

AN ASSESSEMENT APPROACH TO ASSISTED DRIVING SYSTEMS

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ABSTRACT

An increasing number of vehicles on the global market provide Assisted Driving technology, also referred to as SAE Level 2 partial automation, providing the opportunity for increased driver and road safety. It is the next step towards automated vehicles. To ensure its safety benefits consumers need to be aware and informed about the capabilities of these systems. With these systems being at the cutting edge of modern vehicle technology only limited vehicles currently have these systems fitted, although they are slowly being installed into lower priced mass-produced vehicles, and therefore few consumers have experience or know of the capability of these systems.

This paper investigates a way of assessing the driver support capabilities and HMI of vehicles with Assisted Driving systems to provide information of how the systems cope in different everyday scenarios which they may encounter. This paper outlines the development process of these assessments through both desk-based literature considerations and on track testing methods. Ten different vehicles were put through the assessment process to prove out the test method and offer information on the abilities of various systems. The vehicles are all produced by different manufacturers and range from cheaper less capable to higher end advanced systems with the purpose of showing that within Assisted Driving systems there is vast difference in the performance outcome in both everyday driving and safety critical situations. The assessment of the systems will allow for a basis which will be expanded on for greater in-depth evaluation into the overall safety of the systems and ultimately the assessment of automated vehicles.

The assessment protocol has been developed in agreement with Euro NCAP for the evaluation of ten production vehicles available to buy late 2018, looking into developing the protocol for future testing and grading of new vehicles to be released with Assisted Driving technology.

INTRODUCTION

Latest advances in Advanced Driver Assistance System (ADAS) technology implemented on modern vehicles has seen the introduction of Assisted Driving technology, also referred to as SAE Level 2 partial automation. Assisted Driving provides braking and acceleration control in combination with a steering support function that assists with keeping the vehicle in the driving lane. To achieve this systems use a combination of radar, lidar and camera sensors fitted variously at the front, rear, sides, corners and windscreen of the vehicle to monitor the driving environment and immediate traffic. These functions allow for simultaneous longitudinal and lateral control support, facilitating potentially reduced driver workload and an associated road safety benefit.

Currently no defined assessment protocols exist for Assisted Driving systems and systems developed to date have evolved with notable differences between the technical solutions implemented by various vehicle manufacturers. This has caused differing functionality, performance and Human Machine Interaction (HMI) designs for vehicles fitted with Assisted Driving systems, with the potential to confuse drivers. If a vehicle equipped with Assisted Driving technology is used correctly and the driver works in collaboration with the system, then there is the potential for improved vehicle and road safety. However, if the consumer is uninformed regarding the capability of the system that their vehicle is equipped with then those safety benefits maybe lost in over reliance on the system by the driver, or the driver not having the confidence in using the system and never activating it.

Assisted Driving system functionality that is anticipated to be of benefit to road safety given the effects in regular driving include:

- 1) Headway maintenance: Adaptive Cruise Control (ACC) operates to maintain speed or a set headway to traffic ahead, the shortest setting of which is typically greater than maintained by drivers in regular driving.
- 2) Lane guidance: helps maintain the vehicle within the lane, reducing the possibility of drifting into oncoming or overtaking traffic or running off the road.
- 3) Reduced driver workload: assistance with controlling the vehicle has the potential to reduce driver fatigue through supporting the actions required.

For safe and effective Assisted Driving there is the need to strike a balance regarding the level of assistance provided to deliver a perceivable benefit whilst ensuring the driver remains engaged with the driving task, and not relying on driver monitoring systems to force the driver to pay attention. Studies show that if the system effectively performs fully effective Object and Event Detection and Response (OEDR) drivers can develop over-trust in its capability and fall out-of-the-loop^[3]. As a result, if the vehicle enters a situation the system is unable to manage, and the driver is not attentive to identify the developing situation, there is an increased risk of collision. This also works in the opposite way in that if the system is not very capable the driver is less likely to use the system and not gain the additional safety benefits. **Error! Reference source not found.** represents this 'irony of automation' in graphical form.

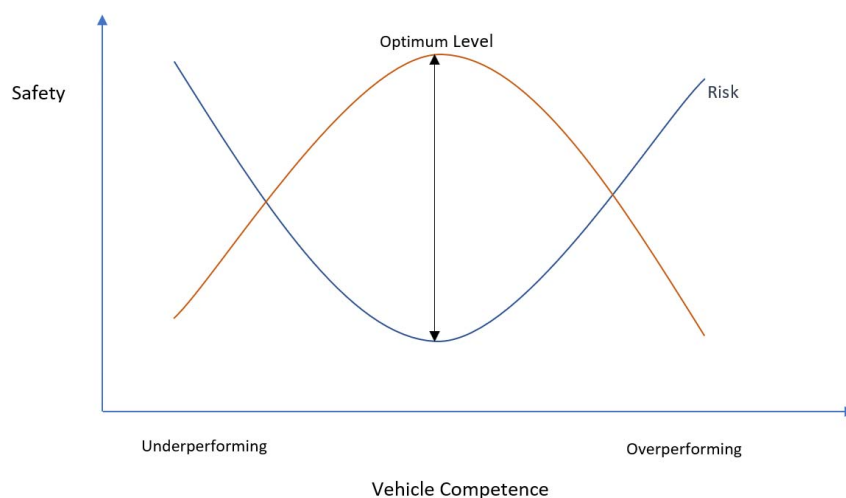


Figure 1. Assisted Driving – safety against vehicle competency

AIM

The aim of this research is to develop an assessment protocol for evaluating Assisted Driving technology that provides a means of considering the system naming and associated literature and testing the system for safety in an objective and repeatable format. It will provide the consumer with information describing the system capability, performance and limitations in typical real world driving scenarios and emergency situations, helping the consumer to understand the system and use it effectively and responsibly to the benefit of road safety. Ultimately the assessment protocol will develop into a consumer grading scheme for Assisted Driving safety.

METHOD

In the absence of any proposals or formalised procedures for assessing Assisted Driving systems the ‘Assisted and Automated Driving Technical Assessment1’^[1] was used as a basis to create initial assessment criteria. Within the literature the criteria for Assisted Driving is outlined under ten headings of:

- 1) Naming
- 2) Law abiding
- 3) Design domain
- 4) Status
- 5) Capability
- 6) Driver monitoring
- 7) Safe stop
- 8) Crash intervention
- 9) Back-up systems
- 10) Accident data

For developing the assessment, the criteria were regrouped because of the nature of their complementary content to desk-based literature review and track-based testing.

Literature Review

The literature associated with a vehicle’s Assisted Driving system, such as online promotional material, operational tutorials and the vehicle handbook etc. can influence a driver’s anticipation of the capabilities of the system, how it will perform and what their role and responsibilities are whilst using the system^[4]. Assessment commences by reviewing the literature accompanying the vehicle describing the system to gather information on the functionality, performance, limitations and driver responsibility. The information therefore needs to be clear and accurate. The following is assessed:

- The naming of the system: it should not specify or suggest automation. The source material should not imply self-driving or automation.
- Capability and limitations: a description of how the driver can expect the system to function and any situations in which the system is limited or unable to perform.
- Operational environment: whether functions are generally available or limited to specified design domains e.g. highways.
- Initial operation: whether a quick start operational guide is provided to explain the system.

Track Testing

To assess the safety aspect of the Assisted Driving system it must be presented with typical the real-world driving situations that can be readily expected to be encountered on the public road. However, to ensure a safe environment and achieve repeatable testing this activity must be performed within the confines of a controlled test track. Vehicles are assessed in the following scenarios.

Longitudinal testing The current Euro NCAP AEB test protocol scenarios were used as a basis for testing the longitudinal capabilities of the ACC system replicating the case where a lead vehicle is directly ahead in lane on a straight section of road. Speeds were increased to those typically encountered on highways (130km/h) because this is the environment in which current systems are recommended for operation.

ACC Test Scenarios:
CCRs: 50 to 130km/h (10km/h increments)

CCRm: VUT 80 to 130km/h
Target 20km/h & 60km/h

CCRb @ -4m/s^2 : VUT 55km/h
Target 50km/h

In addition to these in-line traffic scenarios additional lane changing tests based on a typical highway manoeuvres were included. The first is where a slower moving vehicle cuts in ahead from an adjacent lane. A second is a vehicle in front changes lanes into an adjacent lane revealing a stationary vehicle ahead in lane. These two tests were named as cut-in & cut-out scenarios as shown in Figure 2 & Figure 3.

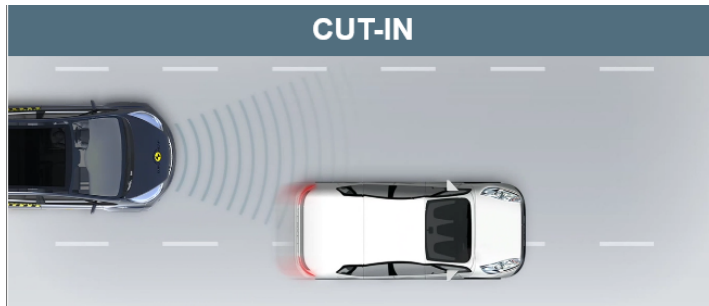


Figure 2. Cut-in test scenario

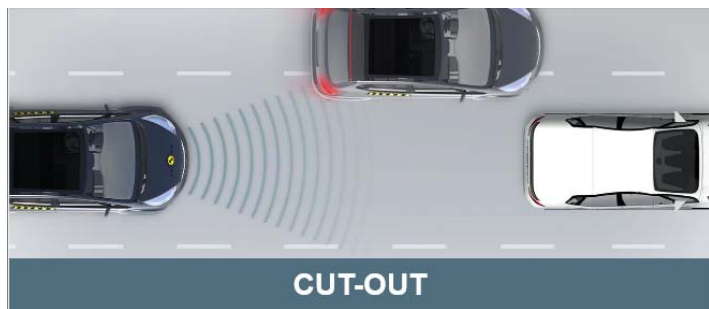


Figure 3. Cut-out test scenario

Cut-in @ TTC -1.5: VUT 50km/h
Target 10km/h
Cut-in @ TTC 0.5: VUT 130km/h
Target 80km/h

Cut-out @ TTC 2.0: VUT 70km/h
Target 50km/h

Cut-out @ TTC 2.0: VUT 90km/h
Target 80km/h

All tests are performed with the ACC set to the nearest following setting.

The test target specified for use is the Global Vehicle Target (GVT) impactable 3D car target according to ISO 19602 Part 1 (see Figure 4). This document specifies the properties of an omni-directional multipurpose vehicle target that will allow it to represent a passenger vehicle in terms of size, shape and sensor attributes for testing purposes.



Figure 4. Global Vehicle Target (GVT) according to ISO 19602 Part 1

Lateral testing Testing the lateral control of an Assisted Driving system involves testing the lane guidance system relative to a marked lane and the interactivity of the steering system in response to driver steering inputs.

The capability of the steering system is evaluated by driving along a straight section of lane markings that transition into a curve to the left immediately followed by a curve to the right, a so-called ‘s bend’ (**Error! Reference source not found.**5). This configuration was selected because it investigated not only the ability of the system to steer into a curve, but also transition between curves in alternate directions as often encountered on the public road.

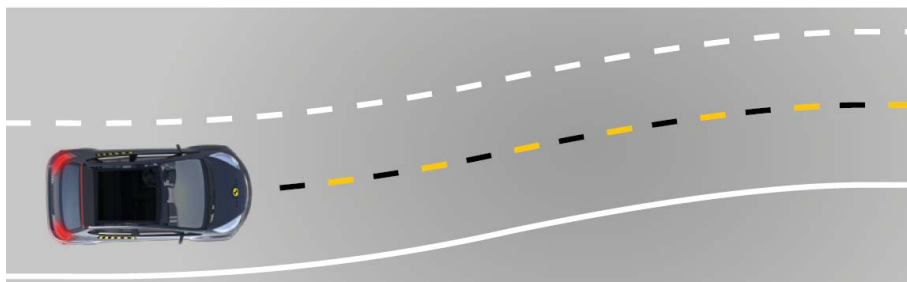


Figure 5. S-Bend test scenario

S-Bend dimensions:

- Left turn radius 900m at 6° angle
- Right turn radius 500m at 6° angle

The S-bend test is performed at increasing speeds from 40mph up to 75mph in 5mph increments.

The test is used to identify the overall level of assistance the vehicle provides driving through the layout. It is considered appropriate that an Assisted Driving system should support the steering through the curves acknowledging necessary directional changes but not necessarily perform complete guidance centering the vehicle in lane throughout the entire manoeuvre. Such authority would infer more automated-like control leaving little for the driver to contribute, potentially affecting perception of the system and ultimately their engagement with the driving

Assessing the driver interactivity with the steering system is performed by investigating the change steering effort required to alter the position of the vehicle within the lane sideways by 0.5m during normal manual driving compared to when the Assisted Driving system activated. The response of the Assisted Driving system to driver inputs is also monitored i.e. does the system shut down or will it tolerate driver inputs and continue to operate. An example of this manoeuvre is avoiding an object, such as a pot hole, within a lane, as shown in Figure 6 below.

