, where the follow-up period for those with attention deficit-hyperactivity disorder (ADHD) had been going on for a considerable period of 40 years. The results of the studies were presented as odds ratios (OR) for the case-control and cohort studies, and as the prevalence for the cross-sectional studies.

According to the results, the airbags contributed little to eye injuries (the prevalence of possible eye injuries was fewer than 4 injuries per 10,000 injured), but the non-use of the seat belt increased the odds of both head injuries (OR 2.50, 95% confidence interval [1.59; 3.97]) and death (OR 5.89 [3.33;10.9]).

In addition, the injury (-29% [-27%;-31%]) and fatal (-58% [-45%; -69%]) crash rates were significantly lower for passenger cars having electronic stability control (ESC) than for older, non-ESC cars. If the ESC cars mentioned above are compared to newer cars having almost all available active safety devices, the analysis showed that the incidence of at-fault fatal crashes could be reduced by another 20-27% per kilometre, i.e. down to 0.48-0.53 crashes per billion kilometres when sudden disease attacks and suicides were not taken into account.

Crashes that are most difficult to prevent using current safety technology are suicides, crashes caused by active but erroneous driver control, and crashes occurring in bad weather or road conditions. In addition to the above, shortcomings in usability, consumer resistance, and behavioural adaptation may be risks in the future. However, the results of this dissertation showed that currently, the most significant negative behaviour regarding safety devices was the non-use of safety devices.

Non-medicated ADHD is an example of a single factor leading to highly complex cause-and-effect relationships regarding risk-taking. In the results, ADHD combined not only with increased mortality but also with elevated criminality (OR 24.3 [3.21; 184]) and drunk driving (OR 5.61 [2.30; 13.6]). The purpose of the example was not to stigmatize people with ADHD but to show how a disease with perinatal exposure factors can lead to crashes that are difficult to prevent.

Keywords road crashes, passive safety, active safety, traffic medicine**ISBN (printed)** 978-952-60-8858-7**ISBN (pdf)** 978-952-60-8859-4**ISSN (printed)** 1799-4934**ISSN (pdf)** 1799-4942**Location of publisher** Helsinki**Location of printing** Helsinki **Year** 2019**Pages** 118**urn** <http://urn.fi/URN:ISBN:978-952-60-8859-4>

Tekijä

Tapio Koisaari

Väitöskirjan nimi

Kuinka autot suojaavat kuljettajiaan ja pitäisikö autoja suojata kuljettajiltaan: turvatyynyistä ajamisen automaatioon.

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Työssä tutkittiin markkinoilla olevien (vuoteen 2018 mennessä esiteltyjen) henkilöauton turvalaitteiden tehokkuutta ja toisaalta onnettomuuksia, joita ei pystytä nykyisillä turvalaitteilla estämään. Tutkimus toteutettiin tilastollisena analyysinä, jonka aineistona käytettiin suomalaisia tietokantoja. Onnettomuusaineistona käytettiin Onnettomuustietoinstituutin hallinnoimia tietokantoja, joita yhdistettiin osatutkimuksissa tarpeen mukaan soveltuviin aineistoihin.

Kaikki tutkimukset olivat luonteeltaan havainnoivia ja määrällisiä. Kolme ensimmäistä osatutkimusta oli retrospektiivisiä turvatekniikkaa koskevia poikittaistutkimuksia, mutta ensimmäisessä osatutkimuksessa oli myös tapaus-verrokki-osa. Viimeinen tutkimuksista oli prospektiivinen kohorttitutkimus, jossa aktiivisuuden ja tarkkaavuuden häiriön (ADHD) omaavien seurantajakso oli jatkunut jo 40 vuotta. Tutkimusten tuloksiin on ostosen osalta laskettu oleelliset ristitulosuhteet (odds ratio, OR) ja poikittaistutkimuksissa oleelliset vallitsevuudet.

Tulosten mukaan turvatyyny ei juuri aiheuttaneet silmävammoja (mahdollisten silmävammojen vallitsevuus alle 4 vammaa/10 000 vammautunutta), mutta turvavyön käyttämättömyys nosti sekä päävammojen (OR 2,50, 95 % luottamusväli [1,59; 3,97]) että kuoleman (OR 5,89 [3,33;10,9]) mahdollisuutta merkittävästi.

Lisäksi ajonvakautuksella varustetuille henkilöautoille sattui merkittävästi vähemmän sekä vammautumiseen (-29 % [-27 %; -31 %]) että kuolemaan (-58 % [-45 %; -69%]) johtaneita onnettomuuksia kuin vanhemmille, ilman ajonvakautusta olleille henkilöautoille. Kun edellä mainittua ajonvakautusautoa verrataan uudempaan, miltei kaikilla saatavilla olevilla aktiivisilla turvalaitteilla varustettuun autoon, aiheutettujen kuolemaan johtaneiden onnettomuuksien voidaan arvioida laskevan vielä 20-27 % kilometriä kohden, aina 0,48-0,53 onnettomuutta per miljardi kilometriä asti, kun sairaskohtauksia ja itsemurhia ei huomioida.

Nykyisen turvatekniikan kannalta vaikeimmin estettäviä onnettomuuksia ovat itsemurhat, kuljettajan virheellisen hallintaliikkeen takia ja huonojen sää- tai keliolojen vallitessa sattuneet onnettomuudet. Edellisten lisäksi muun muassa puutteet käytettävyydessä, kuluttajien vastustus ja turvalaitteiden hyödyn ulosmittaaminen saattavat olla riskejä tulevaisuudessa, mutta tämän työn tuloksissa merkittävin kielteinen käyttäytymismalli oli turvalaitteiden käyttämättömyys.

Lääkitsemätön ADHD on esimerkki yhdestä riskitekijästä, johon liittyy erittäin monimutkaisia syy-seuraus-suhteita. Tuloksissa ADHD esiintyi yhdessä kohonneen kuolleisuuden, rikollisuuden (OR 24,3 [3,21; 184]) ja liikennejuopumusriskin (OR 5.61 [2.30; 13.6]) kanssa. Esimerkin tarkoituksena ei ollut leimata ADHD:a sairastavia, vaan osoittaa, miten synnynnäisiä altistustekijöitä omaava sairaus voi johtaa onnettomuuksiin, joita on vaikea estää.

Avainsanat tieliikenneonnettomuudet, passiivinen turvatekniikka, aktiivinen turvatekniikka, liikennelääketiede**ISBN (painettu)** 978-952-60-8858-7**ISBN (pdf)** 978-952-60-8859-4**ISSN (painettu)** 1799-4934**ISSN (pdf)** 1799-4942**Julkaisupaikka** Helsinki**Painopaikka** Helsinki**Vuosi** 2019**Sivumäärä** 118**urn** <http://urn.fi/URN:ISBN:978-952-60-8859-4>

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I want to thank my supervisor, Professor Kari Tammi for his calm and wise support during my work. Of the Aalto University staff, I want to thank also Chief Engineer Panu Sainio, who has made a substantial contribution to education and research in the automotive field in Finland.

Fellow researchers, Anna-Kaisa Haavisto, Juha Holopainen, Timo Kari, Tiina Leivo, Katarina Michelsson, Risto Maksimainen, Jussi Päivänsalo, Kari Rantala, Ahmad Sahraravand, Niina Sihvola, Pekka Sulander, Roni Utriainen, and Tero Vahlberg, provided new thoughts across a wide spectrum and I learned a lot from them. The multidisciplinary nature of the research has been refreshing and delighting.

However, although research requires brainpower, it also takes money. The Henry Fordin säätiö has funded the publications of this thesis and the Summary was written during my study leave, which was supported by the Employment Fund. Consequently, I am very appreciative to my patient funders.

During the long journey to completion, I received support also from many other communities. Foremost, the Finnish Road Accident Investigation Teams have collected a unique database, which has been the cornerstone of my thesis. Furthermore, colleagues at the Finnish Crash Data Institute (OTI) have deepened my understanding of the complexity of risk factors which finally lead to crashes. Lastly, I would like to express my gratitude to Roger Munn for his helpful language revision.

In the end, work is just working. However, in my case, the work in accident investigation has helped me to preserve my values in my personal life: road fatalities remind us that life is short – enjoy it now! That lesson is the same as that which my parents gave to me – besides the many happy childhood memories. Furthermore, I am thankful to my wife, Paula, who has helped me to keep the family first all these years, which is bearing fruit now.

Thank you, Paula, for being the intriguing but safe mystery of my life.

Helsinki, 7 June 2019
Tapio Koisaari

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List of Abbreviations and Symbols

| | |
|-----------|---|
| AD | Automated Driving |
| ADAS | Advanced Driver Assistance System |
| ADHD | Attention Deficit–Hyperactivity Disorder |
| AEB | Autonomous Emergency Braking |
| AIS | Abbreviated Injury Scale |
| A_i | Presence/absence of the ESC for the vehicle i |
| β_0 | Offset coefficient in the Poisson regression model |
| β_1 | Exposure coefficient in the Poisson regression model |
| β_2 | Predictor variable coefficients in the Poisson regression model |
| BAC | Blood Alcohol Content |
| C_i | Poisson random variable with mean $E_i\lambda_i$ |
| CDS | Crashworthiness Data System |
| CI | Confidence Interval |
| CMOS | Complementary Metal–Oxide–Semiconductor |
| CWS | Collision Warning System |
| DC | Direct Current |
| ECU | Electronic Control Unit |
| E_i | Exposure of the vehicle i |
| ESC | Electronic Stability Control |
| FRA | Fatal Road Accident |
| HUEH | Helsinki University Eye Hospital |
| ISA | Intelligent Speed Adaptation |

| | |
|-------------|--|
| λ_i | Crash involvement rates per registration year or per mileage for vehicles |
| GIDAS | German In-Depth Accident Study |
| GPS | Global Positioning System |
| ICD | International Statistical Classification of Diseases and Related Health Problems |
| LCD | Liquid-Crystal Display |
| LKA | Lane Keeping Assistance |
| MLI | Motor Liability Insurance |
| MVC | Multi-Vehicle Crash |
| NASS | National Automotive Sampling System |
| NHTSA | National Highway Traffic Safety Administration |
| OR | Odds Ratio |
| p | p-value |
| PSU | Primary Sampling Unit |
| SAE | Society of Automotive Engineers |
| SVC | Single Vehicle Crash |
| TFT | Thin-Film-Transistor |
| UNECE | United Nations Economic Commission for Europe |
| VIN | Vehicle Identification Number |

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 (e.g. Publication 1, P1)

- 1.** Koisaari, Tapio; Leivo, Tiina; Sahraravand, Ahmad; Haavisto, Anna-Kaisa; Sulander, Pekka; Tervo, Timo. 2017. "Airbag deployment–related eye injuries". Taylor & Francis. *Traffic Injury Prevention*, volume 18, issue 5, pages 439-499. ISSN: 1538-9588. DOI: 10.1080/15389588.2016.1271945.
- 2.** Koisaari, Tapio; Kari, Timo; Vahlberg, Tero; Sihvola, Niina; Tervo, Timo. 2019. "Crash Risk of ESC-Fitted Passenger Cars". Taylor & Francis. *Traffic Injury Prevention*, volume 20, issue 3, pages 325-331. ISSN: 1538-9588. DOI: 10.1080/15389588.2019.1579907
- 3.** Koisaari, Tapio; Utriainen, Roni; Kari, Timo; Tervo, Timo. "The Most Difficult At-Fault Fatal Crashes to Avoid with Current Active Safety Technology". Submitted to the journal *Accident Analysis and Prevention* in the year 2019.
- 4.** Koisaari, Tapio; Michelsson, Katarina; Holopainen, Juha M.; Maksimainen, Risto; Päivänsalo, Jussi; Rantala, Kari; Tervo, Timo. 2015. "Traffic and Criminal Behaviour of Adults with Attention Deficit–Hyperactivity with a Prospective Follow-Up from Birth to the Age of 40 Years". Taylor & Francis. *Traffic Injury Prevention*, volume 16, issue 8, pages 824-830. ISSN: 1538-9588. DOI: 10.1080/15389588.2015.1029068.

Author's Contribution

Publication 1: Airbag deployment–related eye injuries

The author was responsible for preparing the road crash data, statistical analysis and writing the article except for the sections “Helsinki university eye hospital data” and “Traffic-induced eye injuries in the emergency ward”.

The author accessed: (a) the Finnish road accident database, collected all fatal car and van crashes during the years 2009-13, and subjected to analysis those crashes in which at least the driver's front airbag deployed; (b) the accident case files (in paper format). If relevant information was missing from the database the missing values were supplemented with the information from the case files whenever possible.

The author calculated the odds ratios for death and severe head injuries between the belted and unbelted drivers. In addition, the author accessed the case files to investigate whether the eyewear had caused eye injuries during the deployment of the airbag in fatal crashes. Finally, the author calculated the annual airbag-related eye injury incidence.

Timo Tervo and Pekka Sulander designed the original study setup regarding eye injuries. Tiina Leivo, Anna-Kaisa Haavisto and Ahmad Sahraravand analysed and reported the Helsinki university eye hospital data. All reviewed the manuscript.

The author was the corresponding author of the article and coordinated the manuscript creation process.

Publication 2: Crash Risk of ESC-Fitted Passenger Cars

The author was responsible for the study design, data structure selection, analysis method selection, and writing the article.

The author defined the parameters for the ESC (Electronic Stability Control) and non-ESC vehicle groups in the study, selected and identified the car models for each study group and verified their technical feasibility for the study. He also selected the study method.

The author selected the mathematical analysis method for the data and designed an appropriate data model for this method. He also ran the statistical calculations and post-processed the results.

Timo Kari pre-processed the crash and exposure data to the required format. Tero Vahlberg programmed the Poisson regression model and consulted the statistical analysis. Timo Tervo and Niina Sihvola reviewed the study plan and manuscript.

The author was the corresponding author of the article and wrote the article, excluding a few sentences.

Publication 3: The Most Difficult At-Fault Fatal Crashes to Avoid with Current Active Safety Technology.

The author was responsible for the study design, vehicle tests, preparing and analysing the road accident data, and writing the article.

The author accessed the Finnish road accident database, collected all fatal car accidents during the years 2010-17, and subjected to analysis those accidents in which a car of model year 2010-17 had been the primary party of the crash.

The author selected a real world reference for each active safety system and carried out road tests to verify specific operational details of the safety systems. After the road tests, the author completed the analysis of the avoidable fatal crashes.

Roni Utriainen wrote part of the Introduction chapter and reviewed the study plan and manuscript. Timo Kari pre-processed the exposure data to the required format and reviewed the study plan. Timo Tervo reviewed the study plan and manuscript.

The author was the corresponding author of the article and wrote the article besides certain parts of the Introduction chapter.

Publication 4: Traffic and Criminal Behaviour of Adults with Attention Deficit–Hyperactivity with a Prospective Follow-Up from Birth to the Age of 40 Years

The author was responsible for the literature review, statistical analysis of the results, and co-writing the article.

The author revised the gathered study material and calculated odds ratios for the mortality, criminal activity, and traffic violations of the ADHD (Attention deficit–hyperactivity disorder) cohort.

