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Published in:
Accident Analysis and Prevention

DOI:
10.1016/j.aap.2019.105396

Published: 01/02/2020

THE MOST DIFFICULT AT-FAULT FATAL CRASHES TO AVOID WITH CURRENT ACTIVE SAFETY TECHNOLOGY

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INTRODUCTION

Many of the previous studies about active safety systems have concentrated on either the safety potential or the actual effectiveness of these systems. In other words, how many crashes or what percentage of the crashes these systems had or would have prevented. For instance, the most recent meta-analysis of electronic stability control (ESC) (Høye, 2011) stated that fatal crashes were reduced significantly, i.e., by about 40%, when all crash types were grouped. Moreover, according to Utriainen (2018), autonomous emergency braking (AEB) and adaptive cruise control (ACC) could potentially have prevented a further 41% of fatal rear-end, intersection and pedestrian crashes in 2014-2016 in Finland.

The next advancements from the abovementioned advanced driver assistance systems (ADAS) are partially automated driving and, in turn, fully automated driving (AD). AD has significant safety potential since it will remove the human driver from the control loop. However, the somewhat simplified assumption that full automation would finally eliminate driver error, and thus nearly 90% of the existing crashes, has been much discussed (Noy et al., 2018). We attempted to contribute to this discussion by studying which current fatal at-fault crashes would still occur despite the most advanced current active safety devices (up to SAE level 2 automation, (SAE, 2016)) and how frequent these crashes would be. The core of this study were the limitations of the present systems.

One of the most significant limitations or features of current active safety systems is the driver override function. This function is in all current ADASs, and it will be available in cars in the near future as well. This is because recent amendments to the Vienna Convention on Road Traffic state that AD technologies should conform with the United Nations vehicle regulations; alternatively, the driver should be able to override or switch these systems off (UNECE, 2014). In existing partially automated driving systems up to SAE 2 level, the human driver always has responsibility for driving and therefore even a subtle driver input, such as a steering movement, overrides the safety system operation (Guo et al., 2019; Katzourakis et al., 2013). Unintentional driver input overrides the safety systems, too.

Poor weather conditions (e.g., snowfall or fog), dirt or snow on the lane markings or worn-out markings may also inhibit safety system operation. For instance, the operation of lane keeping assistance (LKA), which provides transient lane keeping support, requires visible lane markings. At least a centre line should be visible, but some systems require both a centre line and an edge line to operate correctly (Logan et al., 2017). Slippery road conditions also affect stopping distances and set the physical limits to vehicle maneuvering capability. Car magazine tests have shown that in winter conditions, current AEB systems were unable to stop the car at speeds above 10-20 km/h, and in the dark, some of the systems failed to detect the target vehicle (Nieminen and Honkanen, 2019).

Furthermore, each safety system has its operational design domain (ODD), and the system manufacturers have often excluded challenging weather and road conditions from the ODD. The ODD usually has other limitations, too, for instance, LKA is usually designed to operate on high-quality roads (e.g., highways) without sharp curves (Tesla, 2019; Toyota, 2017; Volvo, 2017). According to Toyota (2017), a curve radius should be more than 150 m. Also, the systems have an operational speed range. Typically, the maximum activation speed of AEB varies from 140 km/h (Tesla, 2019) to 200 km/h (Daimler AG, 2018a). At higher speeds, Volvo's (2017) and Tesla's (2017) AEB systems decelerate vehicle speed by a maximum of 40-60 km/h, e.g., down from 80 km/h to 40 km/h. It is unlikely that the AEB system will prevent crashes of a vehicle travelling at more than 60 km/h (Utriainen, 2018).

In addition to the above-mentioned general limitations, the list of brand and system specific limitations seems endless. For example, even when a stationary vehicle is positioned in front of an AEB-equipped vehicle, the system may not always activate (Toyota, 2017). Hence, this system is not always able to stop the vehicle in a critical situation. In the case of ACC, sensors may lose the leading vehicle, and the system cannot operate (Larsson, 2012). Because of the numerous limitations, assessing the safety potential of such active safety systems requires proper system specifications and preferably at least some real world testing to verify the system operation.

In our study, we focused on the crashes hardest to avoid. Therefore, in our analysis, we assumed that the drivers would have the driver assistance systems always activated. In real life, however, the safety potential of these systems is not always realized as the systems should be switched on by the driver. Studies have shown that LKA and lane departure warning (LDW) systems are activated for about 50 % of driving time (Flannagan et al., 2016; Reagan et al., 2018).