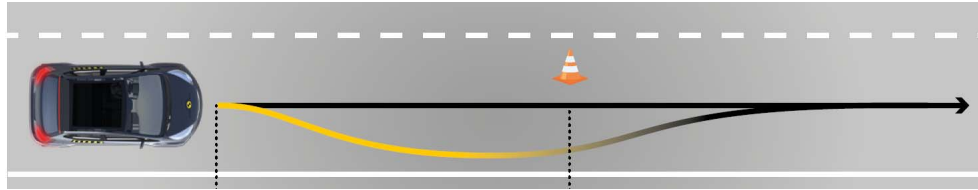


Figure 6. Driver interactivity test scenario

This test is performed with a driving robot following a defined path and investigating the steering torque required for each testing configuration. The baseline reference measurement is then compared with the Assisted Driving measurement to identify the change in steering torque profile throughout the manoeuvre.

Driver inactivity escalation By law Assisted Driving systems must incorporate a means of providing a timely audio-visual warning escalation and ultimately cease assistance in case continuous driver inactivity is detected. However what action to take when ceasing assistance if the driver fails to respond is not specified. Testing is undertaken to investigate the various strategies implemented.

TEST FLEET

A range of ten vehicles equipped with Assisted Driving systems from different manufacturer were assessed. These include:

- 1) Audi A6
- 2) BMW 5 Series
- 3) DS7 Crossback
- 4) Ford Focus
- 5) Hyundai NEXO
- 6) Mercedes-Benz C-Class
- 7) Nissan Leaf
- 8) Tesla Model S (v8.1 software)
- 9) Toyota Corolla
- 10) Volvo V60

RESULTS

Assessing a broad range of state-of-the-art production systems identified the breadth of Assisted Driving capability currently available on the market. A summary of the results of all ten vehicles tested was published in October 2018 on the Euro NCAP website ^[2]. A subset of key results identifying differences between the vehicles tested is presented.

Literature Review

The literature review of promotional material identified that the vehicle manufacturer Assisted Driving system naming conventions were split with five incorporating appropriate ‘assist’ terminology (Audi, BMW, Hyundai, Mercedes-Benz and Volvo), four using inappropriate ‘pilot’ terminology suggesting automation (DS, Ford, Nissan and Tesla), otherwise non-descript terms were used (Toyota). Only two cases of notably inappropriate promotional material were identified from Tesla and BMW, promoting full self-driving capability with respect to future developments and showing hands-off driving respectively.

All the vehicle handbooks included information advising that the Assisted Driving system was a driver support function and that the driver retained full responsibility for the safe driving of the vehicle. The majority identified that the Assisted Driving system was intended for use on highways and all listed various performance and operational limitations regarding the road and traffic situations.

Track Testing

Longitudinal control The Tesla Model S stands out by stopping for the stationary target in lane ahead deploying comfort braking by ACC system throughout the entire speed range tested up to 130km/h. Whereas, for example, in the same test the Audi A6 test avoids up to 70km/h using the ACC system, 70 to 100km/h

avoids using emergency intervention by AEB or FCW, and mitigates the collision speed between 100 to 130km/h.

Generally, the longitudinal control in all vehicles tested performed more effectively at higher speeds when approaching the slow-moving vehicle compared to when approaching the stationary vehicle. It is understood that is because of the confidence of identifying and classifying a moving vehicle compared to a static vehicle.

The highly dynamic cut-in and cut-out scenarios challenged all vehicles. In the cut-in scenario four vehicles issued a late collision warning that was insufficient to respond to for avoiding the collision. In the cut-out scenario one vehicle managed to avoid a collision by emergency intervention, six provided a late collision warning and three did not respond at all.

Lateral control The capability of the steering systems also showed demonstrable differences in performance driving through the ‘s-bend’. For example, Tesla Model S navigates the curves remaining centred in the lane throughout the entire manoeuvre at all speeds tested, whereas the Volvo V60 would steer in lane through the initial left turn and attempt to turn in the opposite direction to the right but start to drift out of lane in the transition to the right turn, especially at higher speeds. This is shown in Figure 7 & Figure 8 below.

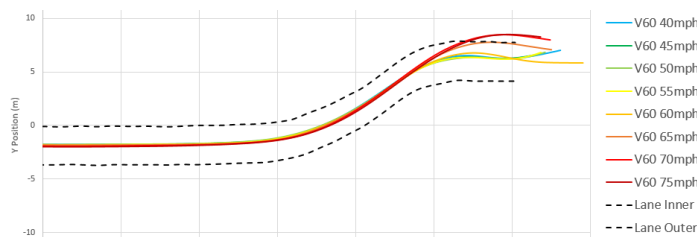


Figure 7. Volvo V60 S-Bend results

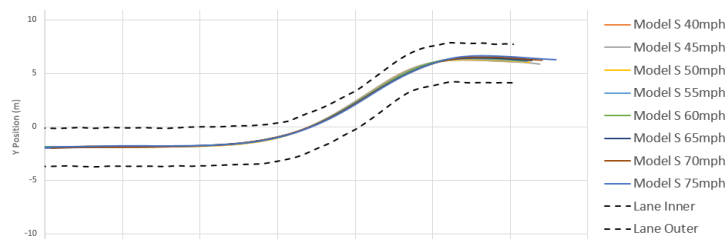


Figure 8. Tesla Model S S-Bend results

The Tesla Model S demonstrated a high degree of steering authority navigating the ‘s-bend’, and this is also identified in the steering interactivity test. The Tesla has the greatest peak proportional increase in steering torque of all ten test vehicles, as shown in Figure 9.

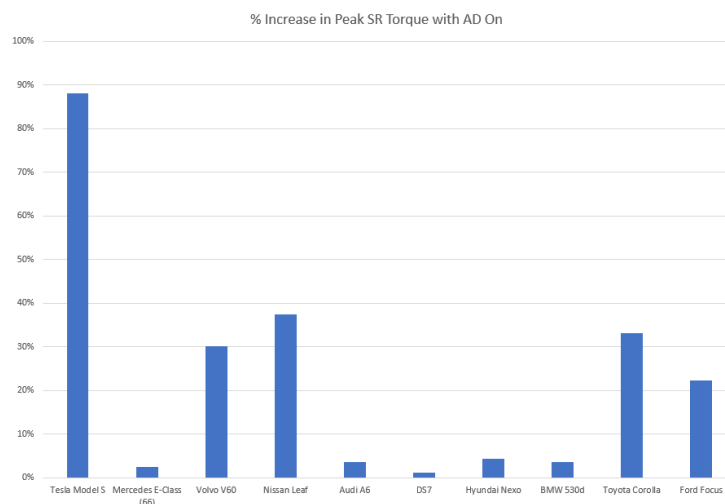


Figure 9. Percentage of steering torque increase during driver interactions test

With the Assisted Driving system active the peak steering torque required to alter the vehicle position within the lane almost doubled compared to that during normal driving. Comparatively the Mercedes, Audi, DS, Hyundai and BMW vehicles demonstrated only modest increases in peak steering torque of less than five per cent. Additionally, the Tesla was the only steering assistance system to completely disengage in response to the driver input with no further operation until the driver reactivates the system. All other systems either continued to provide lane guidance support throughout the manoeuvre or were suspended whilst the steering input was applied and then automatically resumed shortly after the vehicle returned to the centre of the lane.

Driver inactivity escalation Various solutions have been implemented in current production vehicles regarding the action taken if the driver fails to respond to an inactivity warning. This ranges from simply ceasing to provide steering support whilst maintaining ACC speed control, to maintaining steering support and bringing the vehicle to a controlled stop in lane, activating the hazard warning lights and initiating an emergency eCall.

The testing identified that five of the vehicles ceased to provide steering assistance and five came to a controlled stop in lane. Figure 10 is an example of the Nissan Leaf escalating the warnings before beginning a controlled stop after 30 seconds of driver inactivity.



Figure 10. Example of driver disengagement procedure on Nissan Leaf

LIMITATIONS

The tests presented are a first step in assessing Assisted Driving systems and as such are limited to a handful of simplistic, repeatable track tests. However, on the public road drivers, and therefore Assisted Driving systems, encounter a wide variety of road and traffic situations on every journey, not to mentioned changes in lighting and weather conditions etc. Therefore, to develop a meaningful grading scheme a wider range of assessment must be undertaken to inform drivers on the relative merits of the various systems. It would also serve to inform drivers on the limitations of systems thus reinforcing the requirement for them to always remain engaged and vigilant and be prepared to take full manual control of the vehicle. Some examples are discussed below.

Road Environment

Assisted Driving systems have demonstrated a level of competency at managing interactions with other traffic straight ahead in the assessments presented. It has been identified that in a similar traffic situation on a curve system performance can deteriorate substantially with apparently minor changes in the boundary conditions from the driving point of view. To assess this the CCRm & CCRs tests can be performed around the s-bend, at the same speeds, as show in Figure 11.

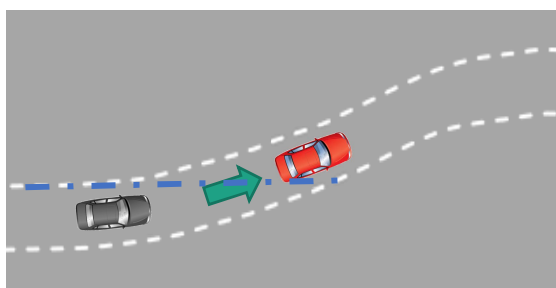


Figure 11. Target vehicle placed within a bend scenario

Vulnerable Road Users

Vulnerable Road Users (VRUs), such as pedestrians and cyclist, frequent roads in which Assisted Driving systems are available to use. The assessments presented are focussed towards highway driving using the GVT to represent other vehicular traffic, however VRUs may also be present if, for example, a traffic queue assist function was used in an urban area. The current AEB VRU test scenarios could be implemented for pedestrians crossing between stop-start queueing vehicles or for cyclists riding in line with the traffic to demonstrate performance or limitations.



Figure 12. Example of ACC longitudinal VRU test scenario

Weather and Lighting

The tests presented are all performed under good testing conditions to achieve repeatability, namely daylight, clear visibility, no precipitation falling etc. Real world experience has highlighted that Assisted Driving system performance can deteriorate in less optimal conditions such as darkness or poor weather conditions. Testing could be considered under these conditions to illustrate the effects to drivers.

Sensor Issues

The sensors used to enable Assisted Driving technology are necessarily positioned towards the perimeter of the vehicle structure to provide a clear view of the surroundings. However, this also makes them susceptible to fouling and damage. Exploratory testing has identified that whilst some systems advise of the need for maintenance almost immediately in case of a sensor blocking issue, others continue to apparently operate for extended periods of time without the driver being advised of a degradation in their functionality and system performance e.g. ACC reverting to normal cruise control.

CONCLUSIONS

Assisted Driving systems are already available in a wide range of vehicles and are rapidly being introduced into mass market affordable vehicles. The combination of lateral and longitudinal assistance, when used responsibly by the driver, could benefit road safety through improved headway, lane positioning and reduced driver fatigue through being supported with the driving task.

The literature review of promotional material identified that the vehicle manufacturer Assisted Driving system naming conventions were split between appropriate and inappropriate terms and only two cases of notably inappropriate promotional material were identified. All the vehicle handbooks included information advising that the Assisted Driving system was a driver support function and that the driver retained full responsibility for the safe driving of the vehicle.

The track tests developed for assessing Assisted Driving systems evaluating longitudinal control, lateral support and driver interactivity proved effective at identifying differences in functionality and performance between vehicles. However, it is acknowledged that the tests themselves are a simplistic representation of typical scenarios encountered in real world driving. A future grading scheme would require a broader range of scenarios to be considered to achieve a more representative grading and illustration of system functionality and limitations. Similarly, the testing was performed under a limited set of controlled conditions necessary to

achieve repeatability. Real-world driving conditions vary substantially, and a more representative assessment could be achieved by considering additional factors e.g. driving in darkness.

This initial assessment of ten production vehicles has identified that there is a range of functionality and performance differences between Assisted Driving systems. Some systems portray a high degree of driving competence in response to the lane geometry and interactions with other traffic whilst others offer more modest performance. For example, the Tesla Model S stood out in CCRs test by coming to a halt behind the stationary target at all speeds up to 130km/h using comfort braking only whereas all other vehicles tested either failed to acknowledge the stationary vehicle at higher speeds or only achieved collision mitigation by emergency response.