Timo Tervo designed the study and co-authored the manuscript. Katarina Michelsson originally selected the cohorts in the study and diagnosed the patients. She also reviewed the manuscript. Risto Maksimainen, Jussi Päivänsalo and Kari Rantala accessed the police registers and analysed the register data. Juha M. Holopainen reviewed the manuscript.

The author was the corresponding author of the article and wrote the Results chapter and text sections that concerned literature review (most of the Introduction and Discussion chapters).

1. Introduction

Road traffic crashes claim more than 1.2 million lives each year and have a significant impact on health and development (World Health Organization, 2015). They are the leading cause of death among young people aged between 15 and 29 years, and cost governments approximately 3% of gross domestic product (World Health Organization, 2015). In Finland, the unit cost of one road fatality is 2.77 million euros, and one severely injured person 0.79 million (Tervonen, 2017).

Vehicle technology is one safety measure to reduce road traffic losses. There are both active safety measures, which are intended to reduce the number of the crashes (at a given exposure), and passive safety measures, which are intended to reduce the severity of injuries in the event of crashes (Elvik et al., 2009). During the last ten years, the role of active safety has been in the spotlight, as a result of the rapid advances in technology.

The evolution of safety technology is progressing towards full automation of driving. However, human-related risk factors are currently the most common ones, and some of them will be challenging even for the most sophisticated technology in the future, since “we all want money without work, sex without courtship, revenge without court delays” as the general theory of crime states (Gottfredson and Hirschi, 1990).

1.1 Aims and Objectives

This thesis aimed to demonstrate how and how well modern passenger cars protect their drivers, passengers, and, finally, other road users, too. However, the focus was more on at-fault drivers since some of the data was not available for passengers and other road users.

The ultimate goal for the performance of safety technology was measured against the benchmark of Vision Zero but without any restrictions. In other words, cars should eventually be able to avoid crashes with vulnerable road users as well as avoiding suicides. Since the technology review in this thesis was restricted to currently (up to the year 2018) available safety devices (up to SAE level 2 automation), this ultimate goal, at this point, had not been achieved, but, hopefully, it will be in the future.

The starting point for this thesis was to review the impact of frontal restraint systems and especially the effect of the most effective safety device (Elvik et al., 2009), i.e. the seat belt (Publication 1) in the present situation. The next step

was to study the most effective active safety device (Høye, 2011), i.e. electronic stability control (ESC; Publication 2).

Publication 1 aimed to study the effectiveness of seat belt use and airbag deployment protecting against eye and head injuries. In ophthalmology, airbag induced eye injuries have been a topic of an exhaustive and frustrating debate. Understanding the role of seat belt use (and documenting it) was essential in this debate. Publication 2 set out to study the crash count of ESC-fitted passenger cars relative to the true mileage exposure.

The following two publications of this thesis examined the challenges that state of the art safety technology faces currently and will face in the future. The main goal of Publication 3 was to examine those fatal crashes that are hardest to avoid using current active safety devices.

Publication 4 specifically focused on one challenging driver population having a disorder with perinatal exposure factors. This disorder, ADHD, is not particularly common (1-6% of adults suffer ADHD (Wender et al., 2006)), but it leads a person to seek additional stimuli to increase pleasurable experiences in his/her ordinary life – including in road traffic – which can result in negative consequences.

1.2 Scope

First, the thesis concentrated mainly on passenger cars. However, in Publication 1, the study group comprised also vans, and in the study regarding the traffic behaviour of persons with ADHD (Publication 4), all modes of road traffic were considered. Moreover, the motor vehicle type of the counterparts of the crashes was not limited in any Publication. Finally, pedestrians and cyclists were included as counterparts in all Publications except Publication 2.

Both passive and active safety devices were examined. However, post-crash systems such as eCall and fire protection were outside the scope of this thesis. In addition, complex behavioural issues such as driver acceptance and adaptation and many usability issues were not studied, although they all are essential problems in current systems.

The maturity of vehicle technology was limited to currently available devices on the market. Therefore, the thesis does not cover future technologies such as SAE level 3 automation, but only level 2 automation. However, level 3 automation would have been included in Publication 3 if production vehicles had been available in spring 2019.

Secondly, the results primarily cover at-fault crashes. Also, the risk of airbag deployment-related eye injuries and the odds of death for unbelted occupants were reported regardless of crash involvement (Publication 1). Furthermore, in Publication 4, the extent of the study was somewhat broader, and the study deals with persons with ADHD as subjects and object of criminal behaviour.

Reported crashes in the study material included both sudden disease attacks and suicides. Consequently, some of the results regarding fatal crashes were reported with and some without the abovementioned crashes, which are usually omitted from the official road crash statistics. Unfortunately, the injury crash

data did not include the information on the immediate risk factor of the crash and therefore, the (failed) suicides and the injury crashes due to sudden attacks could not be separated from the study material.

Finally, the geographic location throughout the thesis was limited to Finland. In Publication 1, the study material of the airbag deployment-related eye injuries was gathered in an even smaller area, i.e. within the service area of the Helsinki University Eye Hospital, which has a population catchment of 1.5 million people. It should also be noted that besides the influence of the traffic environment, some of the results may not be transferrable to all parts of the world due to the long winter in Finland.

1.3 Literature Review

1.3.1 Vision Zero

During the last few decades, road traffic safety work has evolved from tendencies to influence road users to designing traffic system as a whole. Human errors are acceptable in the system point of view, but they should not lead to fatalities or severe injuries. This holistic road safety strategy is known as Vision Zero (Persson and Uusmann, 1996).

The original version of Vision Zero in the context of road safety explicitly states that the responsibility is shared by the system designers and the road user (Tingvall et al., 2000):

1. The designers of the system are always ultimately responsible for the design, operation, and use of the road transport system and thereby responsible for the level of safety within the entire system.
2. Road users are responsible for following the rules for using the road transport system set by the system designers.
3. If road users fail to obey these rules due to lack of knowledge, acceptance or ability, or if injuries occur, the system designers are required to take necessary steps to prevent people being killed or seriously injured in the future.

The main design factor in Vision Zero is the biomechanical tolerance of the human in the case that a potentially harmful event occurs (Tingvall et al., 2000). Therefore, the main interest is to balance the speed limit according to the worst case scenario. For example, if crashes with pedestrians are possible, the speed limit should be low enough for the pedestrians to survive the crash without severe injuries.

Although the basic concept of Vision Zero is evident, applying it is a more complex task. For instance, there are no simple rules for creating the worst case scenario. Furthermore, as stated earlier, driving speed is one key element, but the road infrastructure and vehicle technology also play important roles.

Several car manufacturers have already expressed their readiness to follow the Vision Zero strategy. For instance, Volvo announced in 2016: “Our vision is that

by 2020 no one should be killed or seriously injured in a new Volvo car” (Shinar, 2017). It was a bold statement because the year 2020 was already close and besides road fatalities, also serious injuries were to be prevented. However, the statement included a significant exclusion; “in a new Volvo”. Therefore, older vehicles and counterparts of the crashes were excluded.

1.3.2 Crash Occurrence

The process, which ultimately leads to a crash, comprises a few fundamental key mechanisms. First, risks accumulate before the actual crash. Secondly, risk accumulation is a time-dependent process. Consequently, some of the underlying risks may have evolved over many years before the crash event. Finally, there is a great variety of different risk factors and each factor has a different bearing on the outcome.

Risk Accumulation

The investigation method of Finnish Road Accident Investigation Teams (Figure 1) describes one model of risk accumulation ultimately producing either a change or a deviation in the normal flow of traffic which, in turn, leads to a crash. Salo et al. (2007) have described the method in detail.

The Finnish investigation method uses the term key event for the incident that occurs immediately before the crash. This event may be, for instance, a car crossing the centreline and moving into the oncoming lane in which there is an oncoming vehicle. In turn, an immediate (or primary) risk factor (such as a steering error) explains the key event, and the background (or secondary) risk factors (e.g., intoxication) explain the immediate risk factor. Besides risk factors related to the crash occurrence, there are injury risk factors which explain the severity of the crash.

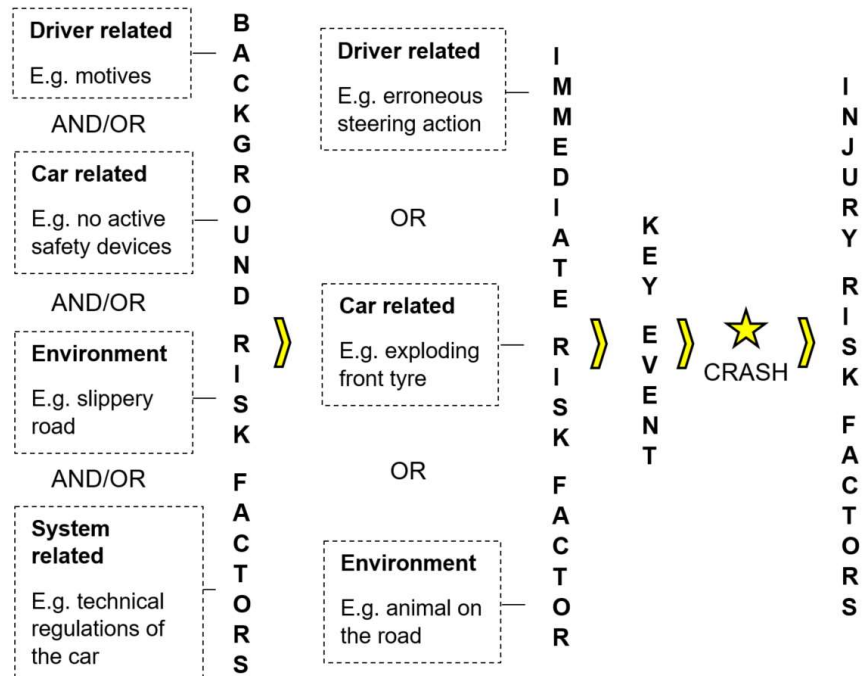


Figure 1. Risk accumulation model as described in the investigation method of Finnish Road Accident Investigation Teams (adapted from Finnish Motor Insurers' Centre (2004))

Timeline of Risk Accumulation

Understanding the timeline of risk accumulation is essential for, among others, developing measures to prevent crashes. Generally, vehicle manoeuvring-related risks are close in time to the crash event, whereas system-level failures such as inadequate legislation have a more long-term impact (Hatakka et al., 2002). The traditional view has been that avoidance action by the driver is the last link in the series of factors preventing the crash. The evolution of active safety technology, however, has changed this.

Before the introduction of active safety devices such as electronic stability control (ESC), it was only the driver who could return the motion of the car to a stable state. Consequently, measures to avoid loss-of-control related driver errors directly on-site were practically non-existent. Instead, more long-sighted preventative measures such as better road maintenance during wintertime were used.

Variety of Risk Factors

The presence of a particular risk factor tempts one to generalize that this factor was the cause of the crash. However, many risk factors act simultaneously. In addition, the variety of risk factors is substantial. Salo et al. (2007) conclude that, for instance background risk factors fall into four typical categories:

1. Road user (factors connected with road user's motives, condition [e.g. alcohol, tiredness, stress, showing off]; vehicle handling [e.g. incorrect methods for handling the vehicle]; controlling the traffic situation [e.g.

- choice of speed, inexperience in controlling a traffic situation]; factors related to the driving task [e.g. haste, nature of driving task, planning the drive, effect of companion on the trip]).
2. Vehicle (factors connected with the driving control of the vehicle [e.g. tyre pressures, loading, wind sensitivity]; observation [e.g. shades, passengers, lights, reflectors]: driver's actions through motivational factors [e.g. capacity of the car and its properties]).
 3. Environment (factors connected with driving control and moving [e.g. potholes, driving ruts and slippery road]; making observations [e.g. poor visibility, darkness, rain]; factors associated with the environment in driver's actions by steering, doing tricks or possibly acting in a way that in turn increases the risk [e.g. poor visual guidance, a deviating bend on an otherwise straight section of the road, a speed limit that is too high for the visibility needed]).
 4. System (risk factors at the system level assessed in an investigation include the following examples and typically have an effect behind the background factors and they are related to the driver, vehicle and environment [e.g. driver training system; the system for monitoring the driver's ability; vehicle technical regulations; regulations concerning vehicle inspection and their implementation; road technical standards and programs; programs related to road maintenance; regulations concerning supervision and punishment; regulations and operating principles applied to public transport; responsibilities of transport carriers; local politics]).

1.3.3 Driver Related Risk Factors

Driver Behaviour

"Human error" is sometimes seen as an umbrella term encompassing all human-related risk factors. However, behavioural science makes a distinction between the concepts of "error" and "violation" (Reason, 1990). The distinction implies that besides just errors, there are other, deeper-rooted human-related risk factors.

Hatakka et al. (2002) have developed a five-tier model of driver behaviour (Figure 2), but several other models exist, too (Fuller, 2005). The hierarchical model starts from an analysis of driver behaviour from the point of view of vehicle control and extends to the effects of society on the driver's lifestyle. An example of the highest levels of the hierarchical model, is the significant reduction in the issuing of driving licenses to youngsters, e.g. in Sweden (Hatakka et al., 2002). This has resulted in fewer young people driving, which, in turn, has decreased the number of crashes.

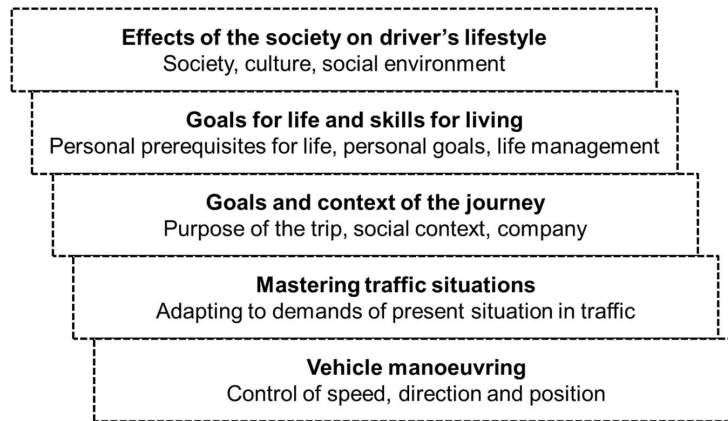


Figure 2. A model of hierarchical levels of driver behaviour (adapted from Hatakka et al. (2002))

Driver-related human risk factors lead ultimately to an error in vehicle manoeuvring (Salo et al., 2007). Human risk factors can be either a part of the cause or the leading cause of the crash. As Hatakka et al. (2002) suggest, the background of a single driver error can be rather complex. Violations tend to be even more complicated.

Reason (1990) divides violations into different categories. The first step is to establish whether there was a prior intention to commit a particular violation (Reason, 1990) and if the violation was deliberate, we need to know whether there was prior intent to cause damage to the system (Reason, 1990). The most common violations are those having some degree of intentionality, but which do not involve the goal of system damage – the extreme end of violations are sabotages (Reason, 1990).

In the context of road traffic, some of the violations are regarded as criminal acts by the law. Studying criminality also gives a slightly different point of view on driver related risk factors. The self-control theory, also called “the general theory of crime” (Gottfredson and Hirschi, 1990), assumes that committing a crime is equally attractive to all; humans are hedonistic and rational. The general factor in this model is self-control – differences in self-control explain variations in criminal behaviour – but this point of view has been challenged and refined (Burt and Simons, 2013; Vaughan et al., 2018).

