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Which not-at-fault crashes are unavoidable by using current active safety technology?

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ABSTRACT

Previous research has focused on analysing crash reduction potential of active safety technology in at-fault passenger cars, but only a few studies have examined counterparties' possibilities to avoid collisions by using advanced driver assistance systems (ADAS). This study quantified the incidence of fatal not-at-fault passenger car crashes that current ADAS (up to SAE level 2) would be unable to avoid. We used data taken from in-depth investigated fatal crashes in which a passenger car was involved, that car having been first registered during the period 1 January 2010 to 31 December 2017 in Finland. The evaluation of unavoidable crashes consisted of two evaluation rounds. The preliminary evaluation round identified potential active safety systems that could have operated in the studied cases. In the following round, we made a five-level case-by-case analysis including a time headway analysis in order to evaluate the possibilities for crash avoidance. The crash data included 63 fatal crashes, of which five were excluded because the death was due to a sudden illness attack. The remaining 58 crashes were classified as follows: probably unavoidable ($n = 51$), avoidable ($n = 3$), and unclear ($n = 4$). The crash incidence of the unavoidable not-at-fault party crashes was 0.67–0.73 fatal crashes per billion kilometers and 14–15 fatal crashes per million registration years. The results indicate that current active safety systems may be able to prevent not-at-fault party fatal crashes only in a few cases and that the driver's role in road safety remains important despite the deployment of the active safety systems.

1. Introduction

Automated vehicles in SAE levels 4 and 5 [1] are predicted to enhance traffic safety by reducing the number of crashes (see e.g., [2]). However, it will take several years, or even decades, before such automated vehicles become mainstream on roads [3]. Consequently, it remains necessary to focus on advanced driver assistance systems (ADAS) in SAE levels 1 and 2, which support the driver. These systems are becoming more widespread in the car fleet and, hence, they may provide traffic safety benefits in the shorter term compared to automated vehicles.

Several studies have evaluated the potential or actual safety impacts of SAE level 1 or 2 active safety systems [4,5]. Some studies have evaluated the combined crash reduction potential of almost all available active safety systems. For instance, Yue et al. [6] concluded that the number of light vehicle crashes could be reduced by 33–46% in the United States by implementing the systems.

By contrast, only a few studies have focused on factors that prevent active safety systems from operating and avoiding crashes. Analysing these crashes is important, since it provides useful information for the development of the future systems. For instance, Koisaari et al. [7] have evaluated the at-fault fatal crashes that are most difficult to avoid. That analysis indicated that intentionally caused crashes (e.g., suicides), active driver inputs (e.g., erroneous control actions), and weather and road conditions are typical factors preventing the proper operation of ADAS in the at-fault car.

This study directs attention to which not-at-fault fatal crashes current active safety systems are unable to avoid, i.e. what possibilities the innocent counterparty has, by utilizing the active safety systems, to avoid collisions. In addition, the crash incidence for these crashes is calculated and factors preventing the crash avoidance are examined. The switch of focus away from the at-fault crash party, which, in previous studies, is typically evaluated and compared, enabled us to provide a new approach to evaluating the safety impacts of ADAS. Existing driver assistance systems are generally designed to help the driver to avoid making mistakes and hence, changing focus to look at the safety

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systems of not-at-fault party is also necessary. By analysing these crashes, we can also address to what extent active safety systems can help the drivers of new cars to avoid falling victim to a crash caused by somebody else's action.

2. Active safety systems of not-at-fault vehicles

When crashes are examined from the perspective of a not-at-fault party, it becomes clear that the active safety systems that are able to provide an avoidance action - i.e. automated emergency braking (AEB) and evasive steering assist (ESA) - are the sole systems that are potentially able to avoid these crashes or mitigate the consequences. For instance, in cases of head-on crashes, an at-fault road user (i.e., who caused the crash) moves into a lane of oncoming traffic. In turn, a car in its own lane (i.e., a not-at-fault party) reacts, but has only two options to avoid a collision: apply the brakes or swerve [8]. Any lane-keeping assistance system of the not-at-fault party is of limited use because it is unable to provide the means to avoid these collisions, even though the system could be helpful from the at-fault party's point of view in cases of avoidance of unintentional lane departures [9].