The Tesla was also the only vehicle to navigate the 's bend' curves remaining centred in the lane throughout the entire manoeuvre at all speeds tested, however it also demonstrated the highest proportional increase in peak steering effort in the driver interactivity tests and subsequently steering support was disengaged whereas all other systems continued to operate after returning to the central lane position. The highly dynamic cut-in and cut-out scenarios challenged all vehicles and little meaningful intervention was identified except for in one vehicle.

Various solutions have been implemented in current production vehicles regarding the action if the driver fails to respond to an inactivity warning ranging from simply ceasing to provide steering support whilst maintaining ACC speed control, to maintaining steering support and bringing the vehicle to a controlled stop in lane.

For safe and effective Assisted Driving there is the need to strike a balance regarding the level of assistance provided to deliver a perceivable benefit whilst ensuring the driver remains engaged with the driving task, and not relying on driver monitoring systems to force the driver to pay attention. The next step is to develop the testing and an associated grading scheme to enable the evaluation of system performance and drive best practice to achieve the road safety benefits associated with Assisted Driving technology maintaining headway, improving lane guidance and reducing driver workload and associated fatigue.

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ASSESSING THE CASE FOR REQUIRING AEB ON CITY BUSES AND DEVELOPING TECHNICAL REQUIREMENTS AND TEST PROCEDURES

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ABSTRACT

In London, around two-thirds of those killed in collisions involving a bus are pedestrians and most of these are killed crossing the road. The time between the pedestrian first being recognisable as a threat and the moment of impact is usually less than 2 seconds. Human drivers have very limited opportunity to avoid the collision. Automated Emergency Braking (AEB) has been developed to avoid such collisions and is becoming widespread on passenger cars. However, city buses pose a unique additional challenge. Bus operations already generate a significant quantity of non-collision injuries because passengers fall during normal operation. This includes when standing, or seated but unrestrained, passengers fall under braking. Automated brake applications where deceleration exceeds what a human driver would have applied increases this existing injury risk.

The research was sponsored by Transport for London (TfL) and aimed to quantify this balance of opportunity versus risk, and generate technical requirements allowing them to encourage or mandate AEB on their London bus fleet. The work involved:

- Traditional collision data analysis
- Case by case review of both collision and non-collision incidents recorded by CCTV systems provided by a London bus operator
- A road trial involving an AEB-equipped bus
- AEB Performance tests on a closed test track.

Up to around 25% of bus-pedestrian fatalities could be prevented. In true positive situations, any additional risk to bus occupants was small. Human drivers rarely failed to brake in collisions with pedestrians, they just braked too late to avoid collision. Earlier intervention would mean that in some cases AEB could achieve avoidance with lower deceleration than the driver actually applied. In others, only a small increase was required.

False positives always create additional risks. The extent of the risk was strongly related to the level of deceleration and increased very substantially at 6 m/s² or above in the modelling. The net balance was a likely increase in slightly injured casualties but a substantial decrease in deaths and serious injuries.

Technical requirements were developed based on adaptations of the Euro NCAP standards with two false positive tests added to discourage systems that were inadequately tuned.

The analysis is strongly dependent on the rate of brake applications in service at different deceleration levels, the number of bus occupant injuries that occur at those levels and the decelerations achieved during an AEB false positive event, which is often of very short duration. Larger scale in-service trials would help to quantify these parameters more robustly.

Despite some risks, overall AEB would have strong safety potential on city buses and can be encouraged through TfL's bus safety standard in co-operation with manufacturers and researchers to mitigate risks as far as possible.

INTRODUCTION

In London, around two-thirds of those killed in collisions involving a bus are pedestrians and most of these are killed crossing the road. In these fatal cases, the time between the pedestrian first being recognisable as a threat and the moment of impact is usually less than 2 seconds. Human drivers have very limited opportunity to avoid the collision.

Advanced Emergency Braking (AEB) is a system that uses forward looking sensors such as Lidar, Radar, Camera, or combinations of more than one sensor, to identify a risk of an imminent collision. It will typically first warn the driver of the risk and, if the driver does not act, then it will apply braking automatically to avoid the collision or to reduce the collision speed and therefore the potential for injury.

AEB systems have been developed to avoid certain types of car, pedestrian and cyclist collisions and is becoming widespread on passenger cars. However, city buses pose a unique additional challenge. Bus operations already generate a significant quantity of non-collision injuries because passengers fall or sway during normal operation. This includes when standing, or seated but unrestrained, passengers fall under heavy braking. Automated brake applications where deceleration exceeds what a human driver would have applied will, therefore, create additional injury risk.

The research was sponsored by Transport for London (TfL) and aimed to quantify this balance of opportunity for the prevention of serious injury, particularly to pedestrians, versus the risk of an increased incidence of falls among bus occupants. The research was also intended to develop technical requirements allowing TfL to specify the fitment of appropriate AEB on their London bus fleet.

DATA SOURCES

Collision Data Analysis

A sample of 48 police fatal collision reports where London buses were involved, previously compiled by (Edwards, et al., 2017), were analysed to provide detailed information about the circumstances of fatalities arising from collisions with a bus.

Additionally, Transport for London's Incident Reporting and Investigation System (IRIS) database was analysed to identify collision incidents, in which someone on board the bus had been injured, and non-collision incidents where injuries had been caused by a slip, trip or fall during normal operation.

These data were supplemented by a sample of mainly lower severity incidents obtained from a review of the CCTV incident records of one bus operator. The CCTV footage included an overlay of some telematics data allowing the timing and magnitude of any driver or passenger actions to be identified (e.g. brake pedal application and x/y acceleration). The ability of the CCTV data to define the moment the pedestrian became recognisable as a threat, the moment the driver braked, and the amount of braking applied, was a major advantage over many other studies that have relied only on approximations and judgement from traditional collision reconstruction.

Track Tests

Two sets of track tests were completed. Firstly, the authors were not aware of any production AEB system fitted to a city bus and only one production AEB system fitted to an HGV that was sensitive to collisions involving pedestrians. It was known from the development of pedestrian AEB for passenger cars that the ability to apply the brakes hard and quickly was important to the potential casualty savings. It is well documented that commercial vehicle air brakes combined with commercial tyres could lead to slower brake build up times and lower peak acceleration potential than for passenger cars. Given this lack of existing information about the likely performance of AEB fitted to buses, independent testing of a system was considered necessary to establish the potential. At the time, Alexander Dennis buses was part-way through the development of an AEB system sensitive to front to rear, pedestrian and cyclists and agreed to provide a prototype vehicle for the test work and to provide technical support, allowing the project team some insight into the details of what the sensor system saw and reacted to.

The Euro NCAP AEB VRU 2018 protocol was selected as the basis for the evaluation testing because it provided the greatest coverage of the relevant test conditions required for a city bus, e.g. pedestrian and cyclist manoeuvres.

Later in the project additional track tests were also undertaken to evaluate two false positive scenarios that were under consideration for inclusion in the final technical requirements based on the false positive scenarios identified during the road trial, and to validate the test protocol defined for true positive testing.

Road Trial

The main objective of the road trial was to characterise the type of false activations that occur during normal driving to support the development of suitable false positive tests within the technical requirements. It should be noted that the prototype system had not, at that stage of development, undergone any tuning to eliminate false positives. It was, therefore, expected that substantial numbers of false positives would occur, and the system cannot be considered representative of what is expected of the fully developed system. However, it could be considered representative of an under-developed system that any technical specification should aim to prevent entering service. A secondary objective was to gather data on the frequency and magnitude of typical brake activations during normal service.

A single decker bus of similar type and construction to that which is typically used in London was used for the road trial. The vehicle was equipped with the prototype AEB system that was set-up to operate in an open loop or “Shadow Mode” – whereby it was actively monitoring the road environment, processing data and making decisions on warning and brake action, but the output signals were not connected to the normal bus controls so that no automated braking could take place. Thus, the control of the vehicle remained fully with the driver. The manufacturer recorded data from the AEB sensors/systems and, within commercial constraints, non-sensitive data was shared with the project team. In addition to this, independent data was recorded and overlaid onto a video that was synchronised to four cameras, as shown in Figure 1, below.

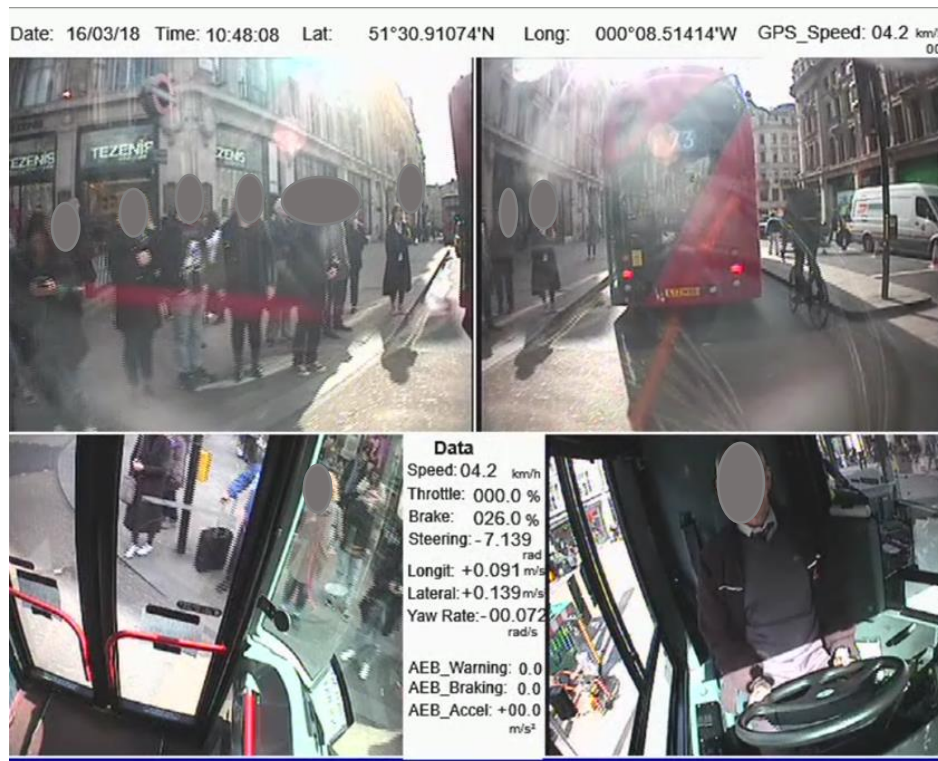


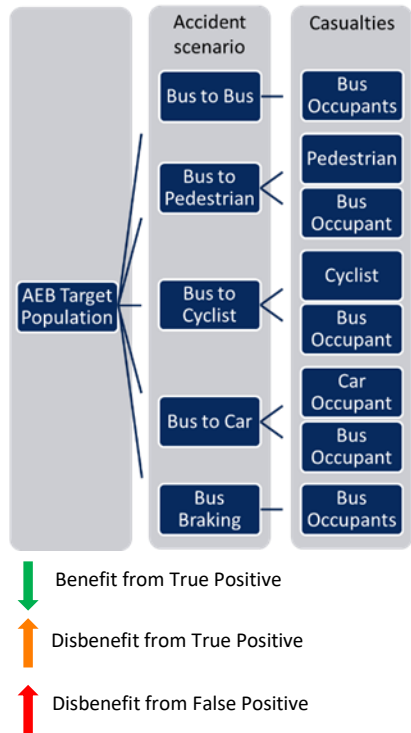
Figure 1: Example of video and data collection during the road trial

Although the bus was not in service during the trial, official London bus routes were followed, driven by drivers from the bus companies operating those routes and familiar with them, and the drivers were instructed to pull into bus stops and bring the vehicle to a stop as they would under normal operation.

Six different drivers drove the vehicle a total of 399km during a one-week road trial, covering five different routes. The routes selected included the wide range of bus driving environments likely to be encountered in service in London, while still being broadly representative of the most common routes and situations. They had been chosen partly based on including routes with both high and low casualty rates per km, as well as practical constraints in terms of ensuring support from the operators of those routes.

METHODOLOGY

The analysis was structured to consider the effects of true positive and false positive activations, as illustrated by Figure 2. For True Positive scenarios, AEB could potentially activate in different types of collision; offering a



casualty saving by avoiding or mitigating the severity of a collision but also potentially risking an increase in the frequency or severity of injury to bus occupants due to falls. The STATS19 database, the bus fatal database and CCTV footage from a bus operator were used alongside data compiled within the system verification and road trial parts of this project to estimate the likely effects on casualty numbers as a result of fitting AEB.

False Positive incidents represent cases in which the AEB system activates when it should not have done so. The effect of such incidents was estimated by analysing the typical bus occupant injury outcome of non-collision incidents caused by vehicle braking (road trial, IRIS data and operator CCTV data) and the magnitude of acceleration applied in false positive activations (road and track trials).