Systems warnings at safety-critical situations help drivers to take evasive action early enough, but it should be acknowledged that people react differently to various warning signals (e.g., generic vs. specific warnings) (Winkler et al., 2018). According to earlier studies, multimodal warnings (reaction time 0.57s) lower the driver's braking reaction time compared to a single, e.g., only a visual warning (0.72-0.81s) and especially compared to no-warning situations (1.61s) (Biondi et al., 2017). Moreover, in a safety-critical situation, drivers are braking rather than steering (Winkler et al., 2018). In this study, we assumed that sober and conscious drivers would have reacted to the system warnings.

Distraction and secondary tasks while driving a partially automated vehicle are potential threats which affect the drivers' capability to monitor the environment (Banks et al., 2018). However, we did not assess the possible adverse effects of ADASs and AD.

MATERIAL AND METHODS

The Vehicle Population in the Study

We limited the vehicle group in our study to passenger cars that were first registered as new during the period 1st January 2010 to 31st December 2017 and were in road-use in Finland. We set no further limitations.

Exposure Data

We aimed to calculate a crash rate for our study group in relation to true exposure. Therefore, we accessed the national Vehicular and Driver Data Register (VDDR) to obtain the mileage information and the registration count for the period of 2010-17. We identified the vehicles in our study group based on the registration date and vehicle category (M1).

The VDDR records the mileage of every vehicle during the mandatory yearly roadworthiness inspection. During the study period (2010-17), the first inspection was performed after three years from the first registration. The fourth year was inspection-free and cars older than five years had undergone an annual roadworthiness inspection.

Because of the inspection schedule, we used the mileage data up to the year 2018 to obtain mileage figures of the newer vehicles. We also performed a quality check for the data and the mileage figure was discarded if it was outside the range of 100 km – 600 000 km.

Because the mileage figures were not available for the newest cars, we had to estimate these. To provide an estimate, we used the mileage of a car of a similar owner profile (age, gender), vehicle weight and age. Appendix Table A1 presents the estimates. Except for the estimation described above, the method to calculate the exposure was the same as in our previous work (Koisaari et al., 2019).

Crash Data

In Finland, the law requires all fatal road accidents to be studied in-depth and on-the-spot by multidisciplinary (police, road and vehicle engineers, physicians and behavioral scientists) road accident investigation teams (FINLEX, 2016). The purpose of these teams is to determine the risk factors that turned an ordinary driving situation into a serious accident and to provide recommendations for improving road safety. The investigation teams do not take a stand on legal or insurance compensation issues. Salo et al. (2007) describe the method of Finnish road accident investigation in detail.

When analyzing accidents, the teams identify the following features: the key event and these risk factors: immediate, background and injury (Salo et al. 2007). Approximately 500 types of data are collected from each accident party and also extra information, such as photographs and sketches. This information is then coded into the Finnish Road Accident (FRA) database. Also, all occupants killed in crashes are subjected to a forensic autopsy, the results of which can be correlated with injuries and pre-crash medical histories and journals.

We accessed the FRA database and included all fatal at-fault crashes among the cars in our study for the period 2010–2017.

Overview of the Crash Analysis

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.

Preliminary Evaluation

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 be-fore 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.

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.

Reference Technology Selection and Literature Search

We wanted a real world reference for each active safety system in our study. Consequently, we chose one car brand 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, we could test the operation of each system on the road.

The preliminary evaluation of the crashes told us which operational details were important in reference technology selection. In our case, the decisive difference was the operation of the vehicle safety systems in a situation where the driver was no longer able to steer the vehicle while the steering assist system was active: they had fallen asleep, had a heart attack, etc. We chose to use Mercedes-Benz passenger cars as the reference since their “Active emergency stop assist” stops the vehicle if the driver does not respond within a certain period to the “hands on the steering wheel” alarm of the steering assist system (Daimler AG, 2018a).

After selecting the reference technology, we searched the available literature for as much information on these systems as possible. Table 1 shows the full list of different active safety systems included in our analysis. The table also contains a short description of how each system works. Figure 1 presents the sectors and reaches of the stereo camera and radars.