The importance of self-control was initially emphasized (Gottfredson and Hirschi, 1990) because the theory also emphasized the (usually financial) reward of crime. According to the theory, a person lacking self-control will exhibit six interrelated characteristics: impulsivity, risk-seeking, temper, self-centeredness, preference for physical tasks, and preference for simple tasks.

Burt and Simons (2013) pointed out that seeking the pleasure of crime, i.e. “the thrill”, differs among individuals. In turn, Vaughan et al. (2018) explored the relationship between the general factor (self-control) and its sub-factors. They studied the relevance of cost consideration, i.e., whether individuals were able to predict the consequences of criminal acts, but overall, they investigated the relationship between the general factor and the underlying mechanisms.

State of the Driver

The model of Hatakka et al. (2002) describes the driver activities and motivations well. This model proposes that each driver activity involves a risk since the driver may make an error or commit an intentional violation. However, besides the activities, the state of the driver in itself may be a risk.

Even emotions such as anger or happiness can increase risk for otherwise healthy drivers. The majority of driving behaviour models have focused more on cognitive than on affective aspects (Jeon et al., 2014). Acknowledging the existence of affective mechanisms, however, is as far as the scope of this thesis allows, since elaborating the subject is difficult because research on the influence of emotions on driving behaviour has revealed mixed and partially contradicting results (Steinhauser et al., 2018).

In addition, tiredness is a possible risk factor among healthy people (Kalsi et al., 2018b). The most recent meta-analysis (Moradi et al., 2018) stated that drowsy driving increases the odds of road crashes by 1.29 to 1.34 compared with driving fully alert, but there are difficulties in determining the level of sleep-related road traffic crashes. Also, various illnesses, such as sleep apnea (Tregear et al., 2009) worsen the effect of driver drowsiness.

The issue of driving under the influence of (legal or illegal) drugs concerns both healthy and ill drivers. The use of most illegal drugs harms health, but short-term use of them does not necessarily lead to permanent illness. However, the prolonged use of illegal drugs tends to lead to the development of various kinds of diseases such as mental and behavioural disorders (International Statistical Classification of Diseases and Related Health Problems (ICD)-10: F10-F19) (World Health Organization, 2016). Earlier studies have shown that several risk factors lead to alcohol and other drug problems: genetic, medical and psychological factors are present but also contextual factors such as legislation (Hawkins et al., 1992).

The influence of different drugs on driving has been frequently reported; the longest tradition concerns alcohol. The relative crash risk arising from alcohol intoxication increases nonlinearly – very similar to the first half of the bell curve – as the blood alcohol content (BAC) rises (Blomberg et al., 2009). Alcohol intoxication is also a rather common risk factor in severe crashes; twenty-five percent of all fatally injured drivers in Finland during 2000-16 were drunk drivers (Kalsi et al., 2018a). By contrast, the effect of an illegal drug on driving depends greatly on the drug itself. While cannabis is documented to increase the odds of a fatal crash to 1.31, the corresponding odds of the effect of amphetamines is over four-fold, 5.61 (Elvik, 2013). In addition, in the case of prescribed medication, failing to use it or using it improperly elevates the crash risk.

An illness may have also deteriorated the state of the driver. The illness can be either the primary cause of the crash, such as a sudden heart attack, or a background risk factor like depression. During the years 2009-13, the share of sudden disease attacks varied between 11% and 15% of all fatal motor vehicle accidents in Finland (Tervo et al., 2015). On average, 90% of the attacks were related to cardiovascular diseases (Tervo et al., 2015).

Mental and behavioural disorders are common when illness is a background risk factor. In Finland, this share is roughly 50%, and the main reason are suicides, which account for 8-10% of all fatal motor vehicle crashes (Tervo et al., 2015). Many of the mental disorders have a significantly raised standardized mortality ratio for suicide (Harris and Barraclough, 1997).

1.3.4 Passenger Car Safety Technology

Operational safety is one of the principal design factors in vehicle engineering. Therefore, various safety aspects concern practically all vehicle systems. This chapter gives a short overview of the most common safety features which are designed especially for avoiding road crashes or diminishing their consequences.

Passive Safety

This thesis views the timeline of the operation of the passive safety systems as running from the moment of first contact of the colliding parties until they are stationary. The following elementary information on passive safety was collected from one primary source (Robert Bosch GmbH, 2018). The Automotive Handbook is a reference book by dozens of authors, and the authors represent various companies. The book is widely accepted in education and therefore it was also chosen as the primary source for this general information, although the authors represent mainly the German industry.

The vehicle body has features for both exterior and interior safety. The former concerns vulnerable road users such as pedestrians, cyclists, and motorcycle riders, and the most common exterior safety design features apply to the front of the car. For example, the headlights are not rigid, the windshield wipers are recessed, and the front of the vehicle is as deformable as possible.

The desired qualities for the interior safety are minimizing the forces acting on occupants and providing sufficient survival space. The decisive factors here are the deformation behaviour of the structures in the crumple zone and passenger-cell strength. Besides these, the potential impact areas in the interior have particular importance for those vehicle body areas which are not protected by airbags.

The seat belt remains the primary restraint device in cars, and the secondary restraint system, i.e. airbags, support it. The standard type is a three-point belt with an inertia-reel device. However, an inertial reel alone leads easily to belt slack, and therefore current systems also have either a shoulder belt pre-tensioner or a buckle tightener, or both. Moreover, the seat belt force is limited in order to protect the occupant's torso against bone fractures and internal injuries. The same electronic control unit (ECU) controls both seat belt pre-tensioners and airbags.

The secondary restraint system is a rather typical mechatronic entity which consists of sensors, actuators, and a control system which runs on an ECU. In the early stage of the crash, peripheral acceleration and pressure sensors detect vehicle contact with an obstacle. High-speed pressure sensors are used because they have a performance advantage over acceleration sensors, and, therefore,

they are used to sense side impact. Before deploying the airbags, the ECU also detects the size and sitting position of the front seat occupants by means of in-seat integrated pressure sensing mats (if available).

Meanwhile, the control system tries also to detect the type of impact (head-on, side, offset, pole, etc.) as precisely as possible in order to deploy the correct airbags. Currently, the set-up of airbags in European passenger cars is front and thorax side airbags for both front occupants, side curtain airbags and in some cases a knee airbag for the driver. In addition, airbags such as bag-in-belt systems and external airbags for pedestrian protection are also available for specific car models.

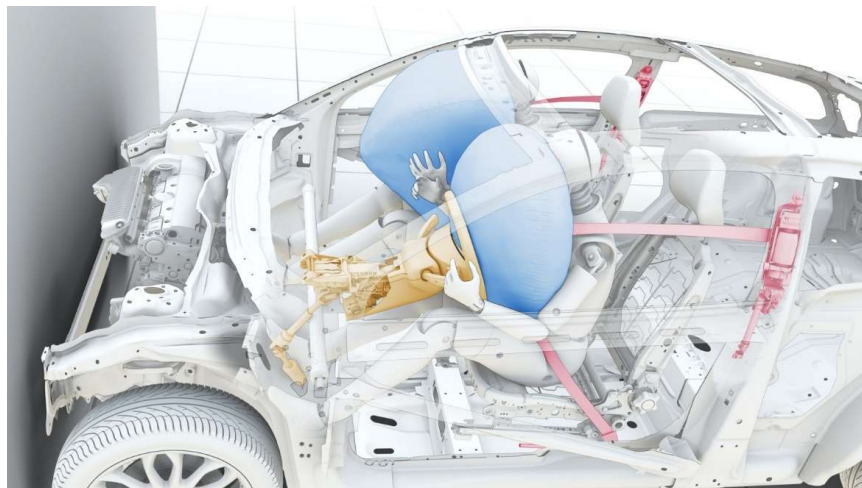


Figure 3. Illustration of the restraint system operation in a frontal crash (Volvo, 2012). Reprinted with permission from Volvocars.

Active Safety

This thesis regarded active safety systems as a combination of traditional active safety devices, such as electronic stability control (ESC) and those driver-assistance systems which were mainly designed to improve safety rather than comfort.

Since there are numerous different active safety devices each of which has various versions and trade names, it was easier to deal with the active safety system as an entity. The abovementioned mechatronic system has an embedded control system and the ECUs of the system are interconnected via different types of databuses. In turn, the sensors and actuators are wired directly to the ECU or they have their own databus communication controller which transmits the sensor signal to the ECU via a databus. The primary source of the following summary was, again, *Automotive Handbook* (2018) unless cited otherwise.

Sensors give information to the active safety device control system about driver action, the internal status of the vehicle and the surrounding environment. The primary function of a sensor is to convert a physical or a chemical quantity into an electrical quantity. Consequently, measuring different physical quantities requires different types of sensors. Table 1 lists some of the sensors used in the active safety system.

Each sensor has its characteristics, which also affect the system level performance. Such features are, e.g., accuracy over the measurement range and the range itself. Besides providing the desired measurement input, the sensors are also exposed to external disturbances, which cause noise in the output signal or block the sensor completely. For this reason, e.g., the field of view in front of the vehicle is detected by a variety of sensors such as radar, lidar, and camera (Figure 4). This concept of sensor redundancy is especially important in highly automated vehicles.

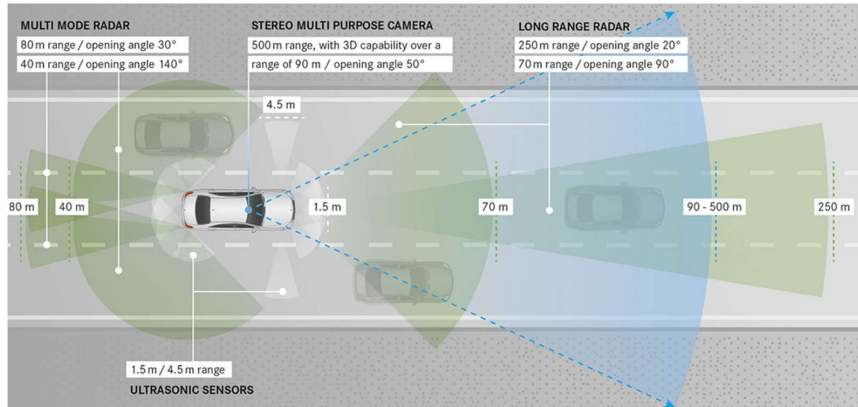


Figure 4. An example of opening angles and ranges of the radars and stereo camera (Daimler AG, 2018a). Reprinted with permission from Daimler AG.

In addition, several sensors are used to do the same task not only for functional reliability but also to provide greater accuracy. Driver-assistance systems use sensor data fusion to increase the field of vision and to improve object recognition. Another advanced method is the indirect measurement of desired variables via model-supported estimation. For instance, ESC controls the vehicle according to, among other parameters, the slip angle of the vehicle, which cannot be measured directly but which can be estimated with the aid of indirect measurements and the single-track vehicle model (Van Zanten et al., 1996).

Table 1. Example of sensors and their function in active safety system (Robert Bosch GmbH, 2018).

| Sensor | Example of type | Example of related function |
|------------------------------|--|------------------------------------|
| Wheel rotation speed | Hall effect | Wheel slip control |
| Vehicle yaw-rate | Micromechanical | Electronic stability control |
| Vehicle lateral acceleration | Micromechanical | Electronic stability control |
| Steering angle | Anisotropic magnetoresistive effect | Driver drowsiness detection |
| Accelerator pedal travel | Potentiometer | Traction control |
| Brake pedal travel (speed) | Potentiometer | Emergency brake-assist |
| Brake pressure | Metal diaphragm | Wheel slip control |
| Close proximity radars | Ultrasonic | Parking aid |
| Short range radar | Microwave (e.g. 24 GHz) | Pedestrian detection |
| Mid and long-range radars | Microwave (e.g. 76...81 GHz band) | Vehicle detection |
| Lidar sensor | Close infrared, multibeam | Autonomous emergency braking |
| Forward-looking camera | Complementary metal-oxide-semiconductor (CMOS) | Lane-keeping support |
| Steering torque sensor | Magnetoresistive | Hands-off steering wheel detection |
| Satellite antenna | Quadrifilar helix | Cruise control route adaptation |

Actuators give the control system the ability to act on the controlled system. During operation, they convert the electrical control signal to either physical or chemical output. If the actuator has a pilot control structure, the control signal operates first, e.g. hydraulic pilot control valve and the final output of the actuator is the movement of a hydraulic cylinder. Table 2 shows some of the actuators used in the active safety system.

In the case of the most advanced passenger cars on the market, the active safety system can operate practically the same controls as the human driver. However, the human driver has still the primary responsibility for driving and the safety system cannot operate the car autonomously. Therefore, some actuators, such as displays, are needed for informing the driver.

Table 2. Example of actuators and their function in active safety system (Robert Bosch GmbH, 2018).

| Actuator | Example of type | Example of related function |
|---------------------------------|--|---------------------------------------|
| Instrument cluster display | Thin-film-transistor (TFT) | 360-degree surrounding view |
| Headlight | Led matrix | Adaptive headlights |
| Loudspeaker | Dynamic diaphragm loudspeaker | Blind spot detection alarm |
| Steering servomotor | Brushless Direct current (DC)-motor | Active lane-keeping assist |
| Steering wheel vibrator | DC-motor with an unbalanced shaft | Lane departure warning |
| Throttle valve servomotor | Brushless DC-motor | Adaptive cruise control |
| Brake pressure-control valve | Pilot-controlled solenoid valve | Anti-lock braking |
| Brake pressure modulator | DC-motor driven self-priming pump | Electronic Stability Control |
| Gear change motor | Brushless DC-motor | Automated parking |
| Electromechanical parking brake | DC-motor operated transmission | Parking the vehicle at emergency stop |
| Head up display | Liquid-crystal display (LCD) with backlighting | Collision warning |

The control system interprets the incoming information from the sensors and controls the system via actuators according to the chosen control strategy. The “controllers” themselves are software which runs on the processors of ECUs.

The traditional way to classify controllers are the concepts of closed-loop and open-loop control. The function of closed-loop control is to place and maintain a particular physical parameter at a specified value, at the so-called set-value. In closed-loop control, the controlled variable, such as driving speed, is continuously measured, whereas, in open-loop control, this feedback is omitted. If the closed-loop controller detects deviation between the set-value and the measurement, it will try to correct the difference by adjusting the system via actuators. By contrast, since the open-loop controller does not have the feedback, it cannot detect such a deviation.

However, performing complicated tasks such as partial driving automation requires more from the control system than elementary open and closed-loop controllers. Instead of speaking of separate sensors, we speak of a sensor layer which produces the information for sensor-data fusion. Data fusion creates a model of the surrounding environment. The next step for the control system is to understand the traffic situation at hand and anticipate how it might develop.

Machine vision is one of the key technologies behind the recent progress in active safety. Its primary function is to detect and classify dynamic objects in a static background. In sensor fusion, the object class helps the control system to

predict the nature of the object's future movement. This together with long-range radars creates synergy effects.