AEB may be unable to avoid head-on collisions, but it can reduce impact speed. Strandroth et al. [8] studied head-on crashes between passenger cars and heavy vehicles in Sweden and concluded that AEB could potentially reduce impact speed by 18 km/h, if only the heavy vehicle is AEB-equipped. Impact speed reduction is highly dependent on time prior to a collision when an oncoming vehicle crosses a centre line on the road. For instance, Strandroth et al. [8] estimated that AEB braking time was on average 0.73 s. According to Daimler [10], AEB systems can activate 1.6 s prior to a collision and detect oncoming traffic in the same lane 80 m before the collision.

A steering maneuver is a more effective way to avoid collisions than a braking maneuver when vehicle speeds are high, if there is enough empty road space for swerving [11]. However, the ESA system of e.g., Mercedes-Benz [10] cannot provide assist in swerving unless a driver initiates a swerving action, in which case the ESA system assists the driver by enhancing the action.

Intersection crashes are another crash type in which AEB or ESA systems can potentially avoid or mitigate crashes. In these cases, typically the at-fault party fails to obey its obligation to yield at an intersection, and therefore avoidance of a collision is dependent solely upon the driver or the activation of the active safety systems of the not-at-fault party. Also, the reaches and sectors of the sensors of each party coupled with their respective speeds influence the potential for preventing a crash. For instance, AEB systems in Mercedes-Benz cars can activate when the vehicle speed is 70 km/h or lower and the intersecting vehicle's speed is 50% or less than that [10]. The AEB systems that are capable of identifying intersecting vehicles are able to prevent collisions with intersecting and other pedestrians and cyclists, too.

Haus et al. [12] estimated that if all cars and light trucks in the United States were AEB-equipped, the fatality risk of pedestrians in collisions with motor vehicles could potentially be reduced by 36–87%. This wide range is due to a critical time interval (e.g., a distance to a collision once the brakes are applied) and a latency in the systems. If AEB is able to detect the danger and apply the brakes 1.5 s prior to a collision, the safety enhancement would be 87%. In a lower bound, the critical time would be 0.5 s. It should be noted that AEB systems can usually be overridden. For instance, if the driver actively steers or decelerates the car, the AEB system cannot activate.

3. Material and method

We made a cross-sectional study of fatal road crashes in Finland to study which not-at-fault party fatal crashes would be unavoidable by the current active safety systems. Also, we calculated the incidence of unavoidable crashes and identified factors preventing the avoidance of collisions.

3.1. Data

We studied a passenger car group that was first registered as new during the period 1 January 2010 to 31 December 2017 and was in road-use in Finland.

The crash data were based on in-depth investigations made by the accident investigation teams during 2010–2017 and those data were provided by the Finnish Crash Data Institute (OTI) that coordinates the investigations. In Finland, the investigation of fatal road traffic crashes is mandated by law [13] and each crash is in-depth investigated by independent investigation teams to provide information on the risk factors, road users, vehicles involved and the traffic environment etc. The investigation method is described in more detail by Salo et al. [14].

In total, the investigation teams reported 1662 fatal crashes during 2010–2017. The driver of a passenger car was the at-fault road user in 1266 cases and the not-at-fault party in 346 crashes of which in 63 crashes the not-at-fault party of the crash was a passenger car from our study group, i.e. the vehicle was first registered as new during 1 January 2010 to 31 December 2017 (Table 1).

Crashes arising from a driver's sudden illness attack ($n = 5$) were excluded before the analysis because in these cases the driver's death resulted from the attack and not the crash, and hence the active safety systems could not avoid the fatal consequences. It should be noted, too, that these crashes are usually excluded from road crash statistics. Altogether, the data included 58 fatal crashes, in which a motor vehicle driver, a pedestrian or a cyclist was determined to be the at-fault road user by the accident investigation team, and a passenger car driver was the not-at-fault party of a crash. Two not-at-fault party vehicles were equipped with the AEB system.

The difference between at-fault and not-at-fault parties is determined by the investigation teams according to the predictability principle. This is usually defined by the law. For instance, an at-fault road user did not typically obey the obligation to yield at an intersection. In some cases, determining who was at fault may be difficult if the driver having right of way was, e.g., travelling greatly in excess of the speed limit. In pedestrian crashes, the crash site typically defines at-fault and not-at-fault parties, i.e., whether the crash occurred on a pedestrian crossing or outside the crossing. In cases of head-on crashes, the at-fault driver typically moved into a lane of oncoming traffic.