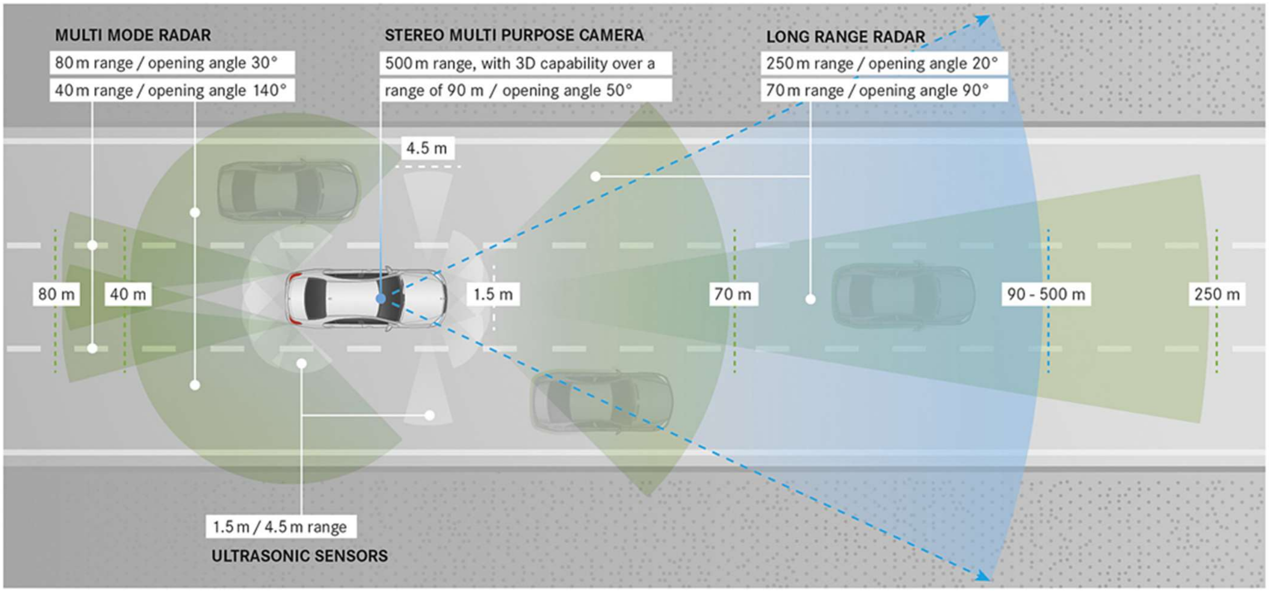
It should be noted that we could not include detailed information on all active safety systems in this article. However, more information is available in the manufacturer's material, such as the owner's manual (Daimler AG, 2018a). Also, the codes in brackets [] in Table 1 refer to the version of the active safety system which we used in our analysis. The following notes provide a useful overview of the most important limitations.

First, all systems included the general limitations introduced in the Introduction chapter regarding driver override function and poor weather and road conditions. Secondly, many of the advanced driver-assistance systems in our reference vehicle required activation of the ACC. Therefore, it was crucial to establish whether the use of cruise control was possible because of e.g. the weather conditions.

Besides the above-mentioned general limitations, almost every system had its system-specific operational limitations.

Table 1. Active safety devices and related systems included in the analysis (Daimler AG, 2018a). 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]	Surveilles and warns of driver drowsiness. Active in the range of 60 and 200 km/h.
Active blind spot assist [23P]	Detects vehicles at blind spots and informs driver; performs an evasive steering action if necessary. Active in the range of 12 and 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 timewise constant. Braking up to 50% of maximum.
Active emergency stop assist [266]	Stops vehicle if driver does not steer vehicle while the 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 with a steering or braking action, 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 highbeam assist plus [P35, 628, 642]	Maximizes the high beam light pattern with active beam control but avoids blinding 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 meter
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 such as T-junctions, roundabouts.
Traffic sign assist [513]	Recognizes traffic signs and displays them on the display; supports the active speed limit assist



Schematic illustration, not to scale

Figure 1. The opening angles and ranges of the radars and stereo camera (Daimler AG, 2018b). Reprinted with the permission of Daimler AG.

Field Tests

We performed real world tests using vehicles having similar technology to that we used as a reference in our analysis method. Our road 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. For instance, the owner's manual (Daimler AG, 2018a) stated that "the system operation may be limited or inhibited on snow-covered roads" but did not specify the term "snow-covered" in any way.

We used a Mercedes-Benz E 220d 4Matic sedan (VIN: WDD2130051A560552) in our road tests, which took place 11th-13th February and 6th-9th April 2019. The first test period examined how snow-covered and icy roads affect the operation of the active safety systems. During the second test set, we tested the effect of single parameters such as darkness, backlighting and worn lane markings. Finally, we used also a second test car, Mercedes-Benz E 400d 4Matic station wagon (WDD2132231A554359) for further studies of the active speed limit assist and route based speed adjustment.

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. During the road tests, we also recorded and repeated simple driving maneuvers, such as turning at different kinds of junctions, overtaking and approaching bends, in order to measure the time taken to perform them.

Case-by-case Analysis Method of the Fatal Crashes

We assessed each fatal crash in the FRA database case-by-case to decide whether it could have been avoided if the current active safety devices had been present. In this assessment, we 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 the Table 1. We also assumed that the driver would have used (activated) each safety system as designed unless the driver showed behavior towards disabling safety systems.