When the control system has completed the situation analysis, it has two options: either act directly via actuators or inform the driver via the human-machine interface. In either case, the driver-override function is always available in current systems. In other words, the human driver always has the final call. Besides the driver override, the human driver can also disable certain parts of the active safety system.

Active safety functions are the result of the rather complicated control system. Currently, the most advanced passenger cars, up to the level 2 of driving automation (SAE, 2016), can perform limited manoeuvres such as remote-controlled parking via a smartphone or drive themselves short distances under driver supervision under certain conditions (e.g., traffic-jam assist). Here the "driving" means controlling the driving speed in respect of other vehicles and lateral control of the vehicle position in respect of the driving lane. In the case of an emergency, the vehicle can perform an autonomous braking manoeuvre but not yet yield to an obstacle – the single exception is the Lexus LS (Lexus, 2019).

The range of driver assistance functions is vast. To date, the most effective active safety device is ESC, which helps the driver to maintain control of the car (Høye, 2011). Besides aid for vehicle handling, there are several collision warning systems from blind spot detection to head-on collision warning on highways. Also, the active safety system supports the driver before emerging situations; adaptive headlights try to maximize the illuminated area during night-time, and even night vision systems are available.

In addition to the driver support, the active safety system also monitors the state of the driver. These functions are somewhat limited, but further steps in driving automation will increase driver monitoring. At present, driver drowsiness and hands-on steering wheel detection are the most common examples. In the latter case, if the safety system incorporates an emergency stop, the system will eventually stop the vehicle if the driver does not react to the hands on the steering wheel alarm.

Future developments will bring a range of new active safety features. One group are the vehicle-to-X communication-related functions. To date, external communication has been scarcely exploited in active safety. One of the few examples is the function which adjusts the vehicle speed according to the road environment when the adaptive cruise control is activated. In this case, the global positioning system (GPS) signal is used for vehicle positioning by means of a digital map, and in the case of a sharp turn, for instance, the set speed of the cruise control is lowered ahead of that turn enabling a smooth and safe negotiation of the turn.

Integrated Safety

Classification of safety devices into active and passive systems is the traditional way to address vehicle safety. However, vehicle systems are interconnected via the databus network and they exchange information. The integrated safety con-

cept operates by adapting protective measures beforehand based on the predicted crash scenario when the crash is unavoidable (Robert Bosch GmbH, 2018).

Present examples of integrated safety functions are e.g., the electrically operated seat belt pre-tensioner and the active side bolster of the seat which pushes the occupant towards the centre of the vehicle when a side impact is unavoidable (Daimler AG, 2018b). In the latter example, the pyrotechnic actuator is activated exclusively based on radar sensors, which is exceptional. Further development of automated driving will increase the number of integrated safety functions (Robert Bosch GmbH, 2018).

1.4 Research Gap

1.4.1 Road-Crash Data

Although road-crashes cause substantial loss of human life, global road-crash databases are limited to rather general information such as aggregated data (Luoma and Sivak, 2007). Some of the national road-crash databases offer more detailed data on each accident, vehicle, and persons involved. However, these databases, such as the National Automotive Sampling System (NASS, United States) and German In-Depth Accident Study (GIDAS) database, are usually only samples (Otte et al., 2003; Zhang and Chen, 2013). The main drawback of samples is representativeness: a sample that is representative of one specific question is most likely not representative for a different question (Ramsey and Hewitt, 2005).

Besides the problems of representativeness, many road safety studies fail to determine the risk, i.e. crashes per exposure. Overall, true exposure is usually determined in studies of small samples or cohorts. For instance, naturalistic driving data provides excellent information on driving-related risk factors and corresponding risks (Dingus et al., 2016). However, this kind of study setup provides limited information on rare events such as fatal crashes.

In some studies, indirect methods such as induced or quasi-induced exposure are used. According to the theory, the quasi-induced exposure method has two underlying assumptions: (1) there is an at-fault and a not-at-fault driver in two-vehicle crashes; and (2) not-at-fault drivers in two-vehicle crashes are randomly selected (Jiang et al., 2014). However, a meta-analysis of the studies exploiting quasi-induced exposure revealed that a majority of the research failed to follow a systematic procedure, and the methodological quality was somewhat compromised (Jiang et al., 2014).

All things considered, comprehensive road safety studies which determine the crash risk, are rare. The underlying root cause is either the lack of data or the quality of it, and these weaknesses are hard to compensate for using other means.

1.4.2 Vehicle Safety

Many of the previous studies about safety systems have concentrated on the safety potential of these systems. In other words, how many crashes or which percentage of the crashes would have been avoided if these systems had been installed in all vehicles. However, it should be noted that passenger car safety has been evolving over a long time, and the number of severe crashes has been diminishing concomitantly, too – towards the final goal, Vision Zero.

On the other hand, even Vision Zero leaves room for interpretation regarding which crashes, injuries, or fatalities should be prevented. The bottom line is: which crashes count? Here, a grey area arises the first part of which comprises disease attacks and suicides, which are usually not included in the official statistics (UNECE, 2010). These crashes are omitted from the official statistics, but are they outside the scope of Vision Zero, as well? Another part of the grey area comprises those crashes in which the road user has taken a substantial amount of risk. To which extent should “the system” tolerate speeding, intoxication or distraction?

Current research has not focused on those severe crashes which remain despite the introduction of the most advanced safety devices. Studies also tend to focus on those crashes which are avoidable by applying traditional road safety measures. Driver illnesses and mental problems are still seen more as a problem of the road user than a system issue.

1.5 Scientific Contribution

1.5.1 Airbag Deployment-Related Eye Injuries (P1)

The most recent review article on eye injuries related to occupant restraint systems (Almahmoud and Barss, 2014) stated that more research on this subject was required. It concluded that although the relationship between airbag deployment and eye injury has frequently been reported, the true incidence of such injuries remains unknown.

The problem in previous studies has generally been either the size of the data set or its quality. Case studies and small sample size studies lack statistical power, and broader studies tend to lack information related to the accident. However, Publication 1 (2017) combined three extensive data sources to determine the true incidence of airbag deployment-related eye injuries. Thus, this study answered the unsolved question regarding airbag-associated eye injuries.

Besides the eye injuries, Publication 1 examined the effect of seat belt use on head injuries and death in fatal crashes where the airbag deployed. These results support previous research.

1.5.2 Crash Risk of ESC-Fitted Passenger Cars (P2)

According to the latest meta-analysis, which summarized the previous research on ESC effectiveness, the stability control reduced the percentage of all crashes involving loss of control by about 40%; all fatal crashes were reduced by about

40%, but less severe crashes remained unchanged when all types of crashes were considered together (Høye, 2011).

Most of the previous studies used only samples and could not directly control the effect of exposure. Consequently, they used indirect methods such as induced or quasi-induced exposure or they did not take into account the effect of exposure at all. Only a few studies (Aga and Okada, 2003; Bahouth, 2005; Farmer, 2006) reported crash rates which were proportioned to vehicle population.

Publication 2 reported mileage-based crash rates with real-life crash data on ESC-fitted cars, and these type of results have not been previously published. The study material was also exceptionally extensive.

1.5.3 The Most Difficult At-Fault Fatal Crashes to Avoid (P3)

Many of the previous studies about active safety systems (Fildes et al., 2015; Høye, 2011; Sternlund et al., 2016) have concentrated on the safety potential of these systems. In other words, how many crashes or what percentage of the crashes would have been avoided if these systems had been installed in all vehicles.

Publication 3 examined which current fatal at-fault crashes would still occur despite the most advanced active safety devices on the market up to SAE level 2 automation (SAE, 2016), and how frequent these crashes would be. There was no previous equivalent to the study setup, and therefore, the results were unique.

The analysis method in the study did not account for issues such as system usability or driver acceptance. Therefore, the results should be regarded as something that was technically achievable when a human driver was aided by the state of the art active safety devices. The observed incidence of the hardest fatal at-fault crashes to avoid also serves a useful reference for AD development.

1.5.4 Traffic Behaviour of Adults with ADHD (P4)

Attention deficit–hyperactivity disorder (ADHD) is characterized by inattention, impulsivity, and hyperactivity. The clinical diagnosis is based on the symptom list defined in the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association and Association, 1994). The long-term consequences of ADHD include criminality, traffic accidents, police citations, substance abuse, and risk-taking behaviour (Barkley and Cox, 2007; Cherkasova et al., 2013; Ramos Olazagasti et al., 2013; Reimer et al., 2010).

The ADHD cohort in Publication 4 was diagnosed in childhood and followed until the age of 40; therefore, the results provide information on the long-term effects of ADHD. Due to the nature of the gathered material at 40 years, the results provided a good overview of criminality and traffic behaviour with regards to ADHD.

Although results similar to those in Publication 4 have been reported in previous studies (Dalsgaard et al., 2015; Kooij et al., 2010), the long timespan of this prospective cohort study was unique.

2. Material and Methods

2.1 Airbag Deployment–Related Eye Injuries (P1)

Publication 1 was partly a retrospective case-control study and partly a retrospective cross-sectional study. The case-control method was used to study the effect of seat belt use on head injuries when the front airbag of the driver deployed. In turn, the cross-sectional study concerned the incidence of airbag-induced eye injuries in passenger car crashes.

The case-control part of the publication was based on the investigated road accidents in Finland during 2009-12. In Finland, the law requires all fatal road accidents (FRAs) to be studied in depth on the spot by multidisciplinary (police, road and vehicle engineers, physicians, and behavioural scientists) road accident investigation teams.

Fatal car and van crashes in which at least the driver's front airbag deployed (n = 409) were subjected to analysis. In these cases, the driver was belted in 272 crashes and not belted in 126 crashes, and information for seat belt use was unavailable for 11 drivers.

The numbers of killed and injured drivers were calculated, and differences in rates were statistically analysed using Fisher's exact test and calculating the odds ratios (ORs).

All new eye injury patients (n = 1,151) at the emergency ward of the Helsinki University Eye Hospital (HUEH) were analysed case-by-case during one year, from May 1, 2011 to April 30, 2012. The HUEH is a tertiary and secondary care eye hospital in Finland and the population catchment is 1.5 million people.

The epidemiological and clinical data were analysed, and all injuries found to be related to passenger car crashes were included in the analysis. Data concerning seat belt use and airbag deployment were collected via telephone interviews. The incidence of passenger car related annual eye injury incidence was then calculated.

2.2 Crash Risk of ESC-Fitted Passenger Cars (P2)

Publication 2 was a retrospective cross-sectional study. The goal was to compare the crash rate of ESC-fitted passenger cars to the crash rate of non-ESC cars. The crash rate was expressed in respect of both registration years and true exposure in mileage.

Cars were divided strictly into two groups: in the first group, all cars of a particular model and model year had been fitted with ESC as standard, and in the second group ESC had not been fitted as standard. If ESC was available as an optional extra for a specific model in a particular year, these cars were excluded from the study.

The study period was 2009-13 and information on the fatal crashes of the study and control group was retrieved from the same FRA database of investigated road accidents in Finland as in Publication 1.

In addition, information on injury crashes was also gathered. The Finnish Motor Insurers' Centre collects data for a database (the MLI database) of all crashes indemnified from the motor liability insurance scheme. Since only the injury-related at-fault crashes are always compensated from the motor liability insurance, we included only these crashes in our study.

The Finnish Vehicular and Driver Data Register was accessed to obtain the mileage information and the registration count for the study and control group. Besides the registration period of each vehicle, this register also records the mileage during the yearly roadworthiness inspection.

According to the Finnish Vehicular and Driver Data Register, the study population of passenger cars fitted with ESC consisted of 725 528 vehicles (average population between 2009 and 2013) and correspondingly, the population of the non-ESC cars was 1 167 990 vehicles. The study populations of non-ESC and ESC cars covered 75% of all registered passenger cars under 19 years old in Finland.

Poisson regression was used to model crash involvement rate ratios both per registration year and per mileage for vehicles fitted with ESC and without the system, controlling the age and gender of the vehicle owner and vehicle mass. The age of the vehicle owner and vehicle mass were categorical con-founding factors.

Separate Poisson regression models were constructed for two degrees of crash severity (injury, MLI database and fatal, FRA database) and for four crash types. The four crash types were: 1) all crashes, 2) multi-vehicle crashes (MVCs), 3) single vehicle crashes (SVCs), and 4) run-off-road crashes separately. A logarithmic link function was used in the Poisson regression models.

In models that examined the difference between vehicles with ESC and without the system, C_i represents the number of crash involvements, E_i represents exposure (registration years or mileage) and A_i represents the presence or absence of ESC for the vehicle i . Assuming C_i is a Poisson random variable with a mean of $E_i\lambda_i$, the statistical models were specified as $\log \lambda_i = \beta_0 + \beta_1(a_i) + \beta_2(\text{co-variates})$. In these models, $\exp(\beta_1)$ represented the rate ratio comparing crash involvement rates per registration year or mileage for vehicles with ESC and without the system.

2.3 The Most Difficult At-Fault Fatal Crashes to Avoid (P3)

Publication 3 was a retrospective cross-sectional study of fatal at-fault crashes that were caused by drivers whose passenger car was of model year 2010-17. The

aim of the study was to identify those crashes which would be the most difficult to avoid using current active safety technology (up to SAE automation level 2) and how frequent these crashes would be.

The study period was 2010-17 and information on the fatal crashes was, again, retrieved from the FRA database of investigated road accidents in Finland as in Publication 1 and 2. Cars in the study group were the primary party in 113 investigated fatal accidents during the years 2010-17. Because the focus was on fatal crashes, altogether 22 sudden illness attacks (driver died because of the attack) were excluded and four other accidents in which the occupant survived the crash.

To calculate the crash incidence for the most difficult at-fault fatal crashes to avoid, the Finnish Vehicular and Driver Data Register was accessed as in Publication 2 to obtain the mileage information and the registration count. The passenger cars (registered 2010-17) in the study group comprised 3,772,864 registration years during the study period, i.e. 2010-17. During the same period, these vehicles travelled 75.9 billion kilometres.

In the study, a real world reference was used for each active safety system and one car brand served as an example. Having a real world equivalent for each system helped to determine its effectiveness in crashes since detailed information on the system operation was available. In addition, the operation of each system could be tested on the road. Table 3 presents the full list of the safety systems included in the analysis.