To calculate the crash incidence, we retrieved the registration year count and mileage information for our study group (i.e., vehicles first registered as new during 2010–2017) from the national Vehicular and Driver Data Register (VDDR). The mileage information in VDDR was collected during yearly roadworthiness inspections, and we used information from the cross section of 1 January 2020, which was the most

Table 1
All investigated fatal road crashes in Finland 2010–2017 and the analysed crash data.

Fatal road crashes in Finland	Number of crashes
All investigated fatal crashes in Finland 2010–17	**1662**
All crashes involving a passenger car (all model years)	**1427**
All at-fault crashes of the passenger cars (all model years)	**1266**
Multi-vehicle crashes	*637*
Single-vehicle crashes	*507*
Pedestrian or cyclist crashes	*115*
Crashes with animals	*7*
All not-at-fault crashes of the passenger cars (all model years)	**346**
Multi-vehicle crashes	*277*
Pedestrian or cyclist crashes	*69*
All not-at-fault crashes of the passenger cars (model year 2010–17)	**63**
Multi-vehicle crashes	*55*
Pedestrian or cyclist crashes	*8*
Not-at-fault crashes of the passenger cars excluding crashes caused by sudden illness attack (model year 2010–17)	**58**
Multi-vehicle crashes	*50*
Pedestrian or cyclist crashes	*8*

recently updated information when the analysis was done. Before using the mileage information, we ran a quality check and the mileage figure was discarded if it was outside the range of 100 km – 600,000 km. For missing mileage figs. (4.6% of the material), we used the mileage of a car of a similar owner profile (age, gender), and vehicle weight and age.

In total, the passenger cars in our study group comprised 3,772,864 registration years during the study period, 2010–17. During the same period, these vehicles travelled 75.7 billion kilometers. The median age of the vehicle owners was 53 years and 66.4% of them were males.

3.2. Method

We made two evaluation rounds to assess which fatal crashes in the analysed crash data would have been unavoidable if a not-at-fault crash party had been equipped with state-of-the-art active safety systems. During the preliminary evaluation, we identified potential active safety systems that could have been activated during the pre-crash events, and which crashes, if any, to exclude from the second evaluation round.

In the second round, we evaluated each crash case-by-case to identify which crashes were potentially avoidable, which were unclear, and which were probably unavoidable. A fatal crash was viewed as avoidable if the system could either prevent the crash or avoid fatal consequences. We used active safety systems of Mercedes-Benz passenger cars [10] as the reference because they represented the latest technology available during the study period. That said, there were also alternatives for the reference technology, but we decided to use Mercedes-Benz to obtain the best possible comparability to the previous study [7]. For instance, according to the Daimler [10], the AEB system's braking is up to 200 km/h and the cross-traffic braking is up to 70 km/h. The AEB system does not operate e.g., in snowfall, fog, or when the sensors are in dirt. Koisaari et al. [7] presented the reference technology in greater detail.

3.2.1. Preliminary evaluation

Our first step in the preliminary evaluation was to confirm what we had already found in the literature: that AEB and ESA are the sole systems that could possibly activate and prevent these not-at-fault crashes. This we did by assessing information on crash types, immediate risk factors, vehicle speed, active driver input, and road and weather conditions.

As noted above, during the pre-crash period, the only possible maneuvers open to the not-at-fault crash party are to decelerate or swerve. However, it should be noted that in the case of our reference technology, ESA was only operational when a driver steered the vehicle in order to avoid a collision with a pedestrian. It was unable to assist in avoiding collisions with other passenger cars or when the driver did not actively steer the vehicle. That said, in none of the crashes in the data did the driver swerve to avoid a collision with a pedestrian and in one of the crashes the driver tried to avoid a collision with another vehicle by steering. Thus, the ESA system could not prevent any of the studied crashes.

Another point to note is that during the preliminary evaluation, we classified rear-end crashes as “unavoidable” because none of the studied systems of the not-at-fault party vehicle was able to prevent an at-fault vehicle from hitting the rear of the not-at-fault party vehicle in front. Hence rear-end crashes were excluded from the case-by-case evaluation round. This confirmed that AEB was the sole system that could activate and possibly prevent some of the crashes in the data.

3.2.2. Five-level case-by-case evaluation

In the case-by-case evaluation, we assessed crashes according to a five-level (Levels A-E) model. Crash types (i.e., rear-end crashes) that none of the systems could address (Level A), were already excluded in preliminary evaluation.