Primary concerns in the analysis were driver activity prior to and during the crash, the crash kinematics, and road conditions generally. We used a hierarchical four level analysis method in which the level one cause for preventing the active safety system operation was the least speculative. Finally, we labeled the crashes either avoidable, unavoidable, or unsolved. We regarded the crash 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 the safety system operation

a) Active driver control and erroneous control act (steering error, foot on accelerator instead of brake, etc.)
b) Erroneous driver input due to e.g. judgement error (turning from a junction in front of another vehicle, overtaking when there is oncoming traffic, etc.)

Level 3: The crash circumstances were beyond the performance 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 for relevant system activation was low

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

Besides indexed information on several variables, the accident investigation files also contain many different analyses regarding e.g. the effectiveness of safety belt use, crash sequence, and vehicle control prior to the crash, and we utilized these ready-made analyses whenever possible.

RESULTS

Vehicle Population and Exposure

The passenger cars (registered 2010-17) in our study group comprised 3,772,864 registration years during the study period, 2010-17. During the same period, these vehicles travelled 75.9 billion kilometers (Table 2). The median age of the vehicle owners was 53 years and 66.4% of them were males.

Table 2. The number of vehicles in the study group each year, yearly registration year count and total mileage per year.

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Total**
Vehicles	111165	239169	353785	462736	576619	695300	826142	960781	
Registration years	58123	179792	304332	410832	523288	637010	763619	895868	3772864
Mileage [billion km]	1.23	3.84	6.52	8.79	10.9	12.7	14.8	17.1	75.9

Preliminary Evaluation

Cars in our study group were the primary party in 113 investigated fatal accidents during the years 2010-17. Because we focused on fatal crashes, we excluded altogether 22 sudden illness attacks (driver died because of the attack) and four other accidents from the study. One of those four accidents involved a suicide outside the car after the crash; in another, an occupant fell with his wheelchair inside the car during braking; and in the two other accidents, an occupant jumped out from a moving car.

Field Tests

Based on the preliminary crash analysis, two active safety systems were most interesting: the active steering assist system and AEB. However, since there were references available for the performance of the AEB in real operation conditions, we concentrated on the active steering assist in our road test.

The tests examined the safety system operation, pre-selected operating conditions, and specific parameter values. Even though we recorded a few parameters, the single value that we eventually needed in the crash data analysis was the duration of the emergency stop (on average, 76 seconds and 1.5 km at 74 km/h). The most useful gathered information concerned system operation under normal and certain challenging conditions.

We identified boundary conditions for system operation in circumstances such as on snow-covered roads, faded lane markings and specific road types (different types of curbs for instance). In these conditions, the active steering assist barely operated, but we could not consider the operation reliable. Figure 2 presents an image of the limit conditions for the snow-covered road.

On the other hand, the tests showed that the active steering assist operated without problems in the dark, during moderate rain and bright backlight conditions. The active steering assist could also continue driving across junctions and past bus stops. At only one of the slightly fewer than one hundred tested junctions did the car deviate from its path, causing the driver to intervene. In this four-legged junction, the traffic island was asymmetrically placed, which created too sharp a turn for the steering assist.