Table 3. Active safety devices and related systems included in the analysis (Daimler AG, 2018b). The numbers in brackets [] express the exact version of the safety system according to the Mercedes-Benz equipment indexing.

| Market name | Description |
|---|--|
| Attention assist [E-class standard] | Surveils and warns about driver drowsiness. Active within the range 60 - 200 km/h. |
| Active blind spot assist [23P] | Detects vehicles in the blind spots and informs driver; ultimately performs evasive steering. Active within the range 12 - 200 km/h. |
| Active brake assist with cross-traffic function [23P] | Autonomous emergency braking up to 200 km/h (stationary vehicles and pedestrians 60 km/h) with cross-traffic detection and collision warning |
| Active distance assist [233] | Adaptive cruise control, set-speed from 20 to 200 km/h; keeps distance to leading vehicle time wise constant. Braking up to 50% of maximum. |
| Active emergency stop assist [266] | Stops vehicle if driver does not steer vehicle while steering assist is on. The system activates hazard lights at 60 km/h. |
| Active lane change assist [K32] | Supports the driver to perform a lane change when the cruise control is active. Active in the range of 80 and 180 km/h. |
| Active lane keeping assist [23P] | Keeps vehicle in lane by a steering or braking act, depending on the situation. Braking function is active in the range of 60 and 200 km/h. |
| Active parking assist [235, 501] | 360-degree camera, 360-degree radar surveillance and assisted parking with automated steering. |
| Active speed limit assist [546] | Changes the cruise control set speed automatically according to the speed limit. |
| Active steering assist [23P] | Steers the vehicle according to lane markings or leading vehicle when the cruise control is active. Active up to 210 km/h. |
| Adaptive high beam assist plus [P35, 628, 642] | Maximizes the high beam light pattern using active beam control but avoids blinding the other road users. |
| Drive away assist [235] | Limits the vehicle speed to 2 km/h for a short period if radars detect an obstacle within 1 metre |
| Evasive steering assist [23P] | Supports the driver in evasive steering when a crash with a pedestrian is imminent. Active in the range of 20 and 70 km/h. |
| Electronic stability control [E-class standard] | Supports the driver in maintaining the desired vehicle path and stable vehicle motion. |
| Route-based speed adjustment [K34] | Adjusts the set speed of the cruise control according to the road ahead; recognizes route events, e.g. T-junctions and roundabouts. |
| Traffic sign assist [513] | Recognizes traffic signs and displays them on the display; supports the active speed limit assist |

Before the actual analysis of the crashes, some real world tests were carried out using vehicles having similar technology as was used as a reference in the analysis. The field tests concentrated on gathering information on specific operational details of the active safety systems which could not be found in the system specifications or other references.

The tests were recorded with a dual camera set-up. One camera recorded the driver view plus GPS data and the other the cockpit. The latter camera recorded the driver operation but also all warning signals and other feedback from the vehicle safety systems. The test cars were a Mercedes-Benz E 220d 4Matic sedan (VIN: WDD2130051A560552) and a Mercedes-Benz E 400d 4Matic station wagon (WDD2132231A554359).

Finally, each at-fault fatal crash was analysed case-by-case. In this assessment, it was assumed that instead of the actual at-fault passenger car being involved in the crash, there was a notional car having the same passive safety features but, in addition, all the active safety features described in Table 3. Another assumption was that the driver would have used (activated) each safety system as designed unless he/she showed behaviour towards disabling safety systems.

The analysis was performed using a hierarchical four level method in which the level 1 cause for preventing the active safety system operation was the least speculative:

- Level 1: The driver caused the crash on purpose (suicide or homicide)
- Level 2: Active driver input would have prevented operation of the safety system
 - a) Active driver control and erroneous control act (steering error, foot on accelerator instead of brake, etc.)
 - b) Active driver control and judgement error (turning, overtaking, etc.)
- Level 3: The crash circumstances were beyond the safety system performance
 - a) Extreme weather and/or road conditions
 - b) Challenging crash kinematics (direction of crash, relative speed difference, short time to react, etc.) for both human driver and safety system
 - c) Crash site or circumstances were otherwise outside the operational design domain of the relevant system (outside the operational speed range, no lane markings, etc.)
- Level 4: The probability for relevant system activation was low
 - a) Driver showed behaviour or possessed a driving history of high risk taking or disabling safety systems

The outcome of the analysis labelled the crash as being avoidable, unavoidable, or unsolved. The crash was regarded as unavoidable if it fulfilled any of the abovementioned conditions.

2.4 Traffic Behaviour of Adults with ADHD (P4)

Publication 4 was a prospective cohort study. The study looked at whether individuals diagnosed as having ADHD and who were followed to age 40 had a higher mortality, more involvement in criminal behaviour, an increased number of road crashes, and greater frequency of registered violations against traffic rules or whether they had been more frequently victims of crimes.

The ADHD cohort (N = 122) was born between 1971 and 1974 was isolated at the age of 9 years from the base cohort of 865 children who had known risk factors at birth and were still alive at the age of 5 years. Ninety-four healthy individuals born during the same years served as control subjects. None of the individuals with ADHD had used psychostimulants before their adolescence.

The follow-up data were available from the neonatal period until the ages of 5 and 9 years. At the ages of 16 and 30, the data were collected via a questionnaire. For subjects who had reached the age of 40 years, this study looked at the national police registers (last 5 years) for traffic violations and for crimes, and also whether the subjects had been an object of a criminal act.

The number of offences in police registers was calculated. Differences in the rates were statistically analysed using Fisher's exact test to calculate the odds ratios.

3. Results

3.1 Airbag Deployment–Related Eye Injuries (P1)

During the eye injury study period, i.e. from May 1, 2011, to April 30, 2012, a total of 31,326 crashes took place in the HUEH area (with a population catchment of 1.5 million people). Correspondingly, in 27,311 crashes a passenger car was involved. In these crashes, a total of 2006 drivers and 748 passengers were injured (a total of 2,754 occupants).

During the study period, only one of the crashes (case 4, Table 4) showed eye injuries which could be regarded as airbag deployment-related. In three other crashes (cases 1-3, Table 4), a car occupant also sustained eye injuries, but in these crashes either the airbag did not deploy or the occupant was not wearing a seat belt, or the injury was not caused by the airbag.

Thus, airbag-related eye injuries occurred very rarely in car accidents in cases where the occupant survived, and the restraint system was appropriately used. The calculated incidence of annual airbag-related eye injuries was less than 1/1,000,000 people, 4/100,000 crashes, and 4/10,000 injured occupants. No permanent eye injuries were recorded during the follow-up.

Table 4. Eye injuries in passenger car or van crashes, Helsinki University Eye Hospital data.

| Case | Vehicle | Gender | Age | Primary ocular or periocular diagnosis | Secondary ocular or periocular diagnosis | Permanent functional impairment |
|----------------|---------|--------|-----|--|--|---|
| 1 ^a | Car | Female | 16 | Facial and lid wounds, facial nerve injury | Orbital fracture | Nervus facialis dysfunction |
| 2 ^b | Car | Female | 17 | Contusion | Optic nerve injury, macular bleeding | Visual acuity 0.1, afferent pupil defect, vision field defect |
| 3 ^c | Car | Male | 20 | Contusion | ^d | No |
| 4 ^e | Car | Female | 61 | Contusion | No | No |

^a Belted co-driver, airbag did not deploy; not within the scope of the study.

^b Non-belted co-driver, no airbag, ejected from the vehicle; not within the scope of the study.

^c Belted driver hit a lamppost, car rolled over multiple times, head hit against car body structures, airbag deployed; not within the scope of the study.

^d Second eye retinal tear.

^e Belted driver involved in a head-on collision, airbag deployed.

The other part of study, the analysis of the FRA data (Table 5) showed that unbelted drivers had a significantly higher risk of death (odds ratio [OR] = 5.89,

95% confidence interval [CI], 3.33–10.9, $P = 2.6E-12$) or of sustaining head injuries (OR = 2.50, 95% CI, 1.59–3.97, $P = 3.8E-5$). Use of eyeglasses did not appear to increase the risk of eye injury in restrained occupants.

Table 5. Severity of the injuries in fatal road crashes (FRA database) in Finland during 2009–12 according to the abbreviated injury scale (AIS): AIS 6 = fatal injuries, AIS 3–5 = severe injuries, AIS 1–2 = mild injuries and AIS 0 = no injuries.

| Severity of the injuries | AIS 6 | AIS 3-5 | AIS 1-2 | AIS 0 | N/A | Total |
|-------------------------------------|-------|---------|---------|-------|-----|-------|
| All drivers (whose airbag deployed) | 253 | 39 | 76 | 41 | - | 409 |
| Unbelted drivers ^a | 108 | 5 | 12 | 1 | - | 126 |
| Belted drivers | 137 | 34 | 63 | 38 | - | 272 |
| Head injuries, unbelted drivers | 32 | 25 | 11 | 57 | 1 | 126 |
| Head injuries, belted drivers | 28 | 49 | 9 | 181 | 5 | 272 |

^a In 11 cases information on seat belt use was unavailable

3.2 Crash Risk of ESC-Fitted Passenger Cars (P2)

Based on the MLI database, between 2009 and 2013, ESC-fitted cars caused 8,827 crashes that led to injuries. During the same period, the cars in the non-ESC population caused 21,437 injury crashes. The majority of the injuries were minor. Correspondingly, in 474 fatal crashes occurring during the study period, a vehicle in our study population was the primary party. Of the 474 vehicles in the FRA database, 97 were fitted with ESC and 377 were not. The total corrected (missing values were replaced with annual means) mileage sum for the 5-year period was 72.419 billion kilometres for ESC-equipped cars and 89.349 billion kilometres for non-ESC-equipped vehicles.

Table 6. Crash counts and crash rates in relation to exposure during the study period 2009–2013.

| Crash type | Injury | | Fatal | |
|---|-----------|-----------|-----------|-----------|
| | Non-ESC | ESC | Non-ESC | ESC |
| Car population ^a | 5,839,946 | 3,352,813 | 5,839,946 | 3,352,813 |
| Exposure [registration years] | 72.419 | 89.349 | 72.419 | 89.349 |
| Exposure [billion km] | 72.419 | 89.349 | 72.419 | 89.349 |
| All crashes ^b | 21,437 | 8,827 | 377 | 97 |
| Crash rate/1000 registration years | 3.67 | 2.63 | 0.0646 | 0.0289 |
| Crash rate/billion km | 296 | 99 | 5.21 | 1.09 |
| Multi-vehicle crashes ^c | 13,689 | 6,432 | 213 | 57 |
| Crash rate/1000 registration years | 2.34 | 1.92 | 0.0365 | 0.0170 |
| Crash rate/billion km | 189 | 72 | 2.94 | 0.64 |
| Single vehicle crashes | 7,708 | 2,377 | 163 | 40 |
| Crash rate/1000 registration years | 1.32 | 0.71 | 0.0279 | 0.0119 |
| Crash rate/billion km | 106 | 27 | 2.25 | 0.45 |
| Run-off-road crashes | 5,079 | 961 | 151 | 33 |
| Crash rate/1000 registration years | 0.87 | 0.29 | 0.0259 | 0.0098 |
| Crash rate/billion km | 70 | 11 | 2.09 | 0.37 |
| All crashes w/o disease attacks and suicides | N/A | N/A | 271 | 59 |
| Crash rate/1000 registration years | - | - | 0.0464 | 0.0176 |
| Crash rate/billion km | - | - | 3.74 | 0.66 |
| Multi-vehicle crashes w/o disease attacks and suicides | N/A | N/A | 153 | 42 |
| Crash rate/1000 registration years | - | - | 0.0262 | 0.0125 |
| Crash rate/billion km | - | - | 2.11 | 0.47 |
| Single vehicle crashes w/o disease attacks and suicides | N/A | N/A | 117 | 17 |
| Crash rate/1000 registration years | - | - | 0.0200 | 0.0051 |
| Crash rate/billion km | - | - | 1.62 | 0.19 |
| Run-off-road crashes w/o disease attacks and suicides | N/A | N/A | 112 | 15 |
| Crash rate/1000 registration years | - | - | 0.0192 | 0.0045 |
| Crash rate/billion km | - | - | 1.55 | 0.17 |

^a The upper limit of the vehicle age was set at 18 years (which was the average scrappage age of the cars in Finland)

^b Passenger cars not in the study groups caused 15,817 injury crashes and 174 fatal crashes during 2009–13 in Finland

^c Does not include crashes with bicycles or pedestrians

The observed crash rate of ESC fitted passenger cars was 2.6 crashes per thousand registration years and 99 crashes per billion kilometres for injury crashes. The incidence of fatal crashes was roughly one percent of the injury crashes. If disease attacks and suicides were excluded, the crash rate of at-fault fatal crashes was 17.6 crashes per million registration years and 0.66 crashes per billion kilometres (Table 6).

Passenger cars fitted with ESC showed lower crash rates than non-ESC cars in all crash types studied (Table 6). In general, the difference in crash rates between ESC and non-ESC vehicles was greater when the crashes were compared to the mileage rather than registration years.

Table 7. Crash rate ratios of the ESC and Non-ESC cars in different crash types (every result had $p < 0.001$)

| Crashes [per exposure] | Crash rate ratio ^a (ESC/non-ESC) | 95% Confidence Interval | |
|--|--|-------------------------|------|
| All fatal crashes [per registration years] | 0.47 | 0.36 | 0.62 |
| All fatal crashes [per mileage] | 0.42 | 0.31 | 0.55 |
| All injury crashes [per registration years] | 0.80 | 0.78 | 0.83 |
| All injury crashes [per mileage] | 0.71 | 0.69 | 0.73 |
| Fatal MVCs [per registration years] | 0.49 | 0.34 | 0.70 |
| Fatal MVCs [per mileage] | 0.44 | 0.30 | 0.63 |
| Injury MVCs [per registration years] | 0.91 | 0.88 | 0.95 |
| Injury MVCs [per mileage] | 0.81 | 0.78 | 0.84 |
| Fatal SVCs [per registration years] | 0.45 | 0.29 | 0.68 |
| Fatal SVCs [per mileage] | 0.39 | 0.26 | 0.60 |
| Injury SVCs [per registration years] | 0.60 | 0.57 | 0.63 |
| Injury SVCs [per mileage] | 0.53 | 0.50 | 0.56 |
| Fatal run-off-road crashes [per registration years] | 0.40 | 0.26 | 0.63 |
| Fatal run-off-road crashes [per mileage] | 0.35 | 0.22 | 0.55 |
| Injury run-off-road crashes [per registration years] | 0.41 | 0.38 | 0.44 |
| Injury run-off-road crashes [per mileage] | 0.36 | 0.33 | 0.39 |
| Below excluding disease attacks and suicides: | | | |
| All fatal crashes [per registration years] | 0.38 | 0.27 | 0.54 |
| All fatal crashes [per mileage] | 0.33 | 0.23 | 0.47 |
| Fatal MVCs [per registration years] | 0.50 | 0.32 | 0.76 |
| Fatal MVCs [per mileage] | 0.45 | 0.29 | 0.69 |
| Fatal SVCs [per registration years] | 0.23 | 0.13 | 0.44 |
| Fatal SVCs [per mileage] | 0.20 | 0.10 | 0.37 |
| Fatal run-off-road crashes [per registration years] | 0.21 | 0.11 | 0.41 |
| Fatal run-off-road crashes [per mileage] | 0.18 | 0.09 | 0.35 |

^a Controlled for the driver age, driver gender and vehicle mass

ESC-fitted cars experienced 58% fewer fatal and 29% fewer injury crashes when the exposure was measured in kilometres. The results were controlled for the age and gender of the car owner and the vehicle mass. The mileage proportional crash rate of ESC cars was 64% [61%;67%] lower in run-off-road crashes resulting in injury, and as much as 82% [65%;91%] lower in fatal run-off-road crashes when suicides and disease attacks were excluded.