Firstly, we assessed whether an AEB system was able to activate (Level B-D). This assessment was made examining crash descriptions and variables provided by the accident investigation teams. If the AEB system could not activate, the crash was considered unavoidable. When the activation was confirmed, we assessed whether AEB was able to avoid fatal consequences (Level E). We regarded the crash as “unavoidable” if it fulfilled at least one of the following conditions:

Level A. Crash types (i.e., rear-end crashes) that none of the studied systems was able to address. In the case of a rear-end crash, the case is excluded from further analysis.

AEB could not activate and operate:

Level B. Active driver input (e.g., the driver steered or accelerated) would have prevented the AEB system from operating. In the case of active driver input, the case is unavoidable.

Level C. Adverse weather conditions or poor ambient light would have prevented the AEB system from operating. In the case of snowfall, rain, sleet, fog, or poor ambient light, the case is unavoidable.

Level D. Intersection crashes: speed was more than 70 km/h, which exceeded the AEB system's operational design domain. In the case of speed of more than 70 km/h, the intersection crash is unavoidable.

The AEB could operate, but the system could not prevent fatal consequences:

Level E. The AEB system would have operated, but it would not have prevented fatal consequences due to insufficient time to activate the system (i.e., the need for AEB activation is identified 0.5 s or less before the collision). In the case of insufficient time to activate the AEB system, the case is unavoidable.

After we concluded that the operational requirements (Level B-D) were favourable, we considered whether the AEB system could have operated sufficiently well to have avoided the crash.

We used crash descriptions and scene photographs together with other variables of the crashes that are described earlier in this text to estimate distances and decelerations from the AEB system's perspective. Firstly, we calculated how many seconds prior to the moment of collision (time headway, t) AEB could potentially have been first activated (Eq. 1).

$$t = \frac{s}{v_0} \tag{1}$$

As the camera or radar sensors were not applied in the actual crash events, the distance (s) was evaluated based on the investigation report. In intersection crashes, the distance was measured from the point where the intersecting at-fault crash party could be first recognized by camera sensors to the point at which the collision occurred. When the at-fault crash party is a pedestrian or a cyclist, the distance is from the point where the road user stepped or cycled on the roadway to the point at which the collision occurred. When the at-fault crash party is a motor vehicle, the distance is from the point from which the motor vehicle was first visible and came to the driving line of the not-at-fault party. In head-on crashes, the distance is from the point at which the at-fault crash party moved into a lane of oncoming traffic to the point at which the collision occurred. Speed (v_0) is the estimated speed of the not-at-fault party prior to the collision, and it is based on reconstruction calculations and investigations made by the investigation team. Cases where the need for AEB activation could have been identified 0.5 s or less before the collision were evaluated as being unavoidable (Level E), because there was no time to decelerate at all or time was very short, considering computational latency or brake delay [15,16]. Cases with a time of more than 0.5 s were still included in the analysis.

3.2.3. Potentially avoidable and unclear cases

Once it was confirmed that the situation could have been identified more than 0.5 s before the collision the new speed (v) of the not-at-fault party at the point of collision was determined taking into consideration any deceleration due to the activation of the AEB system (Eq. 2). The maximum value of time headway was 1.6 s, because the AEB system could only activate 1.6 s before the impact in the best-case scenario.

$$v = v_0 - \mu \times g \times t \quad (2)$$

The deceleration value (μ x g) we applied was 6.0 m/s^2 in normal road conditions, which is based on the average value taken from the studies of Grover et al. [17] and Strandroth et al. [8]. In cases where conditions were slippery, we applied a friction coefficient (μ) provided by the accident investigation teams. After the new speed of the not-at-fault party at the collision point was calculated, we evaluated whether the fatal consequences could have been avoided.

Intersection crashes with pedestrians and cyclists were evaluated as being avoidable, if the speed at the collision point was less than 30 km/h. Pedestrian fatality risk in collisions with passenger cars has been evaluated to be very low at these speeds [18]. Cases where the speed was higher than 30 km/h but lower than the actual speed at the moment of impact, were also evaluated avoidable, if the investigation report stated that even a small change in timing would have prevented the crash (i.e., the at-fault party had more time to pass the collision point and hence, the collision could have been avoided).