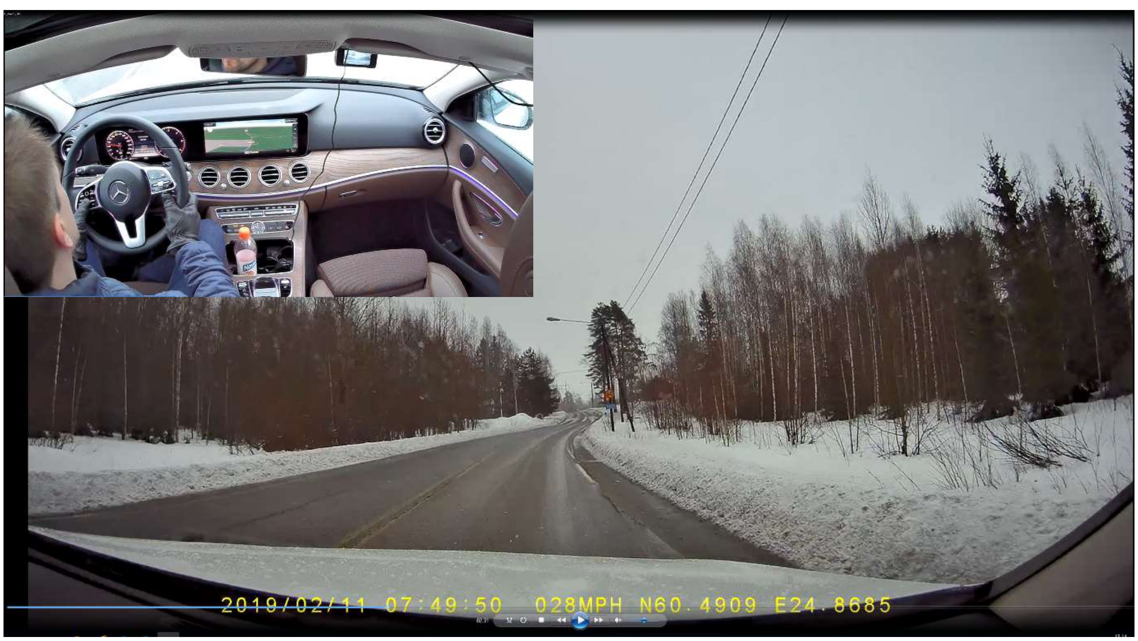


Figure 2. The limit conditions for the active steering assist to operate when the road was snow (slush) covered.

In addition to the active steering assist, we also tested the operation of the other systems presented in Table 1 in their operational design domain and under normal operating conditions. We omitted only the AEB, and evasive steering assist from the tests because results on similar AEBs were already available (Nieminen and Honkanen 2019) and we found it challenging to test the evasive steering assist reliably. The tests showed that systems operated according to the specification under normal operating conditions and, for example, no random sensor faults occurred. The total test length was 940 km.

Case-by-case Analysis of the Fatal Crashes

According to the case-by-case analysis, the 87 fatal crashes were classified as “unavoidable” (n=58), “avoidable” (n=26) or “unclear” (n=3). Figure 3 shows the workflow during the analysis, and Tables A2 and A3 in Appendix give additional information on the crashes. The analysis required five evaluation rounds (evaluations E1-E5, see Figure 3) before both “avoidable” and “unclear” cases were identified.

All level one unavoidable crashes (n=21) were suicides, and the median age of the drivers was 43 years. Accident Investigation Teams had classified the crashes as suicides, and we agreed with the analysis. In turn, the level two crashes (n=21) involved an active but erroneous driver input before the crash. The most common primary causes of these crashes were unintentional erroneous control action (n=10), maneuvering (e.g., overtaking) without checking (n=4) and observational error (n=4). The median age of the level two drivers was 53 years.