The true positive benefit of the system was evaluated on a case by case basis across the samples of police fatal and operator CCTV data available, using reconstruction, calculations and engineering judgments to assess whether the system was likely to have avoided the collision or reduced the impact speed. It was assumed that the above samples were broadly representative of Britain's official Road Accident Statistics (STATS19) data set within the Greater London Area. Therefore, the estimated effect identified in those samples was applied to a similar data set from STATS19 to estimate the casualty savings that could be expected within London each year.

Figure 2: True positive and false positive analysis

True Positive Analysis

For car occupant, pedestrian and cyclist casualties completely avoiding the accident or reducing the impact speed was expected to reduce the number and/or severity of casualties since the magnitude of deceleration experienced during the impact was likely to be greater than that experienced during braking. For bus occupants injured in collision with cars and other vehicles then collision avoidance or a reduction in collision speed would also be expected to substantially reduce the acceleration they experience and, hence, the probabilities of falls or other injuries which may otherwise be likely because of the fact they are standing or seated but unrestrained. However, when a bus hits a pedestrian or cyclist, the acceleration caused to the bus by the impact is negligible. So, the benefit to the bus occupant of avoiding or mitigating the collision is also negligible. An AEB system can brake no harder than the best human driver, so in the best case, there is no difference to the level of risk from braking. However, it is well documented, for example (Perron, et al., 2001) (Dodd & Knight, 2007) that many human drivers do not fully exploit the maximum braking performance available to them and may brake less sharply than the best human driver. Therefore, in some circumstances, an AEB system could brake harder than the average human driver which could increase the frequency or severity of injuries on board the bus.

Of course, emergency braking does take place in bus to pedestrian collisions where AEB is not fitted. Thus, the number of bus occupants injured in single vehicle collisions with pedestrians was taken as a baseline. Data on the

distribution of on-board injuries in relation to peak deceleration, taken from the study of bus operator CCTV incident records, was combined with data on the average occupancy of buses to estimate how this baseline number might change if AEB were fitted to all vehicles.

False Positive Analysis

In a genuinely false positive situation, automated braking always creates a risk of injury to bus occupants that would not have existed if AEB was not fitted. However, it is worth noting that, true and false positives are not as binary as the name implies. There are many situations where whether an activation should be considered false is open to significant interpretation and several studies have considered additional categories of ‘premature’ positive, near miss, or even desirable false positive, e.g. Lubbe (2014). These are activations that occur where there is a clearly recognisable hazard that prompts the activation but where the activation occurs at a time where the driver considers themselves aware of the risk and able to avoid it themselves without assistance. In addition to this, a false positive does not necessarily mean the brakes are applied until the vehicle comes to a complete stop. The sensing, detection and decision system may ‘make a mistake’ and activate the brakes but may also ‘realise it’s error’ only a short time later and subsequently release the brakes. Thus, false positives could potentially be of much shorter duration than true positives (i.e. a lower change in velocity).

At the time of the project no published information was identified to confirm the typical false positive rate experienced by comparable AEB systems in production, the proportion of those that were completely false or just premature, or the proportion that were momentary blips of the brakes compared to full emergency stops.

RESULTS

The two main questions that this research was aiming to answer were:

1. Does the fitment of AEB on buses produce a net safety benefit?
2. If so, develop a test procedure and rating system that can be used to encourage the most effective systems

Does the fitment of AEB on buses produce a net safety benefit?

True Positive Collision Situations. Collision data for London shows that in terms of fatalities from collisions with buses, by far the largest group is pedestrians. AEB was expected to be of benefit where the bus was travelling at normal traffic speeds and the pedestrian crossed the road in front of them or was walking along the road in the same direction as the bus. AEB was not expected to be of benefit where the bus was turning into or out of a side road at the time of collision or where the vehicle was just moving off from rest. A total of 21 relevant fatalities (with sufficient information for the reconstruction) were identified in the Police data and a total of 27 relevant non-fatal casualties were identified in the operator CCTV data. All cases in the sample were crossing scenarios.

For the fatalities, the travel speeds of the buses involved was between 5 and 36 mile/h with an average of 20 mile/h. This is likely to reflect the prevailing speed limits and traffic collisions typically resulting in low travel speeds in London. It was found that in all cases, there was less than 2 seconds available between the pedestrian becoming recognisable as a collision threat and the moment of impact, with an average time of just 0.76 seconds. Given typical human reaction times of between 0.75 and 1.5 seconds, e.g. (Olson & Farber, 2003), then avoiding collisions would be very challenging for human drivers. The study found evidence to show that 45% of the drivers involved did manage to react before impact but even in these cases the action was insufficient to avoid collision and the average impact speed was in fact only 1 mile/h less than the average travel speed before reaction.

For the non-fatal casualties, identified in the operator CCTV data, the bus travel speeds were very similar, ranging from 11 to 30 mile/h with an average of 17 mile/h. However, in these cases, the time between the pedestrian first becoming recognisable as a possible collision threat and the moment of impact tended to be greater, with a range from 0.7 seconds to 4.1 seconds, and an average of 2 seconds (1.24s longer than in the fatal cases). This translated to a higher proportion of drivers reacting before collision (87%) and a greater reduction in speed at the moment of impact, with impact speeds ranging from 7 to 15 mile/h, with an average of 11 mile/h (8 mile/h less than the average in the fatal cases). In the CCTV data it was also possible to calculate the amount of time that passed between the

pedestrian first becoming recognisable as a collision threat and the moment the driver first took avoiding action. This was found to range between 0.7s and 3.9 seconds, with an average reaction time of 1.9 seconds, slower than might be expected based on the body of laboratory and test evidence, e.g. (Olson & Farber, 2003) (Coley, et al., 2008), typically used in collision reconstruction. However, the case involving the 3.9 seconds was a bit of an outlier in an unusual case where the moment the pedestrian became a threat was open to interpretation. Ignoring this case changes the reaction times to between 0.7 and 2.5 seconds with an average of 1.7.

The peak accelerations achieved during braking were available and ranged between -1.4 m/s^2 -8.7 m/s^2 , with an average of 4.3 m/s^2 . Mean accelerations over the course of the stop were considerably lower with an average of 2.9 m/s^2 . This is likely to reflect the well documented fact (Perron, et al., 2001) (Dodd & Knight, 2007) that drivers often do not exploit the maximum braking available to them. Some stakeholders have suggested this may be exacerbated for bus drivers by the training they are given to brake gently during normal driving to help prevent passenger falls.

In each case, the potential benefit of AEB was assessed by replacing the actual driver reaction, with an AEB reaction. The AEB applied braking was assumed to commence at the lesser of the time to collision (TTC) at which the pedestrian became recognisable as a threat minus a system reaction time, or a range of TTC at which the AEB in the prototype bus actually commenced braking in the true positive track tests. The acceleration applied was the lower of the level required to avoid impact or the maximum that the system could achieve. A new impact speed was then calculated based on the initial travel speed, the moment of AEB activation and the level of deceleration applied.

The maximum deceleration that could be applied by an AEB system on a bus was initially based on the levels observed in track tests of the prototype system. However, the debate between maximising protection to collision partners and minimising risks to bus occupants meant that it was conceivable maximum deceleration should be capped. Thus, three 'nominal' systems were defined based on maximising deceleration (9 m/s^2 peak) or capping peak deceleration at either 7 or 5 m/s^2 .

Across all the variations, it was found that between 10% and 48% of the fatal sample and between 48% to 89% of the non-fatal sample could potentially have been avoided by fitting AEB. In addition to this, the results suggested that 14% to 43% of the fatal sample could have had at least some mitigation of impact speed and 4% to 41% of the non-fatal sample. It should be noted that the uncertainty in some parameters meant that ranges were used and thus there is overlap in the populations for avoidance and mitigation. That is, where a case would definitely have been avoided it will not appear in the mitigation figures. Where a case definitely cannot be avoided it may appear in neither figure or the mitigation only. Where there is some chance of avoidance but, if not avoided, a better chance of mitigation, then it appears in both sets of figures.

It was found that a large proportion of the benefits obtained above, were obtained due to an earlier braking intervention than provided by the driver. However, it was also found that on average, the AEB would have applied greater deceleration than the population of real drivers did, even though in some individual cases the AEB had to apply less deceleration to avoid the collision than the driver eventually applied later in failing to avoid collision. On average, the AEB systems increased the mean braking deceleration from 2.9 m/s^2 to between 3.0 and 5.5 m/s^2 , depending on the system characteristics assumed.

Analysis of the CCTV data highlighted that for different ranges of peak deceleration, the proportion of passengers that sustained slight or moderate injuries increased with increasing deceleration (Figure 3). The difference between the proportion of occupants injured from AEB braking to the proportion of occupants injured during driver-applied deceleration represents an additional risk to bus occupants. By applying the change in acceleration from driver-controlled to AEB-controlled to all bus occupants on board at the time of the pedestrian incidents, the total number of bus occupant injuries was estimated. It was assumed that all buses involved in collisions with pedestrians had the average number of passengers on board (19.3)¹.

¹ Source: DfT Bus Statistics Table BUS0304 data for London in 2016/17. Note that the equivalent figure for England excluding London is 9.5 suggesting any risk to occupants would be substantially lower outside of London

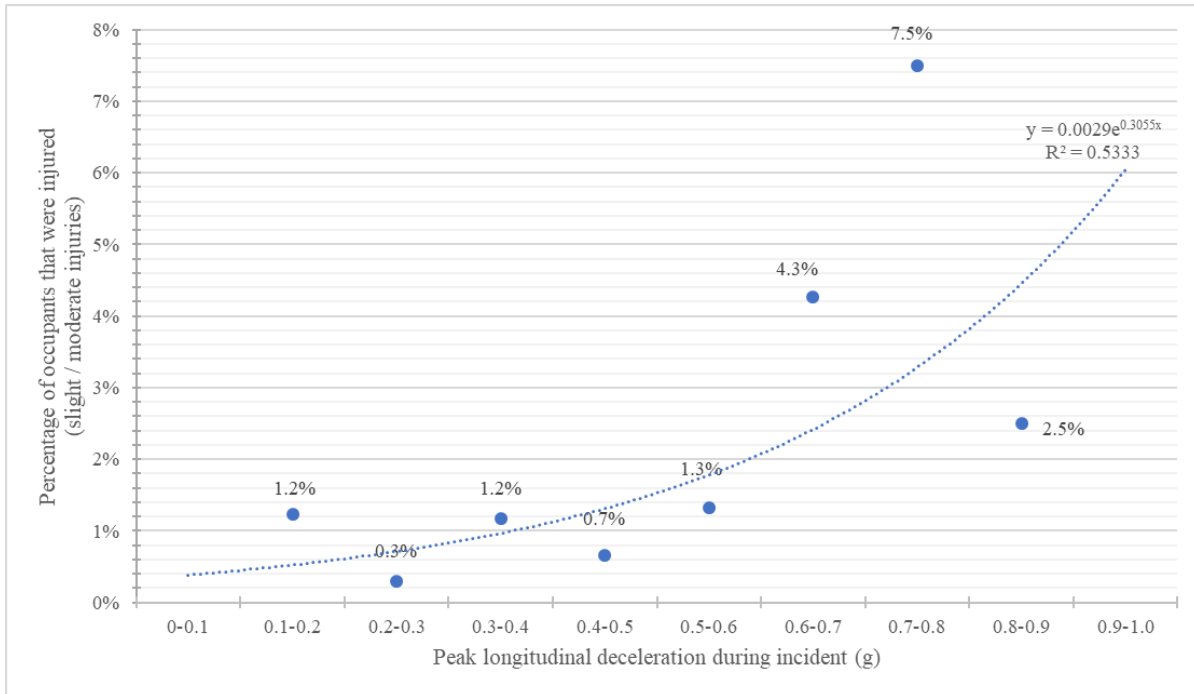


Figure 3: Proportion of occupants on board the bus that were injured during braking events, by magnitude of peak deceleration. Source: Sample of operator CCTV collision records.

This form of analysis was repeated for collisions with cars, other buses, and cyclists. The percentage effectiveness figures were combined with total casualty populations derived from the UK national accident database (STATS19) restricted to London only and the total net casualty effects in true positive situations was calculated.

False Positive Situations. If the AEB system were to apply braking in a situation where most careful competent and alert human drivers would not have applied braking, it can be considered a false positive. In this situation, the braking creates a risk of injury to bus occupants, and potentially other road users though they should still be travelling at a distance to be able to avoid collision with the braking bus. A subtle but important distinction is that this is different from a situation where the system applies braking in response to a recognisable threat of collision but that this is applied a little too early. Such interventions can annoy the driver but are much less likely to cause a direct injury risk because there was a genuine need for braking, whether human or system applied. With a prototype vehicle that had not yet undergone tuning to eliminate false positive brake applications, 17 false system activations were logged during the road trial where braking would have occurred if the system was fully operational. In seven cases, the system demand would have been limited to a deceleration 4m/s^2 and in the remaining 10 cases it would have peaked at a demand of between $8.0\text{m/s}^2 - 9.8\text{m/s}^2$.