3.3 The Most Difficult At-Fault Fatal Crashes to Avoid (P3)

The analysed 87 fatal at-fault crashes were classified as “unavoidable” (n=58), “avoidable” (n=26) or unclear (n=3). Table 8 presents the unavoidable crashes arranged according to the four-level analysis model, and Table 9 presents further information on these crashes.

Table 8. The crashes which were labelled as unavoidable grouped by the primary cause that would have prevented the relevant active safety system operation. *The number in brackets () displays the number of crashes that also included lower level causes. For example, active driver input was the primary cause but also the weather conditions were extreme.

| Primary cause preventing the safety system from operating | Number of crashes |
|---|-------------------|
| Level 1. The driver caused the crash on purpose. | 21 |
| Level 2. Active driver input would have prevented the safety system operating | 21 |
| a. Active driver control and erroneous control action | 13 (6)* |
| b. Active driver control and judgement error | 8 (5)* |
| Level 3. The crash circumstances were beyond the system performance | 15 |
| a. Extreme weather and/or road conditions | 10 (4)* |
| b. Challenging crash kinematics | 3 |
| c. Circumstances were otherwise outside the operational design domain | 2 |
| Level 4. The driver disabled the relevant safety system. | 1 |

Table 9. Detailed information on the 58 crashes labelled as unavoidable. *The percentage was calculated according to those cases which included the information in question.

| | Level 1 | | Level 2 | | Level 3 | | Level 4 | |
|--|---------|-----|---------|----|---------|-----|---------|-----|
| | N | %* | N | %* | N | %* | N | %* |
| DRIVERS | | | | | | | | |
| Male drivers | 20 | 95 | 15 | 71 | 11 | 73 | 1 | 100 |
| Valid driving licence | 20 | 95 | 20 | 95 | 14 | 100 | 1 | 100 |
| Alcohol/drug/medicine intoxication | 7 | 33 | 7 | 33 | 3 | 20 | 1 | 100 |
| Drink driving prosecution during last 5 years | 2 | 10 | 1 | 5 | 0 | 0 | 1 | 100 |
| One or more speeding fines during last 5 years | 7 | 33 | 8 | 42 | 2 | 14 | 1 | 100 |
| Other traffic violations during last 5 years | 1 | 5 | 3 | 16 | 2 | 14 | 0 | 0 |
| Diagnosed mental illness as a background risk | 7 | 33 | 3 | 14 | 0 | 0 | 0 | 0 |
| Diagnosed physical illness as a background risk | 3 | 14 | 3 | 14 | 0 | 0 | 0 | 0 |
| CRASHES | | | | | | | | |
| Single vehicle crash | 2 | 10 | 8 | 38 | 4 | 27 | 1 | 100 |
| Side crash or secondary party crashing from the rear | 0 | 0 | 4 | 19 | 3 | 20 | 0 | 0 |
| Secondary party a vulnerable road user | 0 | 0 | 4 | 19 | 5 | 33 | 0 | 0 |
| Heavy goods vehicle or bus as the secondary party | 19 | 90 | 4 | 19 | 3 | 20 | 0 | 0 |
| Relative crash speed over 80 km/h | 20 | 100 | 14 | 67 | 9 | 60 | 1 | 100 |
| CIRCUMSTANCES | | | | | | | | |
| Slippery road (ice or snow) | 4 | 19 | 1 | 5 | 9 | 60 | 0 | 0 |
| Visible lane markings | 17 | 81 | 14 | 67 | 4 | 27 | 1 | 100 |
| Dark | 6 | 29 | 4 | 19 | 9 | 60 | 1 | 100 |

The crash rate of the most difficult at-fault fatal crashes to avoid was 0.76-0.80 fatal crashes per billion kilometres and 15-16 fatal crashes per million registration years. The results depended on the number of the unsolved cases in the analysis, i.e. whether the three unclear cases were included in the “unavoidable” crashes or not. If the suicides were not included in the figures, the crash rates would be respectively 0.48-0.53 fatal crashes per billion kilometres and 10-11 fatal crashes per million registration years.

3.4 Traffic Behaviour of Adults with ADHD (P4)

Subjects diagnosed as having ADHD showed an elevated risk of being involved in criminality (Table 10) and had a higher risk of dying. Moreover, ten men and one woman with ADHD but none of the controls had died by the age of 40. Of

abovementioned, three died of disease-related incidents, and 8 (13%) died of abnormal causes such as suicide (3), road crash (2), substance abuse (2), or violence (1).

Table 10. Criminology among 111 people with ADHD and 94 healthy controls at the age of 35-40 according to police registers.

| | ADHD | Control | OR | 95 % CI | P value |
|-------------------------------|------|---------|------|-----------|----------|
| Number of persons | 111 | 94 | | | |
| Subject of crime | 23 | 1 | 24.3 | 3.21-184 | <0.00001 |
| Object of crime | 49 | 17 | 3.58 | 1.88-6.82 | <0.0001 |
| No driving licenses | 23 | 4 | 5.88 | 1.95-17.7 | <0.001 |
| Traffic citations (all types) | 43 | 32 | | | N.S. |

No difference was found in traffic citations between those suffering from ADHD and control subjects (at 35–40 years) when all traffic crimes were considered. Also, no difference was observed in the frequency of road crashes. However, there was a significant difference in drunk driving at the age of 30 (OR=5.61, 95% CI 2.30-13.6, $P<0.0001$) and the number of persons without a driver's license at the age of 40 (Table 10).

4. Discussion

4.1 Effectiveness of Passenger Car Safety Devices

Publications 1, 2 and 3 clearly indicated that current safety devices of passenger cars are effective. Publication 2 reported a crash rate of 3.74 fatal at-fault crashes per billion kilometres for conventional older cars without ESC when disease attacks and suicides were disregarded. A comparable figure for ESC fitted passenger cars was 67% less (95% CI 53, 77%, $p < 0.0001$) (Publication 2).

In addition, Publication 3 showed that the incidence of the most difficult fatal at-fault crashes to avoid using current active safety technology was around 0.48-0.53 crashes per billion kilometres if the suicides were excluded from the figures. Even though the figures were not entirely comparable, they showed that state of the art active safety technology up to SAE 2 automation level could offer a significant gain in safety compared to the ESC fitted passenger cars without more advanced active safety technology (Publication 2 and 3).

The effectiveness of safety devices varies according to crash type and crash severity. Publication 2 reported a smaller reduction in injury crashes than in fatal crashes for the ESC fitted passenger cars, and this result was in line with previous findings (Høye, 2011). Unsurprisingly, the effectiveness of ESC was most significant in preventing single-vehicle crashes, which often involve loss-of-control (Publication 2). On the other hand, previous studies suggested that for instance, the current autonomous emergency braking (AEB) systems tend to prevent less severe crashes more effectively and the reduction was greatest in rear-end crashes (Fildes et al., 2015).

Besides the importance of active safety devices, the role of the seat belt was indisputable regardless of vehicle age. Publication 1 showed the importance of proper seat belt use among older vehicles and Publication 3 observed that the seat belt could still save lives during the era of advanced driver assistance systems (ADASs). Even though current technology cannot prevent all crashes, one can still mitigate injuries by using appropriate protective means.

However, the ultimate goal – reaching Vision Zero solely with the aid of vehicle technology and without any restrictions to the definition of Vision Zero – cannot be achieved with current technology. Publication 3 reported that suicides, active driver input before the crash, and challenging weather and road conditions were the most difficult factors for existing active safety systems.

Furthermore, for instance, the concept of driver acceptance may prove to be a more complicated issue than was previously thought. In general, adopting

ADASs and, ultimately, automated driving is a classic example of innovation diffusion (MacVaugh and Schiavone, 2010). However, in the context of driving, there is more to driver resistance than the typical reasons, i.e. irrational and subjective beliefs about the technology in question: individuals with a greater desire to exert control have a significantly lower intention to use driver-assistance systems (Planing, 2014). Publication 4 studied one motivation to be in control: individuals with ADHD favoured high G-forces, but unfortunately, they also demonstrated well-documented driving risks and impairments associated with ADHD.

Finally, Publications 2, 3 and 4 showed that driver illnesses are both common and lead to accidents the outcome of which is hard to prevent using current safety technology. Thirty percent of the at-fault fatal crashes in Publication 2 were either disease attacks or suicides, and the corresponding percentage was even higher in the material of Publication 3: altogether 39%. Physical illnesses such as cardiovascular diseases lead to fatalities which are practically impossible to prevent with current vehicle technology. However, collateral damage can be avoided with such driver support systems as the active steering assist system, and emergency stop assist (Publication 3). Crashes in which a mental illness is a background risk factor are worse since they typically involve also other road users and they are hard to prevent (Publications 3 and 4).

4.2 Aided Human Driver Versus Full Automation

Claes Tingvall pointed out in his presentation titled “An Update of Vision Zero” that it is a common mistake to think that automated driving (AD) would lead to crashes similar to those occurring in manual driving (Tingvall, 2018). This is an interesting point, and it can be approached from the current status of safety technology and crashes, which is considered in this thesis, too.

Firstly, we do not yet know what kind of crashes will be most common among automated (fully automated part of the time or all the time) cars. Due to the limited material, we do not even know whether the crash rate of AD cars is less than that those of conventional vehicles (Blanco et al., 2016; Schoettle and Sivak, 2015). The evidence is limited, thus we can only speculate.

To date, there has been only a few well reported at-fault fatal crashes of SAE level 2 automated vehicles (National Transportation Safety Board, 2017, 2018a) and only one crash of an experimental vehicle of SAE level 3 automation (National Transportation Safety Board, 2018b). However, despite the level 3 automation, also in the latter case a human operator should have constantly monitored the driving. Common to all of the abovementioned crashes was that according to the available information, the AD system was operating normally before the crash but it was unable to recognise the critical situation early enough. In addition, due to the driver’s inattention, s/he could not react either.

Previous studies have suggested that the era before SAE level 5 automation, i.e. full automation all the time, could bring new automation related setbacks in road safety, such as the deskilling of drivers because they drive less due to the

automated driving (Trösterer et al., 2016). Currently, the transition from automated to manual driving appears to be one of the main hurdles impeding the shift to SAE level 3 automation since during automated driving the humans in supervisory control tend to lose awareness of the driving mode (e.g. manual / automated driving mode) (Feldhütter et al., 2017), become tired (Jarosch et al., 2017) and start fiddling with non-driving related tasks (Naujoks et al., 2016). Therefore, the drivers are not ready to resume control of the driving promptly enough.

The abovementioned results also suggest that similar problems could occur with cars with SAE level 2 automation. After the first fatal Tesla crash (National Transportation Safety Board, 2017) Tesla announced that its cars had travelled 130 million miles before that first fatal crash and stated “that Autopilot reduces driver workload and results in a statistically significant improvement in safety when compared to purely manual driving” (Tesla, 2016). However, the abovementioned figures show that the at-fault fatal crash rate was 4.8 crashes per billion kilometres after the first fatal Tesla crash. This was roughly tenfold the crash rate that was found to be achievable when using similar safety devices in Finland if disease attack and suicides were disregarded (Publication 3). Furthermore, it was more than sevenfold the observed crash rate of ESC-fitted passenger cars in Finland (Publication 2, figure excluding disease attacks and suicides). Needless to say, (1) not all Teslas are fitted with “Autopilot”, (2) the crash rates are not directly comparable, and (3) for the sake of statistical significance, the crash rate was calculated based on only one Tesla crash. All in all, it was definitely too early to state that the Autopilot would save lives.

The unintended change in driver behaviour due to the introduction of new safety systems is one form of *behavioural adaptation* (Cacciabue and Saad, 2007). Accordingly, the existing framework for assessing safety system effectiveness (Kulmala, 2010) suggests that there are many factors which increase the probability of behavioural adaptation in the case of, e.g., Tesla’s “Autopilot”. These factors include: (1) the system is easily detectable by the user, (2) it eases the driving task significantly, and (3) it enables access to other utilities such as working while travelling. By contrast, the difference from, e.g., ESC is distinct since many drivers do not even realize that their car is fitted with such a system. However, even though behavioural adaptation may be a significant factor in the near future, it was outside the scope of Publications 1-4. Instead, the lack of use of the safety systems was the main finding regarding negative human behaviour and safety systems (Publications 1-3).

In addition to possible new threats regarding driver passivity, some of the risk factors concerning current crashes will remain in the future. One of the few current safety issues which will definitely be topical in the era of fully automated cars are intentionally caused crashes and cybersecurity. Until now, passenger car traffic has offered limited opportunities to organized crime since the financial driver has been largely lacking. However, networked cars open new possibilities for car theft, blackmail and homicides. In addition, some may sabotage the systems purely as a protest because of personal reasons. One recent example of such crimes was the hacked car sharing app in Chicago (Paul, 2019).

Secondly, AD systems may fail in circumstances similar to those currently experienced by human drivers. Currently, some weather and road conditions are challenging for both ADASs and human drivers (Publication 3) and this could be the case with the AD systems in the future, too. Ultimately, managing challenging road conditions is also a question of system design. It is frequently repeated that automated driving systems will not take risks. However, the system designers define, for instance, an operational design domain for each AD system. If that domain is too demanding for the system, the car is actually driving at risk in that domain. The Uber crash (National Transportation Safety Board, 2018b) is a good example of risk-taking having been included in the system design.

Furthermore, the role of system design is highlighted when the cars operate on full automation all the time. In this case, the human driver is finally removed from the loop, but human error remains possible because the system operation under normal conditions then depends mainly on the design which may include hardware faults and inbuilt vulnerability to (manmade) software bugs. Of course, although a single vehicle is a system, “the system”, and, therefore, also the system risk arising from, for example, a programming error will extend to an entity of connected vehicles and back end systems in the future.

Moreover, during the mixed-traffic phase, the driver errors of the non-automated vehicles will still be present, and, similarly, the environment related risk factors will still remain. The duration of the mixed-traffic phase is also an interesting question, since the element of thrill-seeking is one part of human behaviour in traffic (Publication 4) and petrol heads most likely will not prefer AD cars. As vehicle technology develops, other branches of technology develop simultaneously, too, and it is hard to imagine the interconnected transportation system that will exist when fully automated cars are mainstream.

Finally, the driver override function will be available at least in the near future due to the latest amendments to the Vienna Convention on Road Traffic which state that either the AD technologies should conform with United Nations vehicle regulations, or, alternatively, the driver should be able to override or switch these systems off (UNECE, 2014). The driver override function enables suicides and also crashes which occur due to active but erroneous driver input.

All things considered, it appears that we have very limited real life evidence on the crashes and crash risk of the SAE level 2-5 AD cars, but levels 2-4 seem to involve complex issues of safety, some of which may not have been accounted for. Beyond that, (Noy et al., 2018) question the need to automate in the first place. They discussed whether driving really is too dangerous for humans or whether we are developing AD technology just because we can. Regarding the risk of driving, Publications 2 and 3 showed that one answer to the above questions may lie in the incidence of at-fault fatal crashes, which is fewer than one crash per billion kilometres and closer to one crash per two billion kilometres if disease attacks and suicides were not included – this distance is more than six times to the Sun and back.