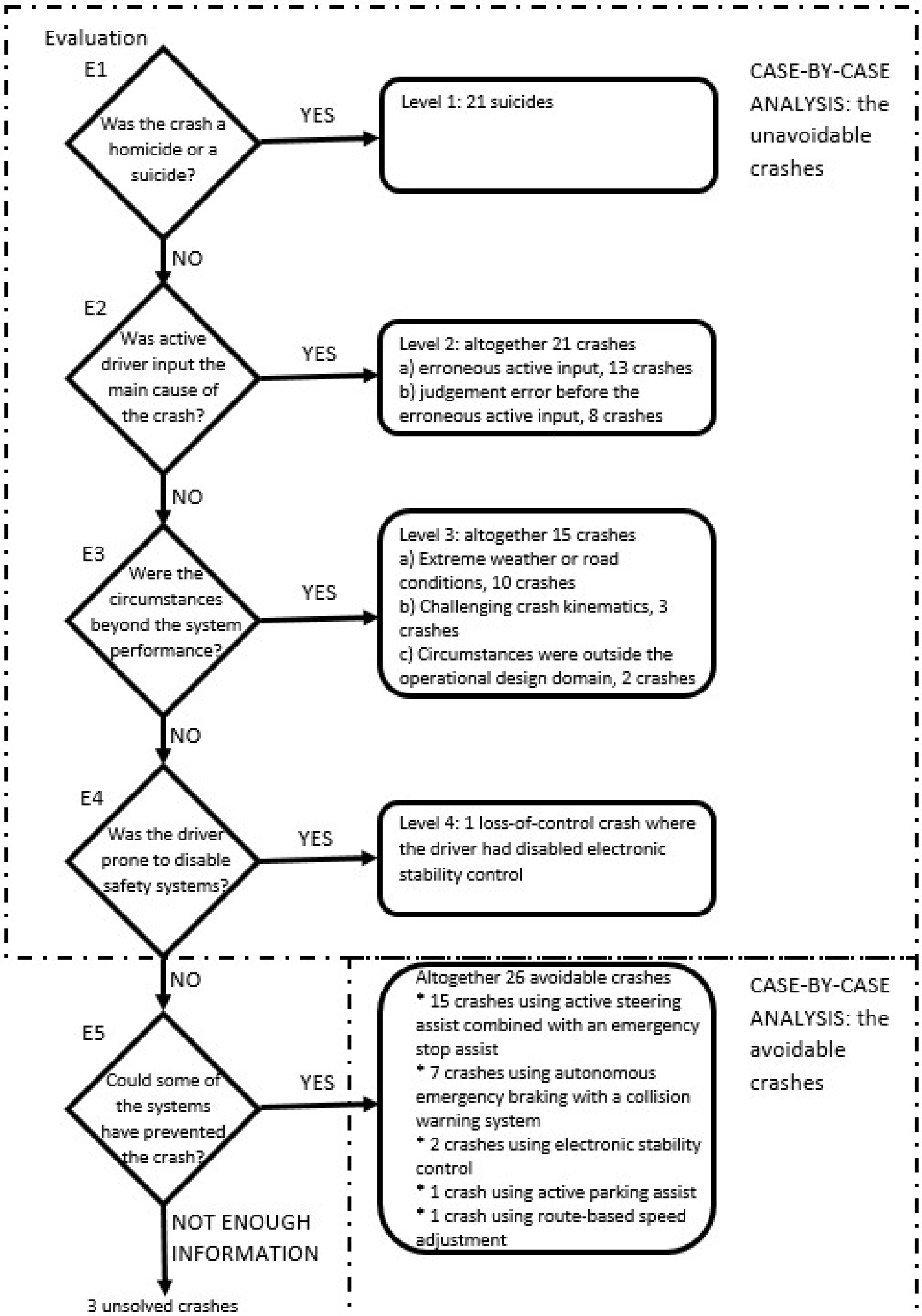


Figure 3. Description of the work flow during the analysis.

Level three crashes (n=15) possessed features beyond the active safety system performance. In nine crash sites, the road was either icy, slushy or snow covered and in five cases, it was also snowing. Nine of the crashes occurred in the dark. Only at four crash sites were the lane markings visible. The median age of the level three drivers was 45 years. Besides the Level 1-3 crashes, there was only one level four crash in which a 36-year-old driver lost control of his car. In this case, the driver had disabled the ESC.

The characteristics of the 26 avoidable crashes contrasted with those of the level 1-4 crashes. Passive drivers drove either tired or ill, or were distracted in good weather conditions and they caused a crash on a road which was in good condition. In addition, the crash circumstances matched the operational design domain of the relevant active safety system.

We concluded that active steering assist combined with emergency stop assist would have prevented 15 crashes if the driver had activated it. All but one distracted driver were passive (sleeping or unconscious due to an attack) and the lane markings were visible farther than the required 1.5 kilometers. The crashes occurred in highway conditions, and there were no major junctions within the 1.5-kilometer stretch after the crash site or just before it. After the 1.5 km distance, the active emergency stop assist would have stopped the vehicle if the driver had not woken up before that.

The AEB with collision warning systems would have prevented seven fatal crashes, according to our analysis. All but one driver was sober and only distracted briefly. The one male who was alcohol intoxicated was close to unconsciousness because his blood alcohol content (BAC) was 0.37%. Most of the crashes (n=5) occurred in an urban environment (speed limit 50 km/h or less) and the weather and road conditions were good in all cases.

Besides the 22 crashes mentioned above, there were four other avoidable crashes. In the first case, the active parking assist would have prevented one low-speed crash involving a pedestrian at a parking lot. In two other cases, the ESC would have avoided a loss-of-control crash. Finally, the route based speed adjustment feature of the ACC would have prevented one crash where the driver was dazzled while approaching a T-junction on a rural road.

All mentioned active safety systems in the context of avoidable crashes were the most effective ones in these individual cases. In addition, their operation was least speculative in these cases.

We left three of the crashes unsolved. In two of the cases, the driver activity before the crash was left open. The first of these cases was a suspected suicide and the other a suspected sudden illness attack. The third crash was close to an avoidable case thanks to the aid of the active steering assist, but 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.

As stated earlier, we did not evaluate the role of the passive safety systems or the vehicle body structure in individual cases. However, from a passive safety point of view, it was notable that in seven unavoidable crashes wearing protective gear (six car occupants and one cyclist) would have avoided the fatalities, according to the assessment of the Road Accident Investigation Teams. Similarly, wearing seat belt would have saved two killed occupants in the avoidable crashes.

Crash Incidence

The crash rate of the most difficult at-fault fatal crashes to avoid was 0.76-0.80 fatal crashes per billion kilometers and 15-16 fatal crashes per million registration years. The results depended on the number of the unsolved cases in the analysis, 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 kilometers and 10-11 fatal crashes per million registration years.