Crashes between motor vehicles in which the situation could have been identified more than 0.5 s (and at most 1.6 s) before the collision were assessed as unclear cases, because the literature does not offer enough information to assess such crashes. We lacked literature about the avoidance of fatal consequences in those collisions where the at-fault vehicle's speed remains unchanged while the not-at-fault is braking.

4. Results

4.1. Preliminary evaluation

In the preliminary evaluation, we excluded rear-end crashes ($n = 9$) from the case-by-case evaluation round and classified them as “unavoidable” (Fig. 1). The remaining crash data consist of 49 crashes, 31 of which are head-on and 18 are intersection crashes (intersection crashes included 2 cyclist and 6 pedestrian crashes). All in all, the study group consisted of 58 crashes of which 49 were evaluated case-by-case.

4.2. Case-by-case analysis of the fatal crashes

According to the analysis, 51 of the 58 fatal crashes (including rear-end crashes) were classified as unavoidable (Table 2). In addition, our analysis showed that three of the intersection crashes could have been prevented by the AEB system. Four head-on crashes were judged to be unclear because of the relatively small decrease in speed. In one case, the weather and road conditions were good and even a short braking by AEB would have changed the crash kinematics significantly. Furthermore, this crash involved three vehicles, which made the analysis more complex. In three other cases, the AEB system could have activated and decelerated the impact speed of the not-at-fault party, but the impulse force remained high due to at-fault party's speed.

Active driver input (Level B) would have prevented the AEB system from operating in 16 cases, adverse weather conditions or poor ambient light (Level C) in 11 cases and speed that exceeds ODD (Level D) in five cases (Table 3). In the other 17 cases, the AEB system would have activated or barely activated, but solely three of these 17 cases were

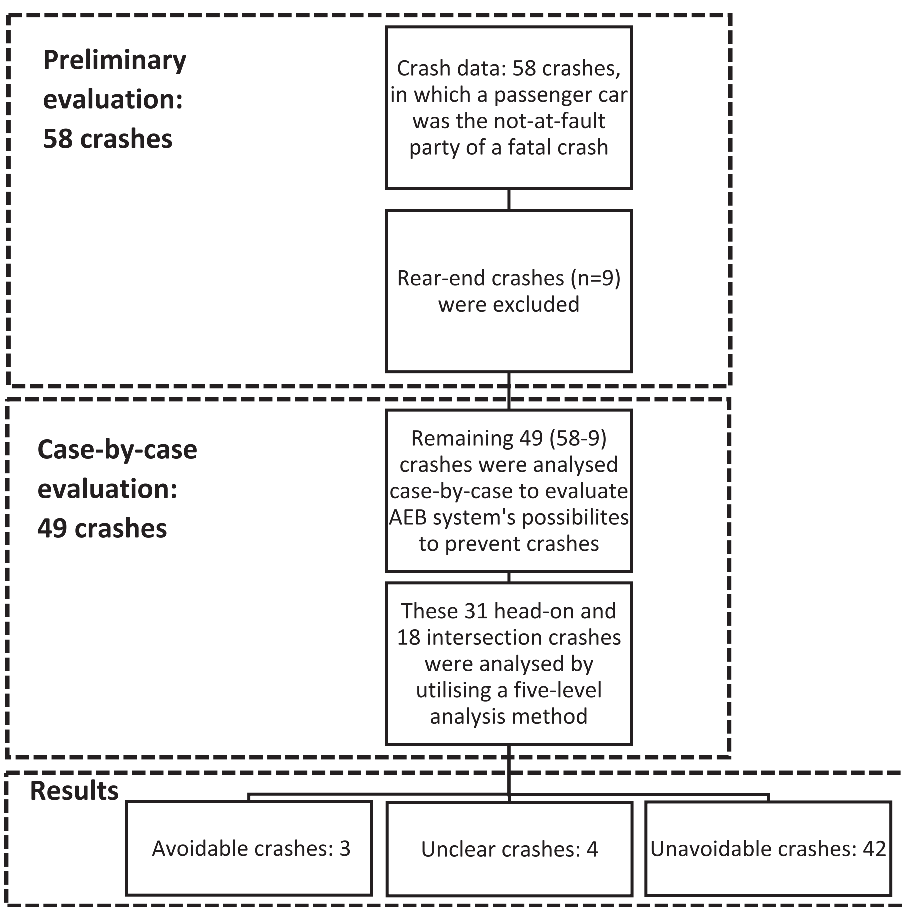

Fig. 1. Steps from a preliminary evaluation round to case-by-case evaluation.