Since the average car fleet is roughly ten years old globally, the present aggregated crash figures do not reflect what is achievable using the current state of

the art safety technology. Therefore, instead of waiting for the SAE level 3-4 AD cars to arrive, governments could support the use of newer cars that use traditional technology and thereby gain significant safety improvements (Publication 2). In addition, many other vehicle types, for example motorcycles, mopeds, and bicycles, currently have substantially higher injury rates than passenger cars, and thus, offer greater potential for raising road safety levels. For instance, the relative injury rate of cyclists is about ninefold compared to occupants of passenger cars (Elvik et al., 2009), and, in the short or medium term (5 to 15 years), improving the safety of cycling and cycles could bring a better return on investment than funding the introduction of level 3-4 AD cars.

4.3 Giving Up the Sacred Cows

Cars are bought not only because of their function, i.e. to travel and to transport, but also for sensational and emotional reasons such as speed, power, freedom, status and superiority (Beirão and Cabral, 2007). The automotive industry is well aware of customer desires, but its response to them is somewhat contradictory. In the domain of road safety this means that car advertisements promote both unsafe and safe driving (Watson et al., 2010). Hence, one could argue that car manufacturers are unwilling to use all means to promote safety since limiting the feeling of freedom, for example, would affect sales.

Secondly, a car usually has a long lifecycle and it serves many users before being scrapped. However, car manufacturers design their cars mainly for the first buyer, who typically has the financial means to afford a new car. Moreover, among these target customers, there are fewer high-risk drivers. A higher economic status is associated with various positive features such as healthier lifestyle (Contoyannis and Jones, 2004), better health in general (Case et al., 2002) and less criminal activity (Fergusson et al., 2004). Nevertheless, eventually, as cars age and in turn depreciate in value they become available to almost everyone, at least in Finland.

According to Publications 3 and 4, for instance people with ADHD, bipolar disorder or drug addiction had access to cars. In addition, some of the above-mentioned persons caused crashes which are very difficult to prevent with current safety technology (Publications 3 and 4). The society could not prevent these crashes either since, for instance, 95% of the at-fault drivers had a valid driving licence regardless of the illnesses or history of substance abuse (Publication 3).

The conclusion is: more could and should be done. For example, enforcement of seat belt use could be more efficient and it would pay off even in the current era of ADASs (Publication 3). Visual cockpit monitoring of seat belt use offers one option; it provides a solution for other present safety issues, too. Machine vision could observe both seat belt use and, for instance, also the driver's behaviour. Aggressive driving or distraction could be observed better and risky driving would lead to warnings and ultimately lower driving speeds.

In addition, the introduction of the intelligent speed adaptation (ISA) could bring substantial safety benefits. By definition, ISA refers here to a system that

would limit speed autonomously according to a given speed limit. Previous studies show that such a system has a significant safety potential but would face customer resistance (Marchau et al., 2005). Assessing ISA could have been included in Publication 3, but it was out of the scope as the study concentrated on currently available driver assistance systems.

However, it is likely that full automation will ultimately solve the abovementioned issues, even if the transition period is long. In addition, if the driver is going to be removed from the loop anyway, it would be useful to start reducing his/her involvement beforehand. After all, not all the aspects of today's automotive business, such as maintaining the elevated status of driver autonomy, will apply in the future.

Volvo Cars has assumedly made similar conclusions. It has already announced that it will limit the top speed of its vehicles to 180 km/h and it is planning to install in-car cameras and other sensors that monitor the driver and allow the car to intervene if a clearly intoxicated or a distracted driver does not respond to warning signals (Volvo, 2019). The shift towards AD will change the old dogmas long before full AD is realized. In addition, AD is not the only effective means at hand to improve the road safety significantly. The safe cars of today could be even safer if the car manufacturers protected their cars better against reckless driving and even drivers with evil intent.

4.4 The Nature and Limitations of the Utilized Data

The most frequently used databases in this thesis were the FRA (Publications 1-3) and MLI (Publications 1-3) road crash databases. In addition, official registers of Finnish Vehicular and Driver Data (Publications 2 and 3) and the Finnish Police (Publication 4) were used. Furthermore, a data set on eye injuries was utilized in Publication 1 and a study cohort of patients both with and without ADHD in Publication 4. This section discusses the nature and limitations of the used data.

The main limitation regarding the road crash data used, and all other data sources, too, is that the data were collected in Finland. As there were no disaggregated road crash data available globally, an option would have been other national crash databases from around the world. Such databases could have been used instead of the FRA and MLI database, or for comparison. However, there is the question of which other databases to use and how, and the limitation here is that to compare all available national crash databases to FRA and MLI would require a study in itself. Therefore, a more general approach was selected.

First, replacing the FRA and MLI databases would require an equivalent that would have similar or better qualities. However, there are many common shortcomings such as incomplete reporting that concern most of the databases. According to Elvik et al. (2009), several factors lead to incomplete reporting in road crash statistics, and these factors vary by country. First, some crashes, such as suicides, are not reported because they do not fit the definition of a road crash (UNECE, 2010). Second, the proportion of unreported crashes that should be included in the statistics (reporting level) varies, and data is both missing and

inaccurate (Elvik et al., 2009). In general, the reporting level is highest for car occupants, and fatal crashes are more likely to be reported than in cases where there is damage to property only (Elvik et al., 2009). As this thesis concentrated on passenger cars that were involved in a fatal or an injury crash, the prerequisites for an adequate level of reporting were good.

If one road crash database should be chosen as an example for comparison, previous research on different road crash databases suggests that the Crashworthiness Data System (CDS) of the National Highway Traffic Safety Administration (NHTSA) would be a suitable candidate (Luoma and Sivak, 2007). CDS is a part of the National Automotive Sampling System (NASS) in the United States, and it focuses on passenger vehicle crashes. It is frequently used to investigate injury mechanisms to identify potential improvements in vehicle design. According to NHTSA, NASS CDS has detailed data on a representative, random sample of thousands of minor, serious, and fatal crashes (Radja, 2016). Field research teams located at Primary Sampling Units (PSUs) across the USA each year study about 5,000 crashes involving passenger cars, light trucks, vans, and utility vehicles (NHTSA, 1999). It should be noted, however, that personal information about individuals – names, addresses, license and registration numbers, and even specific crash locations – are not included in public NASS files (Radja, 2016).

NHTSA has documented the CDS database well, and both the data and the documentation are readily available for researchers. These two qualities alone distinguish the CDS from many national databases, since in many countries the disaggregated crash data are not readily available for the researchers (Luoma and Sivak, 2007). However, the problem of the samples that was mentioned already in section 1.4.1 concerns also the CDS: a sample that is representative of one specific question is most likely not representative for a different question (Ramsey and Hewitt, 2005). In addition, cross-sectional studies (e.g. Publications 2 and 3) cannot utilize samples at all. Furthermore, material similar to that in NASS CDS could not have been used when combining crash data to other databases (such as national vehicle or driver databases) to enrich the crash data. This is because the crash data does not include information such as license numbers to identify vehicles or individual people. However, NASS CDS includes investigated information on minor crashes that does not exist in the FRA or MLI databases. Despite the abovementioned limitations, it could have served as a reference in those publications it was applicable to.

By comparison, the FRA database covers 90–95% of fatal motor vehicle crashes in Finland (Parkkari et al., 2010). Because of the excellent coverage of the data, no sampling-related mathematical manipulations were performed to, e.g., estimate the total number of fatal crashes in Finland. In turn, motor liability insurance is mandatory in Finland and covers all injuries. Therefore, it is the primary source of compensation when people are injured in motor vehicle crashes. However, no studies have focused to date on the coverage of the MLI database. In 2013, the MLI database included 22,903 injured people, whereas the official Finnish road accident statistics included only 6,681 injured people

during the same year (Koisaari et al., 2014; “Statistics Finland - Transport and Tourism - Finnish Road Statistics,” 2015).

Besides the coverage, being able to combine other databases with road crash data is also an advantage. For instance, previous research showed that the eye injury diagnoses in the NASS data were unreliable because it was unlikely that the records of ophthalmologists were used when identifying the injuries and their cause (McGwin and Owsley, 2005). Consequently, the compromised data quality had led to a situation where airbag induced eye injuries still prevailed in those studies that utilized NASS, but otherwise, the problem had practically disappeared in the research literature. To avoid the abovementioned problems, the starting point of Publication 1 was to utilize the diagnoses of eye injuries made by expert ophthalmologists and to combine this data to crash data to calculate the incidence of the of eye injuries per crashes. Similarly, actual mileage figures could not have been collected for millions of cars without exploiting the license plate number to identify cars and retrieving the mileage information for these cars from Finnish Vehicular and Driver Data register (Publications 2 and 3).

Many of the limitations depend on the specific database being used, but problems such as missing and inaccurate data are universal. Regarding missing data, missing values were not imputed in this thesis. Therefore, no data was created using mathematical manipulations. The only exception was the missing mileage values, which were replaced with estimated mileage figures from similar vehicles in Publications 2 and 3. Otherwise, the number of missing values was presented always when necessary, and the missing values were omitted when, e.g., distributions of parameter values were calculated. Most of the missing values were randomly missing values, and there was no systematic cause. Missing mileage values were an exception since due to the reporting procedure, all mileage figures of the newest cars were missing and they could be estimated. On the other hand, the problem of systematically unreported information was worst in Publication 4 as the individuals with ADHD self-reported higher drink-driving figures than the official police registers. The risk of being caught, and, in turn, being entered into a police crime register depended on the type of the crime. In addition, due to law, the police register also had another downside: the criminal records are available only for a period of five years.

Assessing the quality of the collected information content in crash databases was the most challenging task since previous research on this matter was not available for the selected databases. As there are several criteria for the quality of information, the task was even more demanding. First, the aim in this thesis was to utilize categorized information as much as possible because this format supports the interpretability of the information – both for the crash investigator and the researcher. In the purest form, the information was binary – either a crash took place or it did not. However, producing categorized information required, in some cases, expert evaluation. To avoid problems of a lack of expertise or compromised objectivity, the author of this thesis avoided performing any analysis that was based only on the expertise of the evaluator. For instance, medical doctors diagnosed all injuries and illnesses. In addition, many of the analyses could not be made afterwards. Publication 3 was an exception since the

author of this thesis performed some road tests which served the analysis performed in this publication. The author has more than ten years of experience in tire and vehicle testing, which explains this exception. Otherwise, the effort of the author concentrated on verifying the information quality. In particular, the information in the FRA database could be crosschecked on many occasions as the same information was available in many sources. In general, it was easy to identify the number of missing values, but ensuring, e.g., the quality of the diagnosed injuries was more or less impossible. The most questionable material in this thesis quality-wise was the information that was collected via questionnaires when the individuals suffering from ADHD were 30 years old. Self-reporting compromises the objectivity of the information, for example.

Some of the limitations of this thesis depended on the chosen scope. The focus was on at-fault drivers, and therefore, the secondary parties and other occupants received less attention. In addition, there were also unanticipated limitations. First of all, using solely Finnish data leads to weighting the effect of winter conditions in Publications 2 and 3 compared to, e.g., countries near the equator. Therefore, in those countries, the ESC-fitted passenger cars may not show equally significant safety improvements compared with more traditional vehicles as presented in Publication 2. In addition, state-of-the-art active safety devices could show even lower incidences of crashes than are presented in Publication 3. However, there were also some other limitations which could counter the effect of the long winter : both the ESC fitted cars in Publication 2, and the cars in Publication 3 were fairly new, relatively expensive and therefore, bought mainly by people having higher socioeconomic status. The higher car price ruled out, e.g., many younger car drivers, who have higher crash risk (Williams and Carsten, 1989). Younger car drivers could benefit more from ESC than older drivers, but they could also show behavior that would be challenging for current safety technology.

The benefits of the used data were coverage and, thus, representativeness. The crash data also included suicides and sudden illness attacks, which are absent in many crash databases. In addition, the extensive crash data could be enriched using other information, since the identification of occupants and vehicles was possible, and, thus, these individuals and vehicles could be identified in other databases, too.

4.5 Future Research

The basic human machine interface of the car is more than hundred years old. Similarly, many areas of research in the automotive industry have decades of history. This dissertation has approached the subject of road safety from the perspective of traditional safety devices and driver support systems.

During the research, it became clear that even though many advanced technologies were under development, some elementary information regarding the study subject was missing. For instance, various driver support systems are in use but there is no database which details which cars in Europe are equipped

with these devices. Furthermore, we do not know the mileage exposure or the number of crashes of these cars.

Looking forward, connected cars will produce online information and this data will be the cornerstone of future research on vehicle safety. It is vital that this information is widely available and not restricted to only car manufacturers because there is considerable need for new research in this area. The delay in the transition to SAE level 3 automated cars has shown that not everything is as simple as it seems and complex issues require interdisciplinary research and reliable data.

The results of this thesis imply that although the number of severe crashes will decrease, contributions to the field of traffic safety beyond technological expertise will play an important role in the future. Many challenging medical, psychological, and social aspects are related to those crashes that were the hardest to avoid using current safety technology and a multidisciplinary approach is also therefore required.

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Appendix 1

A Detailed Description of the Crash Analysis to Identify the Most Difficult At-Fault Fatal Crashes to Avoid Using Current Active Safety Technology

The Process

The crash analysis was a two-step process which consisted of a preliminary database search for all investigated fatal crashes in the study group and a case-by-case analysis of each crash using a hierarchical four-level analysis method. Between these two steps, there was an information-gathering phase which included both literature search and field tests.

Tapio Koisaari performed the preliminary database search, did part of the literature search, performed the field tests, developed the analysis method and analyzed the crashes case-by-case. All authors of the Publication 3 agreed on the four-level analysis method and its details, and Roni Utraiainen did the other part of the literature search.

The purpose of the preliminary evaluation round was to form an overall picture of the investigated crashes and to establish which information regarding the safety systems was essential for further analysis of these crashes. During this evaluation, it became clear that a detailed description of each safety system was required.

Accordingly, to make the analysis possible in the first place, we chose one real world reference for each active safety system in our study. Furthermore, we decided to use only one car brand as an example. This decision was made for practical reasons such as making the information inquiry more straightforward and for real-world testing. After choosing the brand, we gathered all available information concerning the active safety systems of this brand.

Because the literature search failed to produce all the essential information required, some field tests were required to fill in the gaps. However, these field tests did not aim to form a perfect test set to cover all active safety systems studied. Finally, a hierarchical four-level analysis method was used case-by-case to establish whether some of the studied active safety systems could have prevented the crash or not.

The crash was regarded as unavoidable if it fulfilled at least one of the following conditions:

Level 1: The driver caused the crash on purpose (suicide or homicide)

Level 2: Active driver input would have prevented operation of the safety system

- a) Active driver control and erroneous control act (steering error, foot on accelerator instead of brake, etc.)
- b) Active driver control and judgement error (turning, overtaking, etc.)

Level 3: The crash circumstances were beyond the performance of the safety system

- a) Extreme weather and/or road conditions
- b) Challenging crash kinematics (direction of crash, relative speed difference, short time to react, etc.) for both human driver and safety system
- c) Crash site or circumstances were otherwise outside the operational design domain of the relevant system (outside the operational speed range, no lane markings, etc.)