DISCUSSION

Properties of the study group and analysis method

Both our analysis method and study group selection affected the results. The most important implication of the latter contributor was the age and gender distribution of the car owners. Since all cars in our study were at most seven years old, they were also relatively expensive and available mainly for people with higher socio-economic status. Higher car price ruled out many younger car drivers, who have higher crash risk (Williams and Carsten, 1989) and, for instance, the percentage of car owner less than 25 years old was 1.4.

The reason for limiting the analysis to the crashes of quite new vehicles was that we could avoid speculation about the effect of better passive safety, and, foremost, the effect of ESC. Besides a few exceptions, all cars in our study were fitted with ESC, and consequently, we had to assess the effect of the ESC only in few crashes. Furthermore, all cars possessed rather modern passive safety features. The downside of the chosen car population was the low number of fatal crashes, which increased the role of random variation in the results.

As we used an existing real world reference for each active safety system, our analysis results also depend on the chosen technology. For instance, if the brand specific active steering assist had worked poorly, the calculated crash rate would have been higher. Furthermore, we studied the technology up to SAE level 2 automation since currently only driver support (not automated driving) systems were available. Using a different car brand or SAE level 3 technology as a reference would have given different results.

In our analysis, we assumed that the active safety devices listed in Table 1 were fitted only in at-fault passenger cars, not in other vehicles. Assuming similar technology in all vehicles would have made the analysis substantially more demanding. We also assumed that the drivers would always activate the relevant safety systems. In other words, we omitted driver acceptance, adaptation and many usability issues which all are essential problems in current systems (Fleming et al., 2018; Kulmala, 2010).

Besides our choices, there were also a few practical issues, which made the analysis easier than we anticipated. First, the driver override function was a significant drawback for current systems. Secondly, in many of the crashes concerning active driver input before the crash, the timespan was also very limited. The timespan was the same order of magnitude as the reaction time of an ordinary driver. Third, the performance of current AEBs was very limited under slippery conditions (Nieminen and Honkanen, 2019), and finally, the active steering assist operation was very robust in normal operating conditions.

Lastly, the crashes had been well investigated, and, e.g., several sources of information were available for examining the driver operation before the crash. The files included interviews of the occupants and eyewitnesses; the skid marks were documented; some of the files included reconstruction calculations and printouts from the event data recorder (EDR). Most importantly, the investigation files reported causalities between different risk factors and the crash rather than merely noting a possible correlation between these factors and the crash.

Nature of the ”unavoidable” crashes

In our study, 21 (36%) of the “unavoidable” crashes were suicides (level 1 crashes). The role of such crashes will (probably) continue to be significant into the future and they pose a risk for other road users, thus this crash type deserves more prominence in crash statistics and safety discussions. Besides, in the future, there may be even more motivation factors for intentionally caused crashes.

The extreme end of violations are the sabotages, which are one feature of human behavior (Reason, 1990). Networked mobility services and traffic systems open new possibilities for both sabotages and criminal activity. This has been already demonstrated, as a car-sharing app was hacked (Paul, 2019). Until now, passenger car traffic has offered limited opportunities for organized crime since the traditional driver for crime, financial reward, has been lacking. A possible scenario is that in the future someone could cause crashes intentionally to commit not only suicide or homicide but also other crime. Therefore, deliberately caused crashes should always be taken into consideration in the design of future systems.

Besides intentionally caused crashes, active driver input before the critical situation was also a challenge to the current active safety systems due to the driver override function. Of the 58 unavoidable crashes, 21 (36%) showed either active steering, pedal input or both before the crash (level 2 crashes). We categorized these crashes into two groups: A stereotype of the first category driver was an intoxicated person who was driving aggressively and finally performed an erroneous control act. He differed considerably from the second archetype, an ordinary driver who drove to the critical situation without understanding the danger because of, e.g., observation error. In both categories, the driver controlled the car actively until the crash and the time from ordinary driving situation to the point of no return was typically short.

In the abovementioned level 1 and 2 unavoidable crashes, the active safety systems had minimal possibilities to operate because an active human driver dominated the event. Besides these crashes, we found 15 (26%) unavoidable crashes in which the circumstances were beyond the safety system performance (level 3 crashes). Common to all these crashes was that the circumstances were challenging for the human driver and they would have been demanding for active safety system operation too. This was a very adverse feature for the studied systems, as they could not have helped when the need was greatest.

If the AEB had worked better under slippery conditions, some of the level 3 crashes would have been more difficult to assess. However, in most of the level 3 crashes under slippery conditions, the driver started reacting promptly, but the driving speed should have been well below the speed limit in the first place. The driver had made a misjudgment regarding the tire grip. Since slippery road conditions were the most common challenging circumstances in level 3 crashes, our results − in Finland − are not necessarily transferable to countries having shorter winters.