Table 2
Avoidable, unclear and unavoidable crashes according to the case-by-case analysis.

	Head-on crashes	Intersection crashes	Rear-end crashes	Total
Avoidable	0	3	0	3
Unclear	4	0	0	4
Unavoidable	27	15	9	51
Total	31	18	9	58

evaluated as being potentially avoidable. In ten of the unavoidable cases (Level E) in which the AEB system would have activated, there was too little time to decelerate and avoid the fatal outcomes.

In total, 14 head-on crashes and three intersection crashes were evaluated at Level E because other crashes were excluded in Levels B-D or in the preliminary evaluation. In ten head-on crashes, the time leading up to the collision was evaluated to be less than 0.5 s and these crashes were evaluated as being unavoidable. In these crashes, the at-fault car's speed varied between 80 and 130 km/h, and in one crash the speed was 40 km/h. The not-at-fault party's speed ranged from 70 km/h to 105 km/h. In one case, the speed was 50 km/h. The remaining four head-on crashes where AEB could have been activated 0.5 s or more before the impact were evaluated as unclear cases.

Finally, three intersection crashes were assessed to be potentially preventable. In each of these cases, the AEB system could have operated for the maximum time ($t = 1.6$ s). Furthermore, two of these crashes were collisions with a crossing cyclist and one crash involved a pedestrian outside the limits of a pedestrian crossing.

4.3. Crash incidence

The crash rate of the unavoidable not-at-fault party crashes was 0.67–0.73 fatal crashes per billion kilometers and 14–15 fatal crashes per million registration years. The spread in the results depended on the number of the unsolved cases in the analysis, i.e. whether the four unclear cases were included in the "unavoidable" crashes or not. If the suicides (the at-fault driver committed suicide, $n = 3$) are omitted from the figures, the crash rates would be respectively 0.63–0.69 fatal crashes per billion kilometers and 13–14 fatal crashes per million registration years.

5. Discussion

Advanced driver assistance systems offer great potential for reducing the incidence of crashes caused by mistakes made by drivers of ADAS-equipped vehicles, but less is known about their potential to prevent crashes caused by the actions of others. In these cases, the driver of the ADAS-equipped vehicle is an innocent victim of somebody else's mistake. This study found that 51 of the analysed 58 not-at-fault fatal crashes could not have been avoided by ADAS, which highlights the fact that current active safety technology does not offer the secondary party victim much likelihood of avoiding these crashes. In addition, four of the remaining seven cases were assessed as unclear. The results of this study thus indicate that almost all not-at-fault fatal crashes are difficult to avoid.

Table 3
The number of causes of unavoidable crashes when only the highest level cause (only one cause per a case) is considered.

	The number of primary causes that would have prevented AEB's operation
Level A. Crash types that no system can address	9
Level B. Active drive input	16
Level C. Adverse weather or light conditions	11
Level D. Speed exceeds ODD	5
Level E. AEB cannot prevent fatal consequences due to insufficient time to activate the system	10
Total	51

5.1. Characteristics of the unavoidable crashes

The results showed that most ($n = 51$, 88%) of fatal not-at-fault party crashes of modern passenger cars were unavoidable even using state of the art safety technology. This differs significantly from similar at-fault fatal crashes: Koisaari et al. [7] found that only 67% of the at-fault fatal crashes were unavoidable using similar SAE level 2 safety technology. Thus, the crash rate of highly automated cars may noticeably higher than expected in mixed traffic phase due to the limited potential of automation to prevent not-at-fault party crashes.

As stated earlier, the behaviour of not-at-fault drivers differed notably from that of at-fault drivers. Not-at-fault drivers did not show the typical risk-taking behaviour of at-fault drivers but rather they reacted promptly when possible. In general, most of the studied crashes were such dynamic events that neither the driver nor the safety systems could react to prevent the crash or mitigate its consequences significantly. This is especially the case in head-on crashes, where there is usually very little time to react. Therefore, the development of the operation of AEB systems does not seem to make a notable contribution to safety. Instead, as we shift towards more automated vehicles, it would be more useful to develop ESA systems that can perform evasive actions to prevent not-at-fault parties from being involved in head-on crashes.