Level 4: The probability of relevant system activation was low

- a) Driver showed behavior or possessed a driving history of high risk taking or disabling safety systems

Preliminary Evaluation

In line with normal practice, Finnish road accident investigation teams had made initial investigations of each of the crashes used in this study. These multidisciplinary teams investigated the crash scene, accessed several official registers concerning the occupants, vehicles, and road infrastructure, and finally, the teams analyzed the crash according to the official investigation method (Salo et al. 2007). The case documents include a four-page standard form report, an over-500-item Fatal Road Accident (FRA) database and several attachments such as photos, police reports, autopsy reports, sketches and, possibly, video footage, reconstruction calculations, and other relevant files.

During the preliminary evaluation, the following items were retrieved for each crash from the FRA database: case id, primary cause of the crash, crash type (classified according to crash kinematics), the type and number of involved vehicles, first crash object, second crash object, third crash object, gender of the driver, age of the driver, validity of the driving license, sitting position of the killed occupants, sitting position of the injured occupants, sitting position of the unharmed occupants, intoxication of the driver (alcohol/drugs/medicine), passenger car model, model year, speed of the primary party before crash, speed and direction of the secondary party before the crash, speed limit, use of seat belt (by killed occupants), analysis result for seat belt use effectiveness (for killed occupants), road conditions, weather conditions, light conditions, road defects (multiple variables, such as missing lane markings), driver action prior to and during the crash (multiple variables) and cause of death. In addition to the previously mentioned information, the fitted safety systems of each passenger car were examined.

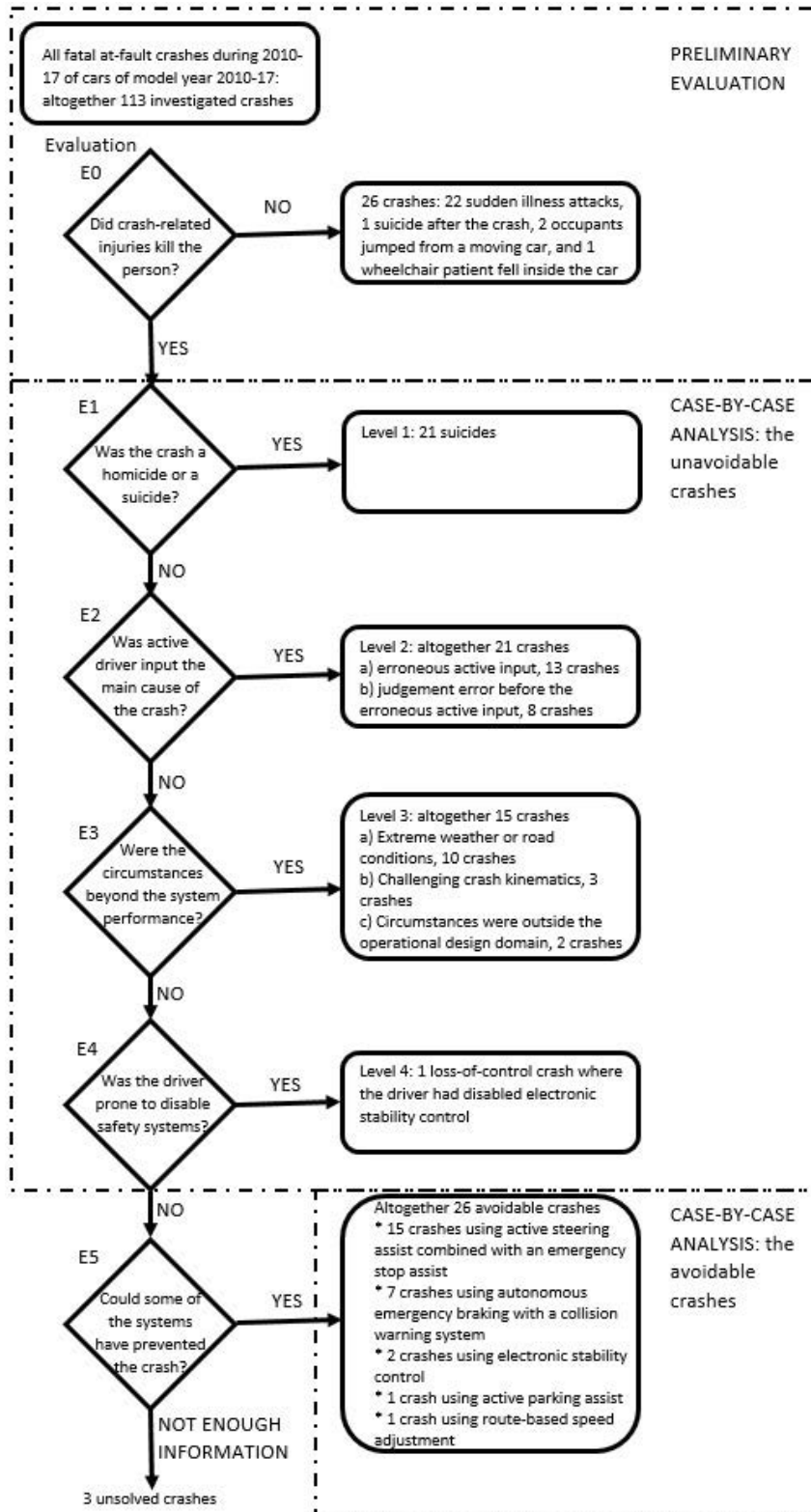


Figure A1. Description of the work flow during the analysis.

The initial evaluation (evaluation E0, see Figure A1) started with 113 at-fault fatal passenger car crashes. After the evaluation, 26 crashes were excluded from the study because the cause of death was not crash-related. Among the 87 remaining crashes, the number of missing values was minimal (for several reasons). First, most of the collected information was basic data that was readily available for the investigations teams. Secondly, most of the more challenging data items, such as the primary cause of the crash, driver operation before the crash and vehicle speed before the crash, are critical variables in the crash investigation and analysis and therefore, this information was also well documented. Finally, there were multiple sources for the same information. For instance, there were a few variables for road and weather conditions (for instance, variables KELITYY, KITKA, KELVAIH, KELPOIK, POLANNE (Finnish Crash Data Institute (OTI), 2008)) in the FRA database, but some of the same information was also in the attached police reports, and ultimately, the photos from the crash site showed the prevailing road and weather conditions. The worst result in terms of the missing values concerned blood alcohol content (BAC) right after the crash: in two cases (2/87, 2.3%) the driver was not breathalyzed since no intoxication was suspected.

At the end of the preliminary evaluation, each crash was checked against the gathered information. The purpose was to identify which crashes would be challenging to analyze and why. This check showed that analyzing the crashes requires precise and accurate information on the operational design domain and the limitations of each safety system. It also revealed that the focus of further examination should be on the active steering assist system, active emergency stop assist, and autonomous emergency braking.

Case-by-Case Analysis of the Crashes

After the preliminary evaluation, literature search and field tests, each fatal crash in the FRA database was analyzed case-by-case to decide whether it could have been avoided if the state-of-the-art active safety devices had been present. In this assessment, it was assumed that instead of the actual at-fault passenger car involved in the crash, there would have been a car with similar passive safety features but with such active safety features as described in Table 1. It was also assumed that the driver would have used (activated) each safety system as designed unless the driver showed behavior towards disabling safety systems.

The final analysis of the fatal crashes relied on several expert assessments: First, multi-profession Finnish Accident Investigation Teams had investigated and analyzed the cases according to the standardized method. Secondly, the authors of this publication agreed on the four-level analysis method and its details. In turn, the corresponding author of this article analyzed the cases according to the abovementioned four-level method. In a few cases, a second opinion was requested from the staff of the Mercedes-Benz importer regarding the safety system operation. The final analysis started by identifying potential cases for level 1, 2, and 3 a) crashes with the aid of the FRA database. After the potential cases were identified, they were further evaluated to ensure that they fitted the selected level.

First, all level 1 crashes were identified with the aid of a single variable called “VRISKI” (Finnish Crash Data Institute (OTI), 2008), which is in the FRA database (evaluation E1, see Figure A1). If this variable showing the primary risk factor of the crash had the value “crash caused on purpose,” the case was labeled as level 1. In addition, all case files of these crashes were accessed to establish that the values in the database were correct. Similarly, the FRA database was exploited to identify level 2 crashes (evaluation E2, see Figure A1). However, multiple variables were used. Thus, variables VRISKI, AJOHALL, and VTESTO (Finnish Crash Data Institute (OTI), 2008) were each searched for values showing active vehicle control during the crash. Also, case files and photos that reported, e.g., the skid marks, were analyzed. The distinction between groups 2 a) and 2 b) was whether the driver made a simple mistake (level 2 a) case) or performed a controlled maneuver (such as overtaking). Overall, common to all level 2 crashes was that the active input of the driver caused the crash and the driver input would have been the primary cause preventing the safety systems from operating. In addition to level 2 crashes, there were other crashes involving active driver input, too, but in these cases, the driver had already tried to prevent the crash or the input did not make the situation worse.

As with level 2 crashes, level 3 a) crashes were also identified by using a multiple variable approach. Crashes occurring under extreme road or weather conditions, i.e. group 3 a) crashes, comprised the last, larger and somewhat uniform group of unavoidable crashes. The challenging weather and road conditions were identified by using variables KELITYY, SAATYYP, and VALOIS (Finnish Crash Data Institute (OTI), 2008). In addition, details of the visibility of lane markings (TMERNAK) and of the friction of road surface (KITKA) were taken from the database (Finnish Crash Data Institute (OTI), 2008). Finally, the photos of the crash scene were viewed to ensure that coded information regarding road conditions and weather was correct. Also, before accessing the case files, the speeds of the primary (OSNOP) and secondary (VPNOP) party were examined (Finnish Crash Data Institute (OTI), 2008). Analysis of the case files (evaluation E3, see Figure A1) showed two types of cases: in the first type, the driver was already trying to avoid the crash, but failed mostly because of the slippery road. In such cases, the safety systems could not have prevented the driver from ending up in such a situation, or they could not have prevented the crash. The most common example was a slippery curve where the car drifted towards the opposite lane, even though the driving speed was within the speed limit. In the second type of crashes, the safety systems could have prevented the crash under normal operating conditions but not in the demanding weather or road conditions then prevailing. The identification of the level 3 a) cases would have been almost impossible without the footage taken from the field tests. These field tests showed e.g., how much snow or sleet was required to prevent the lane keeping assistance (LKA) or steering assist system from working. Besides the road tests in this study, also other reported results of tests carried out in extreme conditions such as those of Nieminen and Honkanen (2019) were utilized. Their results showed e.g. that the autonomous emergency braking (AEB) system of the Mercedes was able to stop the car only up to the speed of 20 km/h on snow-covered surfaces and in the dark.

The remaining crashes that were not labeled as level 1, 2, or 3 a) were analyzed case-by-case (evaluation E3, see Figure A1) in terms of crash kinematics and other limitations regarding the operational design domain of the active safety systems. During this work, also an assessment was made to establish whether the driver showed behavior for disabling safety systems (evaluation E4, see Figure A1). Moreover, it was ensured that no cases belonging to levels 1) and 2) remained. The analysis showed that all crashes labeled as level 3 b) were cases in which the primary party was performing a U-turn and the secondary party was approaching from behind at a speed significantly different from that of the primary vehicle (>40 km/h). The only suitable active safety system to prevent such crashes would have been the blind spot assist, but when the primary party started turning the secondary party was still either out of the range or sector of the blind spot detection radars. In addition, the user manual of the blind spot assist system (Daimler AG, 2018b) mentions that 1) the system does not react to vehicles which are approaching at a significantly greater speed and are overtaking, and 2) the system may not react to narrow vehicles such as bicycles (in two crashes the secondary party was a motorcycle). The distinction between level 3 b) and level 2 crashes was that the active driver input would not have prevented the blind spot assist system from operating in the level 3 b) cases.

Besides the level 3 a) and b) crashes there were two crashes which fell into the level 3 c) category. In the first crash, a car hit an almost stationary cyclist at 70 km/h on a dark and ice-covered rural road which had a speed limit of 80 km/h. The cyclist was also in a blind spot due to a steep uphill gradient and a bend before the crash site. Even under good conditions, the driving speed would have been above the AEB or collision warning system (CWS) specifications. In the second case, a car was turning left at a junction while a bicycle travelling in the same direction then crashed into its left side. The bicycle was driving on a tree-bordered cycle path, which ran parallel to the main street that the car was travelling along. In this case, the circumstances were beyond all design domains of the studied systems. Neither the blind spot detection system nor AEB with cross-traffic detection would have prevented this crash. For these two level 3 c) crashes, a second opinion about the safety system operation was requested from the technical officer of Mercedes-Benz importer. The importer agreed with the analysis.

Finally, there was only one crash which could confidently be labeled a level 4 a) crash. The case-by-case analysis revealed that it was difficult to find firm evidence that a driver was prone to disable the safety devices of his car or that the probability to activate them was low. It was even harder to prove that a driving history involving high risk-taking would lead the driver to deactivate the active safety systems while driving. Eventually, as the goal of this analysis was to find those crashes hardest to avoid using state-of-the-art active safety technology and leave as little room for speculation as to possible, only one investigated crash served enough information to give an unambiguous verdict. In this loss-of-control crash a male driver had turned electronic stability control (ESC) off (the information was saved in the key fob), and he was not wearing a seat belt either. According to the assessment of the Accident Investigation Team, ESC would have prevented the crash.

After the level 1-4 crashes were identified, the remaining crashes were analyzed once more (evaluation E5, see Figure A1). This time the goal was to identify which active safety system had the highest probability of preventing the crash. The previous analysis had already established clearly that in the remaining cases 1) the driver did not cause the crash on purpose, 2) the driver did not give the car any active input that would have been the primary cause for the crash, 3) the road, weather or other conditions were not sufficiently extreme to have prevented operation of the safety system, and 4) it was probable that the driver had activated the relevant safety systems.

However, one more final check had to be made to ensure that all limitations of the systems had been taken into consideration. In addition, all cases in which the active steering assist system with emergency stop assist was the most relevant safety system had an extra check. Namely, in these cases, the road was checked for a 1.5-kilometer stretch after the crash site for any major junctions which could have distracted the steering assist system away from the road. If no such junction was found, the conclusion was that the emergency stop assist system would have finally stopped the car safely in the case where the driver was incapacitated e.g., unconscious.

In the end, three of the crashes remained unsolved. In two of the cases, the driver activity before the crash was unclear. The first of these cases was a suspected suicide and the other a suspected sudden illness attack. The missing information was crucial, as, for instance, the suspected suicide would have been easily avoidable with LKA. However, if the driver had committed suicide, the crash would have been a level 1 unavoidable crash. The third crash was close to an avoidable case thanks to the aid of the active steering assist. However, the characteristics of the driver suggested that he would have disabled the system in any case. Since this case involved too much speculation without hard evidence, we left it unsolved, too.

This thesis examined not only the effectiveness of the currently available safety devices for passenger cars (up to SAE level 2 automation) but also crashes that cannot be prevented by current safety technology.

The research was carried out as a statistical analysis using Finnish databases as material. The material of the Finnish Crash Data Institute (OTI) was used exclusively as the crash data. In the publications, this crash data was combined with appropriate Finnish databases as needed.



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