Finally, we found only one unavoidable crash (2%) providing solid evidence of disabling of the relevant safety system but not falling into the categories of level 1-3. However, the driving history and behavior of many level 2-3 drivers showed that they would very unlikely have activated any safety devices during driving, especially those who were not even wearing a seat belt (n=7 (19%), levels 2-3).

Crash incidence

The two exploited databases, VDDR and FRA database, were extensive and therefore we did not need any mathematical manipulations to, e.g. estimate the total number of fatal crashes. Briefly, the FRA database covers 90–95% of fatal motor vehicle crashes in Finland, and only unregistered cars were not filed in the VDDR. The mileage of the unregistered cars was virtually nonexistent since their road use was either prohibited or granted only with a short-term permit. Both databases are discussed in further detail in our previous publication (Koisaari et al., 2019).

Crash rates of fatal crashes with true exposure have been published very limitedly. Many of the older publications (Lyman et al., 2002; Ouimet et al., 2010) relied on both sampled crash and exposure data. Furthermore, they studied a notably older car population. Current studies exploiting naturalistic driving data (Dingus et al., 2016) fit fatal crashes poorly since the crash incident is low. Besides the differences in exposure calculation, we could not find a previous equivalent to our study setup.

In our previous study, we found a crash rate of 0.66 fatal crashes per billion kilometers for ESC-fitted passenger cars when suicides and diseases attacks were excluded (Koisaari et al., 2019). As far as we are aware, this was also the best point of reference for our current study, which shows 0.48-0.53 crashes per billion kilometers for similar crashes.

The crash rate of a state of the art passenger car technology up to SAE level 2 automation was thus 20-27% smaller than that of ESC-fitted passenger cars. However, the crash rates were not completely comparable because there were small differences, e.g., in the driver populations. In the current study, the median age of the drivers was three years greater, and the proportion of males was five percentage points higher than in our previous study (Koisaari et al., 2019).

In turn, the observed safety potential of seat belt use in the current study gives a comparison of the gain in safety between the state of the art safety technology and ESC-fitted cars. If all occupants in the current study group had been wearing a seat belt, there would have been six fewer “unavoidable” fatal crashes, according to the assessment of Road Accident Investigation Teams. These six cases account for a 0.08 fewer fatal crashes per billion kilometers and a 12% reduction compared to the crash rate of ESC-fitted passenger cars. Therefore, the potential of technology enforcing seat belt use is still significant.

Conclusions

Our study showed that there was an incidence of 0.76-0.80 “unavoidable” at-fault fatal crashes per billion kilometers. According to our analysis, these crashes could not have been avoided with the aid of current driver support systems (up to SAE level 2 automation) and modern passive safety features. We found suicides, active driver input before the crash, and challenging weather and road conditions to be the most difficult factors for present active safety systems. Our analysis did not account for issues such as system usability or driver acceptance, and therefore our results should be regarded as something that is currently technically achievable. However, the observed incidence is a useful reference for AD development.

ACKNOWLEDGMENTS/DISCLOSURE

a. Funding/Support:

Henry Fordin Säätiö (foundation) Finland grant no: 20170074

The test vehicles were provided by Veho Oy Ab.

The funding sources had no involvement in the preparation or writing of the article.

b. Financial Disclosures

Tapio Koisaari	No financial disclosures
Roni Utriainen	No financial disclosures
Timo Kari	No financial disclosures
Timo Tervo	No financial disclosures

c. Other Acknowledgments

The Finnish Road Accident Investigation Teams comprise a total of 300 experts who have collected the fatal road accident data. Without their contributions, this article could not have been written.

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APPENDIX

Table A1. The mileage per year for passenger cars of age three years or less: results per the gender and age of the car owner and the mass of the vehicle.

Owner gender	**Woman**					**Man**					**Average**
Owner age	-25	25-34	35-54	55-64	65-	-25	25-34	35-54	55-64	65-	
Vehicle mass											
-1200 kg	16105	14183	14024	11799	8472	17936	15409	15038	13448	10320	13673
1200-1399 kg	17482	18119	17788	15133	11099	19359	20334	20004	17467	12321	16911
1400-1599 kg	19936	22176	22722	18666	13087	22967	24258	24816	21627	14729	20498
1600- kg	24675	25306	25095	21712	18830	23576	27421	29281	25701	17846	23944

Table A2. The crashes which were classified 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 A3. Detailed information on the 58 crashes labeled as unavoidable. * The percentage was calculated according to those cases which included the information in question.

	Level 1		Level 2		Level 3		Level 4	
DRIVERS	N	%*	N	%*	N	%*	N	%*
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