What the brake system would actually have delivered in response to these braking demands depends on the duration for which they were demanded and the initial speed because air brake systems are relatively slow to react and build up compared with hydraulic systems. To estimate this lag, information from the vehicle manufacturer and data from the true positive test programme was used. Firstly, the manufacturer indicated that it would take approximately 0.15 seconds for the AEB demand signal to be delivered to the braking system. In addition, the results from the true positive tests then showed that it would take a further 0.05 seconds before the deceleration began to significantly ramp up (Figure 4).

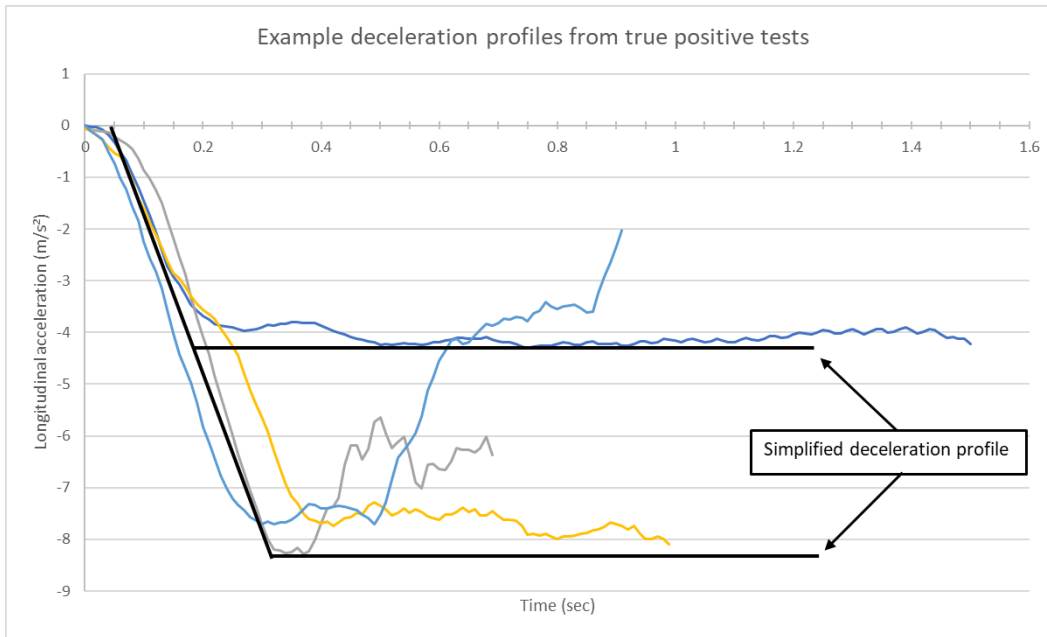


Figure 4: Example deceleration profiles from true positive test

Based on this information, a simplified deceleration profile of the actual level of braking that occurred during each false positive event was calculated, as illustrated by the example in Figure 5.

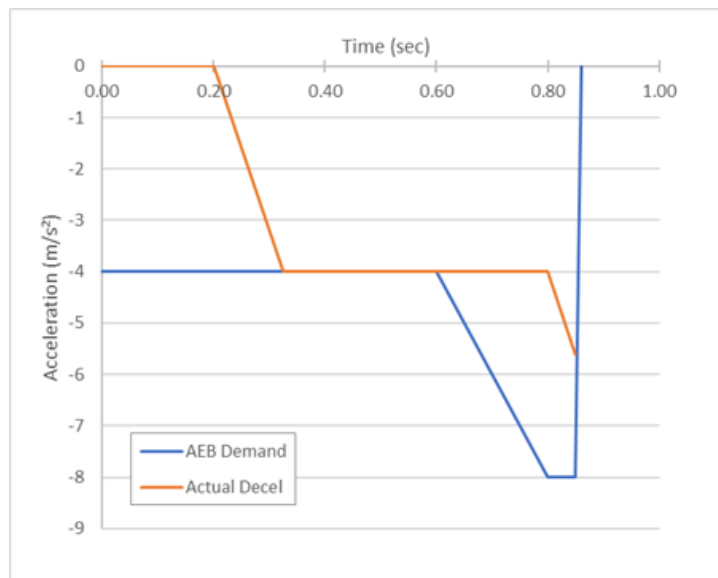


Figure 5: Comparison of braking demand and actual estimated braking

The estimated response of the braking system was applied to the level of deceleration demanded by the system and the actual peak deceleration calculated. Figure 6 shows that in some cases, the actual peak deceleration of the bus was lower than the peak demand, and in four of the 17 false positive events (24%) the duration of the demand would have been too short for there to be any deceleration at all.

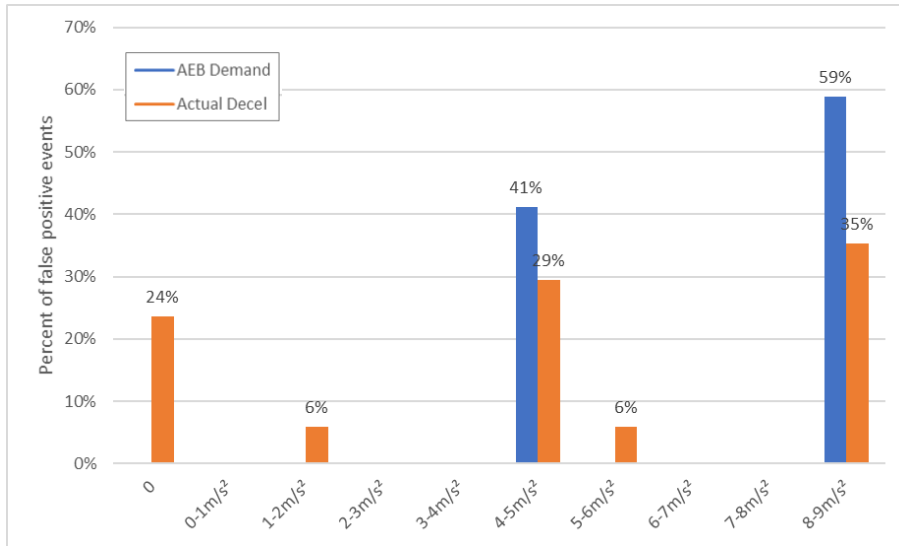


Figure 6: Comparison of AEB demand and actual deceleration for false positive events (road trial)

The false positive events that produced the greatest peak deceleration were all cases in which the level of deceleration ramped up over the duration of the event. Feedback from the manufacturer indicated that this was a result of running the AEB system in an “open loop” mode such that no actual braking took place. For example, Figure 7 shows one event where the AEB system initially demanded a deceleration of 4m/s². The system will check in the next instant and detect that no actual braking had occurred and that the vehicle was now closer to the hazard such that a higher level of deceleration is required to avoid a collision. In reality, a production system would have responded to the initial demand so the ramp up of acceleration may not have occurred or may have been smaller.

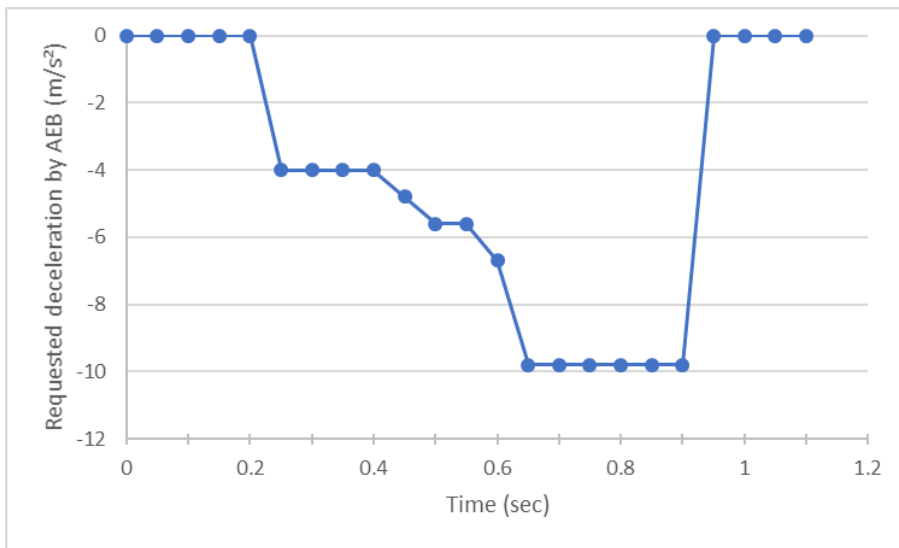


Figure 7: Example of increasing AEB brake demand during open-loop operation

The peak value of deceleration that would have been requested during normal “closed-loop” operation is unknown, but it is reasonable to expect that it would be somewhere between the initial requested deceleration of 4m/s² and the peak deceleration of 7.5m/s² observed during the track tests involving false positive scenarios.

In order to translate information on the deceleration achieved during false positive brake applications to their potential for casualties it was necessary to understand how many falls and injuries occur as a result of braking acceleration more generally. A range of laboratory experimentation has attempted to assess thresholds below which

standing occupants would not fall. For example, (De Graaf & Van Weperen, 1997) found that even very low accelerations ($<1/5 \text{ m/s}^2$) could make a standing occupant fall. They also showed that the rate of change of acceleration (or brake jerk) could be a significant factor in making people fall. The effect of acceleration on the frequency of falls can also be quantified from existing real-world data about buses not equipped with AEB.

The average number of driver-applied brake events per km was recorded during the 400km road trial and divided by peak deceleration. In the relatively short road trial no emergency brake activations were required, so the results were extrapolated to estimate the potential frequency of higher deceleration events (Figure 8). Applying these figures to the total number of bus vehicle km travelled in London each year (490million²) gave an estimate of the number of deceleration events that occur in London each year by peak deceleration.

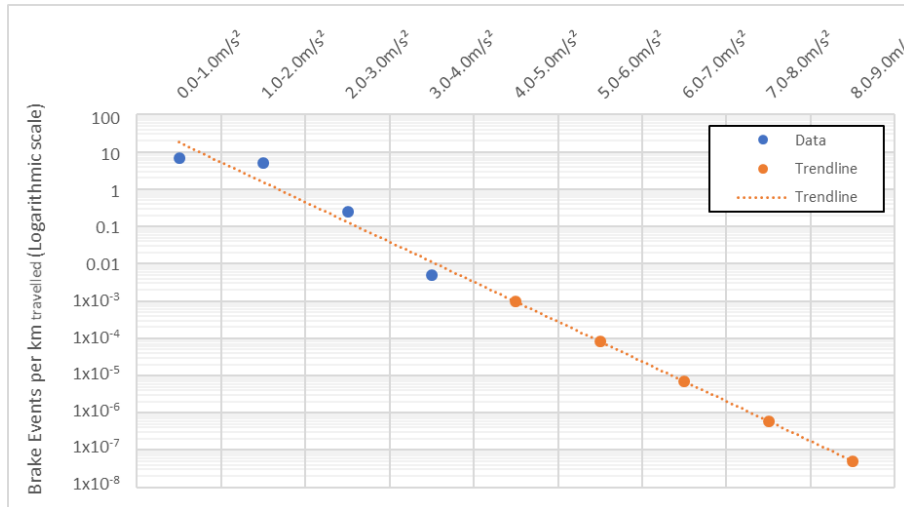


Figure 8: The frequency of brake applications in normal London bus service, by level of peak deceleration.

Data from the CCTV analysis (Figure 9) shows the proportion of casualties that occur at each acceleration level.

