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

Roni Utriainen* and Markus Pöllänen
Transport Research Centre Verne
Tampere University
P.O. Box 600
FI-33014 Tampere University, Finland
E-mail: roni.utriainen@tuni.fi
E-mail: markus.pollanen@tuni.fi
*Corresponding author

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

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

Biographical notes: Roni Utriainen received M.Sc. degree in civil engineering from Tampere University of Technology, Finland, in 2016. He is currently a Ph.D. student in transportation systems in Tampere University, Finland. In his Ph.D. research project, he studies potential safety effects of partially and highly automated vehicles in Finland. He also has other research and teaching responsibilities in Transport Research Centre Verne, Tampere University. Utriainen has published on automated vehicles' safety, cycling safety, serious traffic injuries and mobility as a service. He is a member of Finnish Crash Data Institute's expert group.

Markus Pöllänen received M.Sc. degree in industrial engineering and management from Tampere University of Technology, Finland, in 2001. He is currently a lecturer in transport systems and futures studies at Transport Research Centre Verne in Tampere University. He has been working on versatile research and educational activities throughout his career. With a wide field of interests, his current research relates mostly to futures of transport. His latest scientific publications discuss topics such as mobility as a service and attitudes on automated vehicles. Currently he is a member of Nordic Road Association's committee on traffic safety as well as road safety forum in Tampere region.

1. Introduction

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

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

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

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

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

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

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

2. Aim

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

3. Method and data

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

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

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

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

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

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

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

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

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

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

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

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

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

4. Results

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

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

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

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

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

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

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

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

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

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

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

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

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

5. Discussion

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

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

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

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

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

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

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

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

Table 6 Main assumptions and limitations in the study.

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

6. Conclusions

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

References

Cicchino, J. B. (2017) Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates, Accident Analysis and Prevention, 99, 142-152.

Dávideková, M., Greguš, M. (2017). Nice, Berlin, London – if every car had autonomous emergency braking system for forward collision avoidance. The 12th International Conference on Future Networks and Communications. Procedia Computer Science 110, 386-393.

Euro NCAP. (2018a) AEB cyclist. [online] www.euroncap.com/en/vehicle-safety/the-ratings-explained/vulnerable-road-user-vru-protection/aeb-cyclist/. Accessed 23.11.2018.

Euro NCAP (2018b). Autonomous emergency braking. [online] www.euroncap.com/en/vehicle-safety/the-rewards-explained/autonomous-emergency-braking/. Accessed 22.8.2018.

European Commission. (2018) Vehicle safety systems. Intelligent transport systems. [online] ec.europa.eu/transport/themes/its/road/application_areas/vehicle_safety_systems_lt. Accessed 27.4.2019.

European Commission. (2019) Road safety: Commission welcomes agreement on new EU rules to help save lives. [online] http://europa.eu/rapid/press-release_IP-19-1793_en.htm. Accessed 20.5.2019.

Fildes, B., Keall, M., Bos, N., Lie, A., Page, Y., Pastor, C., Pennisi, L., Rizzi, M., Thomas, P., Tingvall, C. (2015) Effectiveness of low speed autonomous emergency braking in real-world rear-end crashes, Accident Analysis and Prevention, 81, 24-29.

Glassbrenner, D., Morgan, A., Kreeb, R., Svenson, A., Liddell, H., Barickman, F. (2017) A target population for automatic emergency braking in heavy vehicles, U.S. Department of Transportation, National Highway Traffic Safety Administration, p. 54.

Haus, S., Sherony, R., Gabler, H. (2019) Estimated benefit of automated emergency braking systems for vehicle–pedestrian crashes in the United States. Traffic Injury Prevention, 20, 171-176.

Isaksson-Hellman, I., Lindman, M. (2016) Using insurance claims data to evaluate the collision-avoidance and crash-mitigating effects of collision warning and brake support combined with adaptive cruise control, IEEE Intelligent Vehicles Symposium, Gothenburg, Sweden.

Kitajima, S., Shimono, K., Tajima, J., Antona-Makoshi, J., Uchida, N. (2019) Multi-agent traffic simulations to estimate the impact of automated technologies on safety. Traffic Injury Prevention, 20, 58-64.

Kusano, K. D., Gabler, H. (2011) Method for estimating time to collision at braking in real-world, lead vehicle stopped rear-end crashes for use in pre-crash system design, SAE International.

Li, Y., Li, Z., Wang, H., Wang, W., Xing, L. (2017) Evaluating the safety impact of adaptive cruise control in traffic oscillations on freeways, Accident Analysis and Prevention, 104, 137-145.

Lubbe, N., Kullgren, A. (2015) Assessment of integrated pedestrian protection systems with forward collision warning and automated emergency braking, International research council on biomechanics of injury, Lyon, France.

NHTSA. (2011) Advanced crash avoidance technologies program – Final report of the Honda-DRI team, U.S. Department of Transportation.

Noy, I. Y., Shinar, D., Horrey, W. J. (2018) Automated driving: Safety blind spots, Safety Science, 102, 68-78.

Rizzi, M., Kullgren, A., Tingvall, C. (2014) Injury crash reduction of low-speed autonomous emergency braking (AEB) on passenger cars, IRCOBI conference.

Sander, U. (2017) Opportunities and limitations for intersection collision intervention – A study of real world ‘left turn across path’ accidents, Accident Analysis and Prevention, 99, 342-355.

Sander, U., Lubbe, N. (2018) Market penetration of intersection AEB: Characterizing avoided and residual straight crossing path accidents. Accident Analysis and Prevention, 115, 178-188.

Savino, G. (2016) ABRAM, Autonomous braking for motorcycles, European Commission.

Silla, A., Leden, L., Rämä, P., Scholliers, J., Van Noort, M., Bell, D. (2017) Can cyclist safety be improved with intelligent transport systems? Accident Analysis and Prevention, 105, 134-145.

Tan, H., Zhao, F., Hao, H., Liu, Z., Amer, A.A., Babiker, H. (2020). Automatic emergency braking (AEB) system impact on fatality and injury reduction in China. International Journal of Environmental Research and Public Health, 17, 917.

Tervonen, J. (2016) Tieliikenteen onnettomuuskustannusten tarkistaminen. Kuolemat sekä vakavat ja lievät loukkaantumiset [Revision of road traffic accident costs. Fatalities and serious and slight Injuries], Finnish Transport Safety Agency research reports.

Tiwari, G. (2018) Safety of ‘the vulnerable road users’: current challenges and need for a new approach, International Journal of Injury Control and Safety Promotion, 25, 1-2.