According to our analysis, the rear-end-crashes (Level A crashes, $n = 9$, 16%) were the most difficult for current safety systems to prevent. In most of these cases, the not-at-fault party car was turning left and it was stationary or travelling at low speed. The challenge with the rear-end-crashes was simply the fact there was no safety system designed to prevent them. Cicchino [4] has estimated that the combination of AEB and forward collision warning system (FCW) could actually increase the risk of being rear-ended due to an increase in hard-braking events.

Another group of crashes that were difficult to prevent was the Level B crashes ($n = 16$, 28%), i.e. crashes in which the driver was actively controlling the car before the crash. The issue here is that current safety systems possess a driver-override function which prevents the system operating if the driver provides active driving input. In the remaining crashes (Levels C-E, $n = 26$, 45%), the challenging kinematics and high impact energy were typically combined with adverse road or weather conditions. A northern feature of these crashes was the snow- or ice-covered roads that become very slippery when the temperature is near zero degrees Celsius.

5.2. Crash rate

The closest reference to our results regarding crash rate was the study of Koisaari et al. [7] which examined the most difficult at-fault crashes to avoid using current active safety technology. The results of the present study which focused on Finland in 2010–2017 showed that if suicides and sudden illness attacks were excluded, the incidence of "unavoidable" fatal crashes using current safety technology was higher among not-at-fault party crashes (0.63–0.69 fatal crashes per billion kilometers) than among primary party crashes (0.48–0.53). It should be noted that the present study included fatal crashes where a passenger car driver was the not-at-fault party of a crash and the car was registered as a new during the period 2010–2017. The analysed crash data represents 4% (63/1662) of all fatal crashes investigated in Finland in the study period.

The composition of traffic affected the results notably. The higher the exposure of vulnerable road users and risk-taking drivers is, the greater is the crash rate of fatal not-at-fault party crashes. Therefore, a similar study in another country could produce a noticeably different result.

5.3. Properties of the material and method

We studied exclusively in-depth investigated crashes, which gave us many advantages. First, there were usually multiple sources from which to obtain specific information, e.g. regarding timespans, distances and weather conditions. Secondly, we could exploit ready-made analyses such as reconstruction calculations, risk assessments and final reports of the crashes.

In addition, examining not-at-fault parties gave us the benefit that most of the drivers survived the crash. Hence, they could give first-hand information about the crash. However, this information suffers from the same subjectivity issues as all eyewitness statements.

Regarding the method, the main factors contributing to the results were the chosen reference technology and the case analysis method itself. Firstly, the obvious limitation associated with choosing a single vehicle brand to be the reference was that the results obtained from other reference technologies would be slightly different. In our case, one of the crashes could have been prevented if ESA had reacted not only to pedestrians but also to vehicles. However, according to the specification of our reference system, ESA reacted only to pedestrians.

The reliability of our analysis method varies in respect of the different groups of crashes. First, we were able to identify multiple crashes (e.g., nine rear-end crashes and five sudden illness attacks) that were completely outside the operational design domain of any available active safety device. Second, in two other crashes the not-at-fault party was actually fitted with the active safety system (AEB) which was the most suitable one to prevent such crashes. Thus, it was easy to conclude that in these two cases modern safety systems would not have been able to avoid the crash.

All in all, 49 fatal crashes proceeded to case-by-case evaluation. The remaining crashes were not as easy to assess since the analysis included uncertainties regarding the crash kinematics and driver behaviour. As usual, all presented velocities, distances and timespans included error and, e.g., it was almost impossible to assess the driver's response to the FCW if it had alerted the driver before the crash. The countering factor to these uncertainties was the fact that, usually, more than one adverse condition appeared simultaneously to hinder the operation of the safety systems. These conditions included short timespan from the safety-critical key event to the crash, high impact energies, slippery roads and poor visibility. In most cases this led to the conclusion that even though the safety system had operated, its impact on the fatal outcome would have been negligible.

6. Conclusions

Our research showed that most of the fatal not-at-fault party passenger car crashes studied would be unavoidable even for the current active safety systems up to SAE Level 2. In other words, these safety systems bring limited benefit to human drivers in helping them to avoid being a collision counterparty in a fatal crash caused by another road user. In contrast, other studies have shown promising results on the potential of ADAS in preventing driving errors of the at-fault drivers. The findings of this study call attention to the importance of passive safety features. Regardless of the level of automation, fatal crashes will continue to occur well into the future due to the risks posed by other road users. Therefore, other approaches and improvements, such as better road infrastructure (e.g., central barriers), should continue to be used and enhanced in the future, too.

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Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

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