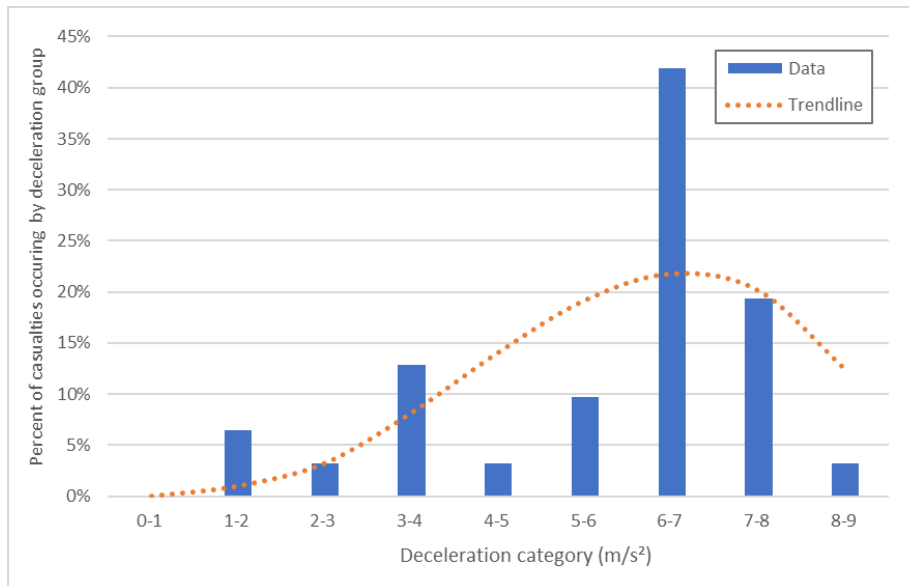


Figure 9: Proportion of bus occupant casualties that fell under braking by peak deceleration.

² Source: DfT Bus Statistics Table BUS0203b. Note TfL data suggests a total of 492.3 million bus km for 2016/17

Analysis of the IRIS database identified an average of 974 casualties per year that resulted from non-collision incidents in which braking was coded as the cause of the injuries. Combining this total with the proportions in Figure 9 produced an estimate of the annual average number of London bus occupant casualties that occur at each braking level. Combining this with the frequency of brake events by deceleration allows an estimate the number of casualties per braking event at each acceleration level. The results are shown in Table 1, below.

Table 1: Estimated number of casualties per braking event by deceleration level

Deceleration (m/s ²)	Brake events/year in london buses (number)	Bus occupant casualties per deceleration event (rate)
0.0-1.0m/s ²	3,277,342,050	0.00
1.0-2.0m/s ²	2,420,568,735	0.000000026
2.0-3.0m/s ²	119,064,478	0.00000026
3.0-4.0m/s ²	2,454,938	0.000051
4.0-5.0m/s ²	468,428	0.000067
5.0-6.0m/s ²	40,020	0.0024
6.0-7.0m/s ²	3,419	0.12
7.0-8.0m/s ²	292	0.65
8.0-9.0m/s ²	25	1.26

This analysis shows that the laboratory experiments on balance and falling cannot be taken to directly map to a probability of falls. It certainly does happen that standing passengers fall at accelerations of 1.5 m/s² as expected by (De Graaf & Van Weperen, 1997). However, in real service with more than 2 billion brake applications in London each year reaching that sort of level, then if a fall was anything but extremely rare in light braking, then the total number of casualties from falls under braking would be huge. The empirical evidence (974) suggests that this is not the case. Based on the CCTV study, the proportion of those at less than 2 m/s² is small. Overall, the probability of injury as a result of that level of acceleration is tiny. The probability of injury rises very sharply at accelerations of around 5 or 6 m/s².

Net effect of true and false positive situations. Given the information above, and knowledge of how many false positives brake applications would be likely to occur in service, it was possible to estimate the total number of bus occupant casualties that would occur as a consequence of false positives. The casualties were divided by severity based upon the observed distribution in bus occupant falls resulting from normal bus driving. However, at this stage of the research, and of the development of the prototype system that has been studied, the eventual false positive rate of a production London bus system is fundamentally unknown. The rate observed during the road trial with the early prototype vehicle is in no way indicative of expectations of the final production version. No published information has been identified that can confirm the typical false positive rate experienced by comparable systems already in production. Thus, results have been expressed in terms of the effect on casualties given different assumptions about the distribution of decelerations in false positive events and different frequencies of events (Figures 10 and 11).

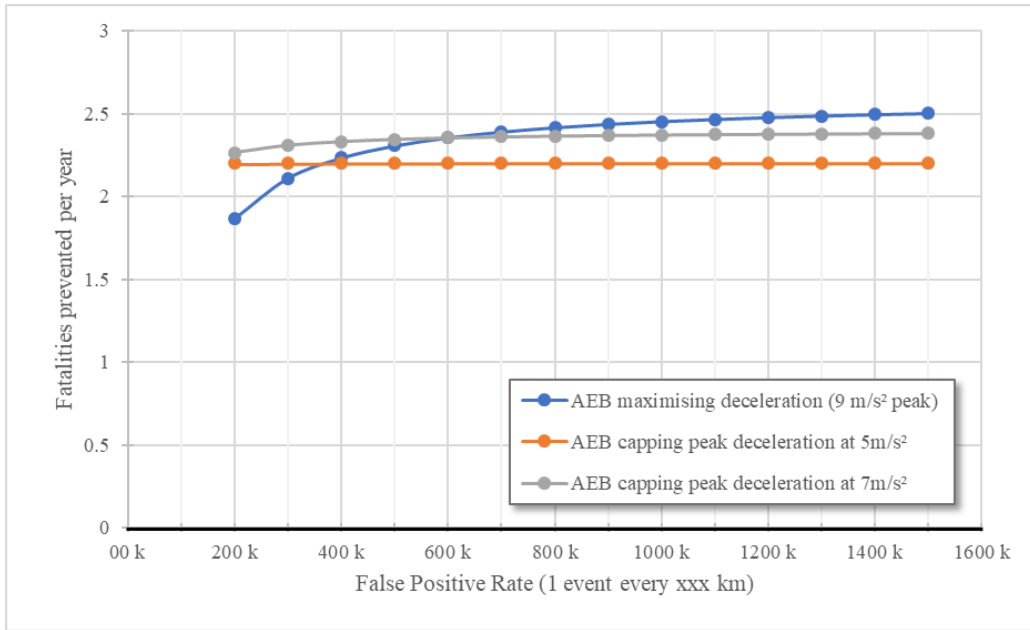


Figure 10: Central prediction of AEB effect on fatalities by false positive rate

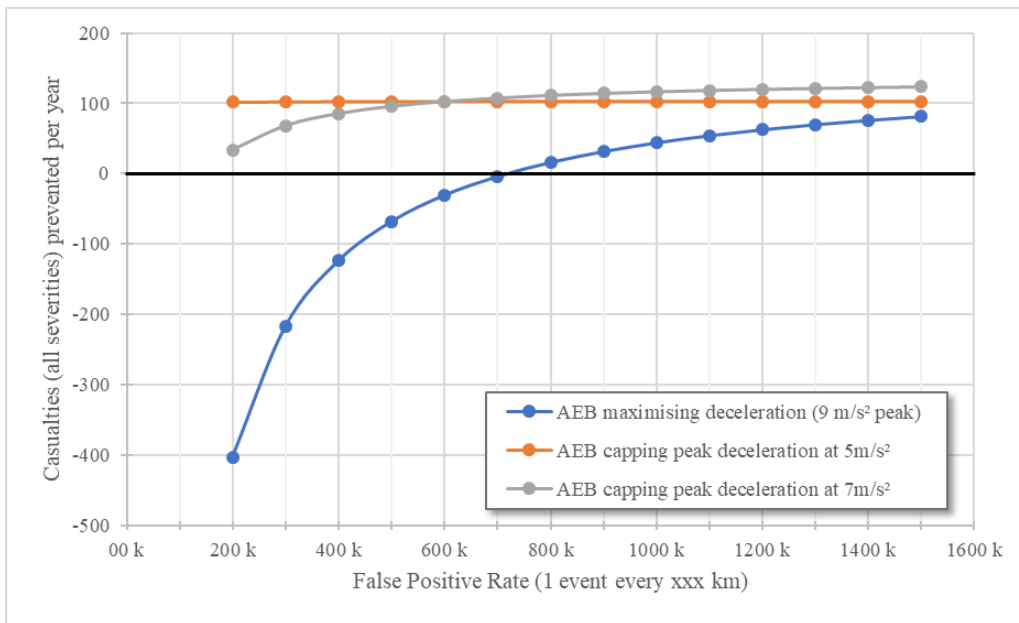


Figure 11: Central prediction of AEB effect on casualties of all severities by interval between false positives

It can be seen that the smaller the distance travelled between false positives, the less the benefit is. At intervals between false positives of greater than 700,000km, all of the AEB braking strategies considered offer a net benefit in terms of the total number of casualties prevented. For fatalities, the most effective system is that with the highest deceleration provided a good false positive rate is achieved. However, this is the least beneficial system if all casualties are considered, because of the effect of false positives on bus occupants falling under braking, which predominantly result in slight injuries. In order to balance these considerations, the casualties were monetised according to standard valuations provided by the UK Department for Transport and the results are as shown in Figure 12, below.

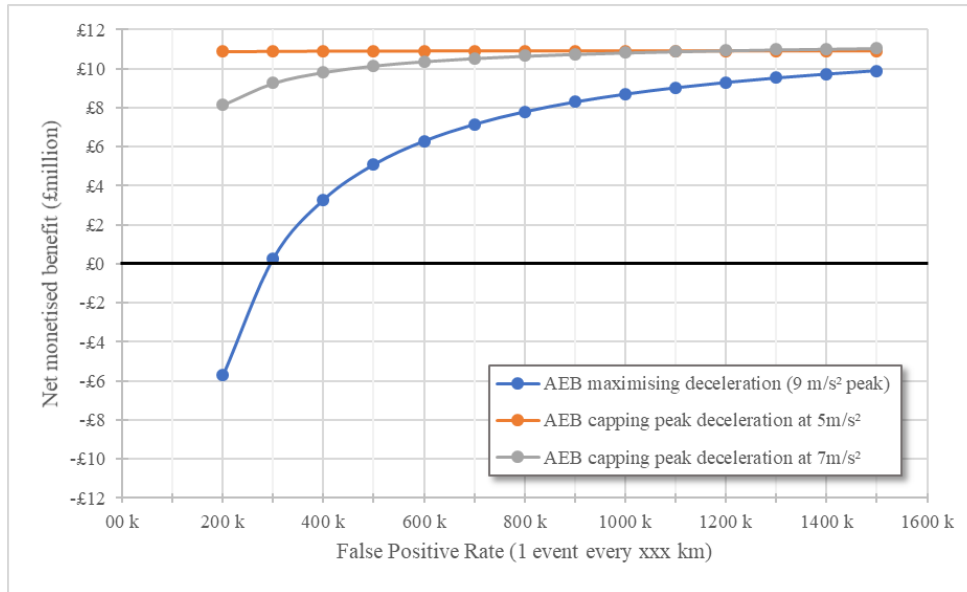


Figure 12: Central prediction of AEB effect on net monetised benefit of casualty prevention, by interval between false positives

Development of test procedures and rating scheme

Test Scenarios. The approach of this project was to base decisions on the inclusion of different test scenarios, and the weighting of each variable within an overall test score, based on the risk to casualties defined using casualty data extracted from the STATS19 database. On this basis, the following test scenarios were selected for inclusion in the Bus AEB test protocol (equivalent EuroNCAP test code shown in brackets):

- Pedestrian crossing.
 - Adult walking from nearside (CPNA-25 & CPNA-75)
 - Adult running from farside (CPFA-50)
 - Child walking from nearside - obstructed by car (CPNC-50)
 - Longitudinal cyclist - 25% and 50% overlap (CBLA-25 & CBLA-50)
- Bus to stationary car (CCRs)

The adult walking from nearside test is to be repeated in night-time conditions because the collision statistics show that performance at night in street lit conditions will be an important feature of an effective system.

Longitudinal pedestrian tests were not included because the collision data highlighted that, over a 10-year period, there were no pedestrian fatalities with a bus when the pedestrian had been walking along in the road. Cyclist crossing tests were also excluded because the prototype vehicle that was used for testing in the project was unable to achieve significant performance in this configuration.

In addition to the above tests, an aborted crossing test was also added to assess the false positive performance of a system. It has the same test geometry as the true positive test that assesses an adult walking from the nearside. However, instead of crossing into the path of the bus, the VRU dummy stops at varying lateral distances from the path of the bus. An effective system will need to activate before the pedestrian enters the path and the scoring is set such that it is acceptable to activate a small distance outside the path but where activations occur while the pedestrian is still at greater distances, the score is penalised to disincentivise this.

A 'bus stop' scenario was also added based on some of the false positives observed during the road trial (Figure 13). For this false positive test, the vehicle follows an s-bend path driving past a stationary pedestrian positioned to the

nearside of the vehicle. At all times in this test the VRU is easily avoidable by steering and, therefore, the AEB should not intervene. Thus, passing this test is considered a pre-requisite that all vehicles must achieve. However, a concern was flagged that the easy way to achieve this would be to switch off AEB whenever steering angle was applied, which would be undesirable. To ensure that this does not happen, a true positive version of this scenario was also included. For the true positive case, test geometry is the same as for the false positive test except that the pedestrian movement is configured such that it is on a collision course with the centre of the front of the bus.

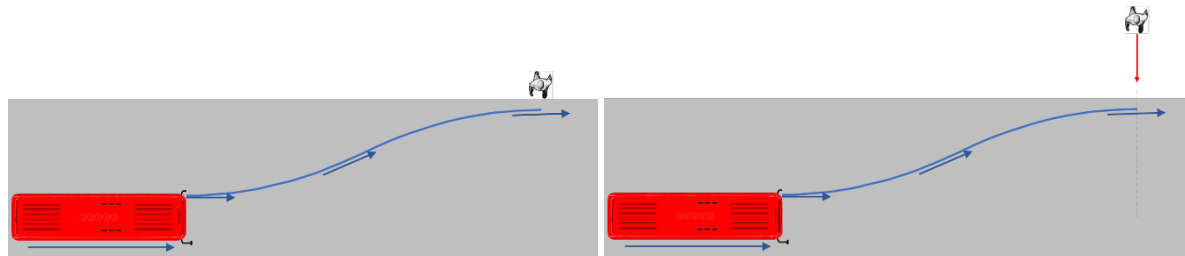


Figure 13: Bus- stop tests. False positive test (left), true positive test (right)

DISCUSSION

Strong potential benefits of fitting AEB to city buses exist in true positive situations, in particular for preventing pedestrian fatalities. Up to around 25% of pedestrian fatalities caused in collision with a bus could be prevented. In addition to this, there are significant benefits in reducing more minor collisions with other vehicles, particularly cars and buses. This will have little effect on fatality statistics but should benefit bus operators in terms of reducing high frequency damage and low severity injury claims, reducing operating costs and downtime.

The risk that AEB causes injury to unrestrained or standing bus occupants in true positive situations exists but is very low due to low numbers of true positive events, potentially earlier brake intervention and only small increases in required decelerations compared to those recorded in driver applied situations.

The risk to bus occupants as a consequence of falls during false positive events is substantial and a good false positive rate is very important to minimise this risk. The level of deceleration applied in false positive events will also be very important.

Permitting an AEB system that maximises the braking performance of the bus (AEBmax) has the potential to save the most fatalities, provided that false activations occur less than once every 600,000 vehicle-km on average. However, capping peak deceleration to a maximum of 7 m/s^2 has the potential for the largest reduction in monetised casualty benefit. This is because the analysis shows that the reduced deceleration substantially reduces the risk of large numbers of slight injuries to bus occupants as a consequence of false positive activation while reducing the monetised benefits to fatalities by less.

However, this analysis will only hold true if the correlation between the risk of injuries to standing and seated but unrestrained occupants is with peak deceleration only. Experimental data suggests that the rate of change of deceleration (brake jerk) is also an important factor in the risk of injury. The empirical analysis could not account for that factor and with a capped deceleration there would be an incentive to increase the brake jerk to improve true positive performance. Thus, there is a risk capping deceleration could fail to achieve the benefits expected by the analysis or even reverse them.

The analysis of benefits versus disbenefits is also very strongly dependent on two key input parameters that are weakly based (due to small sample sizes): the frequency with which heavy brake applications (5 m/s^2+) occur in real service and the frequency with which bus occupant casualties occur under different levels of braking acceleration. This is particularly true when considering an AEB system that can apply peak braking of 9 m/s^2 . Further research is proposed to increase the sample size available for these elements with a view to increasing confidence in the results.

Requirements have been developed for AEB that effectively define a minimum standard that must be achieved in terms of true and false positive performance to be considered an AEB system suitable for a London bus. In addition to this, the tests then measure and rate additional performance in excess of this standard. Thus, if implemented in an appropriate purchasing specification in this form, the market would be free to choose how to implement AEB in terms of deceleration levels, brake jerk etc.

The test track assessments developed are based on the Euro NCAP tests for cars, with adaptations to account for different collision patterns observed with London buses. The assessments contain two novel false positive tests because of the degree to which false positive rate is considered critical to the net benefit of the system. However, the track test assessments merely ensure to the extent possible that the systems are well designed and will work in the real world. There are an almost infinite range of circumstances that can be encountered in the real world and not all can be tested on a test track. It is, therefore, very important that industry design for real world use and not just test track performance. This is of particular concern in relation to false activations. The inclusion in any resulting specification of a requirement for industry to demonstrate to TfL how they have satisfied themselves that they will achieve a defined false positive rate in the real world, would add additional reassurance of proper design diligence.

CONCLUSIONS

AEB on city buses offers clear potential benefits in true positive situations, particularly in collisions involving pedestrians, preventing up to around 25% of pedestrian fatalities based on the analytical modelling presented in this paper.

False positive activations clearly risk significant increases in typically lower severity injuries to bus occupants who are standing or seated but unrestrained. The frequency with which false positives occur, and the deceleration achieved in false positive events will be critical to the success of any implementation.

Analysis suggests that if, in service in a busy city, the average interval between false positives is more than 600,000km, then substantial net benefits would be achieved.

The analysis is particularly sensitive to two results derived from small sample sizes and additional research is planned to improve the robustness of the data.

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Car-to-car accidents at intersections in Europe and identification of Use Cases for the test and assessment of respective active vehicle safety systems

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ABSTRACT

The Intersection 2020 project was initiated to develop a test procedure for Automatic Emergency Braking systems in intersection car-to-car scenarios to be transferred to Euro NCAP. The project aims to address current road traffic accidents on European roads and therefore sets a priority of the identification of the most important car-to-car accidents and Use Cases. Taking into account technological and practical limitations, Test Scenarios are derived from the Use Cases in a later stage of the project.

This paper presents parts of a larger study and provides an overview of common car-to-vehicle(at least four wheels) collision types at junctions in Europe and specifies seven Accident Scenarios from which the three scenarios “Straight Crossing Paths (SCP)”, “Left Turn Across Path – Opposite Direction Conflict (LTAP/OD)” and “Left Turn Across Path – Lateral Direction (LTAP/LD)” are most important due to their high relevance regarding severe car-to-car accidents. Technical details about crash parameters such as collision and initial speeds are delivered. The analysis work performed is input for the definition and selection of the Use Cases as well as for the project’s benefit estimation.

The numbers of accidents and fatalities in accidents at intersections involving a passenger car were shown per intersection type. In both statistics, it was found that accidents at crossroads and T- or staggered junctions are of highest relevance, followed by roundabouts. Focusing on accidents at intersections between one passenger car and another road user shows that around one-third of all accidents and related fatalities could have been assigned to car-to-PTW accidents and one-fifth of all accidents and fatalities to car-to-car accidents.

Regarding car-to-car accidents with at least serious injury outcome 38% out of 34,489 car-to-car accidents happened at intersections. These figures correspond to 18% of the fatalities (4,236 fatalities in total). Considering all intersection types, around half of all related accidents happened in urban environments whereas this number decreased to one-third of all fatalities. Further, the proportion of road fatalities per country occurring at intersections varies widely across the EU. Also, there are proportionately more fatalities in daylight or twilight conditions at junctions.

Use Cases are supposed to be derived from Accident Scenarios and by adding detailed information for example about the road layout, right-of-way and the vehicle trajectories prior to the collision. Instead of applying cluster algorithms to the accident data, a pragmatic approach was finally preferred to create them. Note: Use Cases serve as an intermediate step between the Accident Scenarios and the Test Scenarios which describe the actual testing conditions. Finally, 74 Use Cases were identified. This large number indicates the complexity of intersection crashes due to the combination of several parameters.

INTRODUCTION

General View on Road Traffic Accidents at Intersections

Junctions are intended to operate where vehicles often must share space with other vehicles and pedestrians. Negotiating a junction requires many simultaneous or closely spaced decisions, such as selection of the proper lane; maneuvering to get into the proper position; need to decelerate, stop, or accelerate; and need to select a safe gap [1]. Three- or four-arm non-signalized at grade junctions: These junctions may provide satisfactory road safety level when operating in low traffic volumes and speeds. Traffic islands and pavement marking, delimiting traffic directions and creating special lanes for left turning movements have a positive road safety effect [2]. When traffic volumes increase, it is necessary to establish traffic signals or consider modifications of the junction layout. In urban areas, changing a three- or four-arm level junction into a roundabout may lead to around 30% accidents reduction [3]. Signalized level junctions are the most common junction type in urban areas. Fatal accidents at signalized junctions are predominantly multivehicle [4]. The majority of accidents on signalized junctions concern left-turn vehicle movement or pedestrian's movement. Moreover, a higher accident involvement, in relation to their traffic volumes, may be observed for motorized two-wheelers and bicycles [5].

Roundabouts

Roundabouts have higher capacity than three- or four-arm non-signalized junctions; Roundabouts appear to have considerable safety advantages over other types of at-grade junction and are now being widely used in many countries [6]. However, in some countries they appear to be related to higher accident involvement of motorized two-wheelers and bicycles [5]. Roundabouts reduce the number of injury accidents depending on the number of arms and the previous form of traffic control. There appears to be a larger effect in junctions that used to have yield control than in junctions that used to be traffic controlled. Fatal accidents and serious injury accidents are reduced more than slight injury accidents [7]. Montella et al. reported in [8] that "The use of roundabouts improves intersection safety by eliminating or altering conflict types, reducing crash severity, and causing drivers to reduce speeds. However, roundabout performances can degrade if precautions are not taken during either the design or the operation phase."

Accident Data

The European project TRACE (funded by the European Commission) also investigated accidents at intersections in the EU-27 [9]. The authors reported that:

- Approx. 43% of all road injuries occur at intersections in EU-27;
- Approx. 70% of intersection accidents occur inside urban area;
- Approx. 80% of intersection accidents occur with at least one passenger car in urban area;
- 45% to 68% of intersection accidents occur at intersections with traffic regulation.

The authors also note issues about the definitions of intersections. For example, "intersections" in the UK include the point where the roads cross plus the 20 m on either side.

The European Commission arranged intersection accident data analyses using the Community Database on Accidents on the Roads in Europe (CARE) and published the results in a special issue of the series "Traffic Safety Basic Facts" [10] in 2015. It was estimated that more than 5,000 people died in road accidents at junctions in the EU in 2013. Note: European figures have to be handled with care as there is no common definition for crashes at junctions in Europe and not all countries provide related figures in the same quality. It was summarised that the proportion of fatalities occurring at junctions is higher on urban roads than on rural roads or motorways and varied widely across the EU. The proportion of fatalities occurring at junctions is highest for pedal cyclists and moped riders, and lowest for HGV, lorry and car occupants. However, proportions change when considering seriously injured casualties. Regarding the light conditions at the point of time of the accidents at intersections, proportionately more fatalities occurred in daylight or twilight compared to dark light conditions. With regard to the weather condition, the proportion of accidents with fatal outcome that occurred at junctions was highest for dry conditions (87%), followed by rainy conditions (7%) and lowest in adverse conditions such as snow.

Accident Clusters and Methods for Identification

Nitsche et al. analysed in [11] accident data from the United Kingdom with the aim to identify critical pre-crash scenarios at T- and four-legged junctions ("crossroads"). The method employed k-medoids to cluster historical junction crash data into distinct partitions and then applies the association rules algorithm to each cluster to specify the driving scenarios in more detail. The study resulted in thirteen crash clusters for T-junctions and six for crossroads. Association rules revealed common crash characteristics, which were the basis for the scenario descriptions. Exemplarily for all clusters, some are detailed:

Cluster T-C1 is the largest cluster with a size of 212 crashes, from which all resulted in slight injury. More than 90 percent of the accidents occurred at T-junctions with a minor road joining from the left. There is no clear indication on the collision type of this cluster. The third largest cluster T-C2 groups collisions while turning,

with a highly significant representativeness of frontal and nearside impacts, all of which occurring at roads terminated by a major road. Powered two-wheelers (PTW) and bicyclists have relatively high frequencies, but the car is still the dominant crash partner. Cluster T-C3 with 62 samples represents car-to-car collisions at roads with minor roads joining from the right, mainly resulting in slight injury. Since there are mainly impacts on the back of the car, this cluster can be seen as rear-end crash group. The second largest cluster Cluster T-C5 indicates rectangular collisions with another car crossing the car's trajectory from the right. Cluster X-C1 is the largest cluster with 142 samples, which mainly includes rear-end collisions. Cluster X-C2 groups situations on crossroads broken by a major road, with high numbers for turning left or right as well as first front impact collisions. Cars and PTWs were mostly involved.

Sander and Lübke investigated the potential of different clustering methods to define intersection AEB test scenarios [12]. The “study investigates whether clustering methods can be used to identify a small number of test scenarios sufficiently representative of the accident dataset to evaluate Intersection Automated Emergency Braking (AEB). Data from the German In-Depth Accident Study (GIDAS) and the GIDAS-based Pre-Crash Matrix (PCM) from 1999 to 2016, containing 784 SCP and 453 LTAP/OD accidents, were analyzed with principal component methods to identify variables that account for the relevant total variances of the sample. [...] Test scenarios were defined from optimal cluster medoids weighted by their real-life representation in GIDAS. The set of variables for clustering was further varied to investigate the influence of variable type and character. [...] Despite thorough analysis using various cluster methods and variable sets, it was impossible to reduce the diversity of intersection accidents into a set of test scenarios without compromising the ability to predict real-life performance of Intersection AEB. Although this does not imply that other methods cannot succeed, it was observed that small changes in the definition of a scenario resulted in a different avoidance outcome.”

Feifel and Wagner described a method to cluster accident types and proposed a catalogue of harmonized pre-crash scenarios [13]. The method uses GDV accident types, that describe the conflict situations which lead to crashes and that classify causer and non-causer participants, respectively [14]. The catalogue describes the dynamic scenarios and allows for all degrees of freedom of the ego and object participants. Looking at each accident from the perspective of the causer and of the non-causer, sensor-equivalent accident types are clustered to pre-crash scenarios. This inductive approach requires in-depth knowledge of the functionality and performance of environment sensors, thus as an advantage the scenarios can be easily mapped to the respective safety systems. It is essential to consider both, the causer and the non-causer perspective, to develop a holistic picture of the traffic accident distribution between two participant types, such as car versus car. Therefore, the number of accident scenarios will be twice the number of accidents. Due to the pre-crash nature of the scenarios, they can ideally be used as a basis for analyzing the target population of an active safety system and for the evaluation of its performance using virtual simulation.

METHODS AND DATA SOURCES

Definitions

Accident Scenarios (AS) describe the basic road layout and basic motions of vehicles (here, at least four wheels each) relative to each other participating in a road traffic accident. Use Cases are derived from accident scenarios by adding detailed information for example about the road layout, right-of-way and the vehicle trajectories prior to the collision. They can be derived using statistical methods such as cluster algorithms applied to the available accident data. Note: Use Cases serve as an intermediate step between the Accident Scenarios and the Test Scenarios which describe the actual testing conditions.

Available datasets for analysis

Various accident datasets have been considered for the data analysis, see Table 1.

Table 1: Accident datasets considered in Intersection 2020

Country / Region	High-level crash data	In-Depth Crash data
Europe	CARE	IGLAD
France	BAAC	-
Germany	DESTATIS	GIDAS
Spain	DGT	-
United Kingdom	STATS19	-

CARE is a Community database on road accidents resulting in death or injury (no statistics on damage-only accidents). The major difference between CARE and most other existing international databases is the level of aggregation, i.e. CARE comprises detailed data on individual accidents as collected by the Member States.

The legal basis for the German Official Road Accident Statistics (DESTATIS) is the law on the statistics on road traffic accidents. Pursuant to this, federal statistics are compiled on accidents due to vehicular traffic on public roads. The national database for injury road traffic accidents in France (BAAC) is initially filled by the police. The data is checked afterwards by local road safety observatories, under the umbrella of the national road safety observatory. The Dirección General de Transito or Directorate General of Traffic (DGT) is the official body of traffic in Spain. As part of managing the traffic licenses, traffic safety actions and vehicle registration, it develops different statistics regarding vehicles and traffic issues which are at the disposal of the citizen.

Road accidents on the public highway in Great Britain, reported to the police and which involve human injury or death, are recorded by police officers onto a STATS19 report form. The form collects a wide variety of information about the accident (such as time, date, location, road conditions) together with the vehicles and casualties involved and contributory factors to the accident (as interpreted by the police). The Department for Transport has overall responsibility for the design and collection system of the STATS19 data.

IGLAD was started in 2010 by European car manufacturers and is an initiative for harmonisation of global in-depth traffic accident data to improve road and vehicle safety which has grown greatly during last years. A database was developed containing accident data according to a standardised data scheme that enables comparison between datasets from different countries.

The German In-Depth Accident Study (GIDAS) was founded in 1999 and is a co-operation between the Federal Highway Research Institute (BAST) and the German Research Association for Automotive Technology (FAT). Investigation teams record data of road traffic accidents involving personal injury in two regions of Germany (cities of Hanover and Dresden and their surrounding regions).

Categorization of Intersection types

To assign and categorize road accidents at intersections, their geometries / layouts were required to be grouped. Most countries in Europe distinguish between intersection layouts; however, the comparability among each other is limited. The lowest common denominator was found in the categorization based on an initiative by the EU to create a Community database on road accidents, see Table 2.

Table 2: Categorization of „intersection“ [15]

Categorisation	Description
Crossroad	Road intersection with four arms. Includes arm sections within 20m distance.
Multiple junction	A junction with more than four arms (except roundabouts). Includes arm sections within 20m distance.
Roundabout	Circular road. Includes sections leading to it, within 20m distance.
T or staggered junction	Road intersection with three arms. Includes T, or staggered junction (a junction with an acute angle). Includes arm sections within 20m distance.
Not at grade (interchange)	Not all roads intersect at the same level.
Other	Other junction type not in the list of the previous values. Includes arm sections within 20m distance.
Not a junction	The accident has not occurred at a junction or at a distance greater than 20m from a junction.

Contrarily, in Germany road traffic accidents at intersections are coded by the police using seven pre-defined “characteristics of the accident scene” from which a maximum of three characteristics could be selected per accident. These characteristics are “Intersection”, “T-junction”, “Property entry / exit”, “Steep hill upwards”, “Steep hill downwards”, “Bend” and “Roundabout”. It has to be noted that accidents at roundabouts were coded as accidents at intersections until the year 2015 and only a few federal states provided more details. Since 2016, accidents at roundabouts are coded separately in the national statistics. However, to provide possibilities for direct comparisons with other countries different approaches were considered.

The most promising approach was found in a work by the Fraunhofer Institute IVI which was commissioned by a project partner to conduct a study focusing on accidents at intersections in Germany. Relevant results were kindly provided to the Intersection 2020 project. The analysis referred to 9.7% of accidents classified as intersection accidents by the road accident databases of the police of the four German federal states Saxony, Hesse, Brandenburg and Saxony-Anhalt between years 2010 and 2015. The dataset contained all accidents, hence, including also accidents with material damage only if selected.

CARE analysis

The CARE database has been analysed applying specific filter criteria, see Figure 1. A country selection was required because only 11 countries delivered satisfying data about the abovementioned commonly agreed European definitions of an intersection. For the present analysis accidents with fatalities AND serious injuries were included under the assumption that the structure of type of junction (variable R13) is comparable and even if the total number of serious injuries is not fully comparable between different countries.

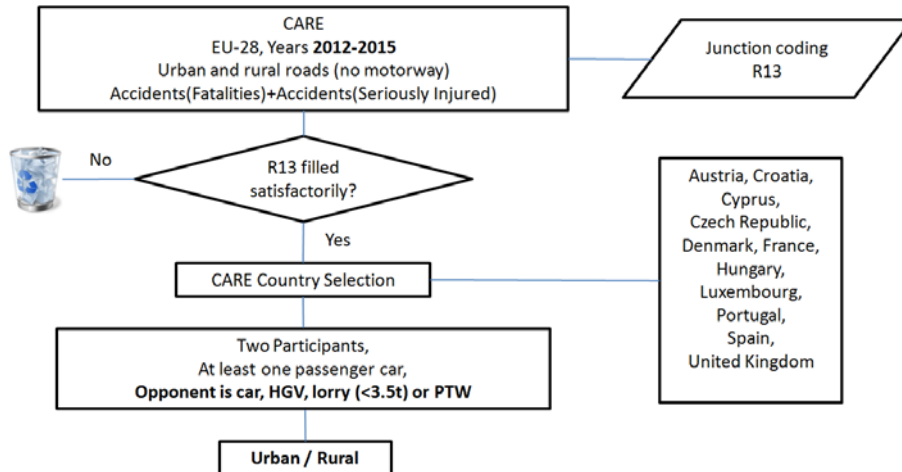


Figure 1: Approach for CARE analysis

Derivation of Accident Scenarios

According to the Federal Statistical Office of Germany “the kind of accident describes of the entire course of events in an accident the direction into which the vehicles involved were heading when they first collided on the carriageway or, if there was no collision, the first mechanical impact on a vehicle” [16]. It can be distinguished between 10 kinds of accidents. To address accidents being of highest relevance for enhanced AEB systems specifically designed for intersection scenarios (and thus considering existing AEB systems, e.g. car-to-rearend systems), it was determined to focus on accidents either assigned to kind of accident 4) Collision with another oncoming vehicle, 5) Collision with another vehicle which turns into or crosses a road or 10) Accident of another kind.

Figure 2 describes the data filter criteria to derive the AS for car-to-car accidents using data from the German national statistics. The focus was on accidents on urban and rural roads (but not on motorways) with at least one killed or seriously injured (KSI) person.

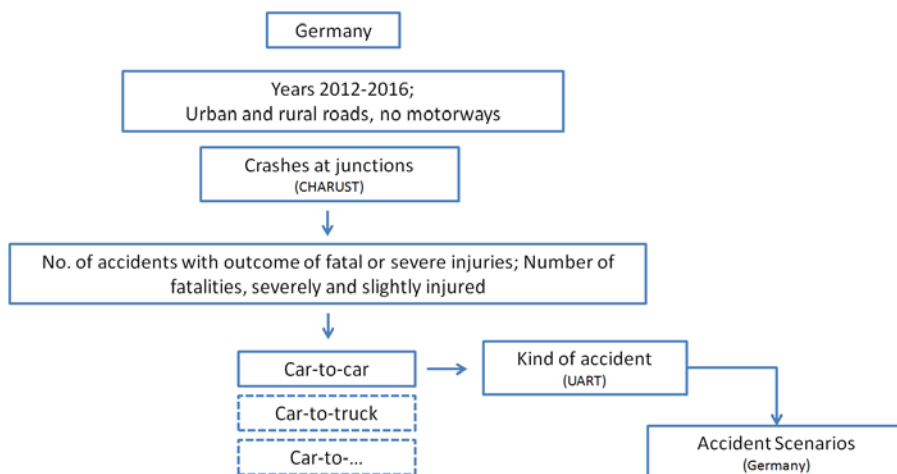


Figure 2: Approach for the derivation of Accident Scenarios from the German national statistics

In the German statistics there are seven types of accidents (coded as type 1 to type 7) describing the conflict situation prior to the accident. Each of these types can be further detailed into sub-types (e.g., accident type

“301”), see also [14]. However, in the German accident statistics this 3-digit accident type information is not available for all federal states of Germany but is provided by 5 (out of 16) federal states (Lower Saxony, North Rhine-Westphalia, Rhineland Palatinate, Saxony-Anhalt and Saarland) which by random, represent the German accident occurrence quite well, as non-published studies have shown. It was concluded that only data from these 5 federal states were used for the subsequent analyses regarding AS.

Various studies have already defined groups of accidents at intersections. Finally, for the purpose of comparisons and for harmonization it was aimed to select the AS of Intersection 2020 considering mainly findings from the US Department of Transport in [17].

Detailed analysis of Accident Scenarios regarding technical parameters

Basic crash parameters have been analysed for the most frequent AS SCP, LTAP/OD and LTAP/LD using GIDAS according to the following filter criteria:

- 1) Accident years 2005-2016 (GIDAS database version 07/2017)
- 2) Completed and reconstructed cases
- 3) Car-to-car (two parties exactly), first major collision
- 4) Only urban and rural roads, no motorways
- 5) Two injury severity groups:
 - a. Seriously and/or killed car occupants (**KSI**)
 - b. Slightly, seriously and/or killed car occupants (**ALL**)

Derivation of Use Cases

Use Cases had to be developed aiming to serve as an intermediate step between the identification of AS and defining the Test Scenarios describing the final testing conditions. A first attempt to generate a proper list of Use Cases based on the available collision data, using clustering algorithms and having the principal goals of the project in mind failed as the application of the statistical models to the data directed quickly into various issues and uncertainties but also similar results as presented in literature, see [12] (note: both datasets were greatly based on the same data source). Further, it became clear that vehicles' trajectories are important but could not be derived from GIDAS and various parameters (e.g., varying lane width, view obstructions), identified as being meaningful, could not be transferred to any Test Scenario for consumer programs in next years for which reasons a pragmatic approach was finally preferred. As a consequence, the GIDAS-based Pre-Crash Matrix (PCM) data was analyzed providing more information for example about the vehicles' trajectories up to five seconds prior to the collision. It was aimed to apply the same filter criteria as used for the GIDAS analysis. Further crucial parameters were identified and investigated. Subsequently, the frequency distributions of these parameters have been evaluated with regard to the pre-crash and the collision phase. Finally, the most relevant ranges of values were considered to be transferred into Use Cases. Use Cases were derived for the most relevant Accident Scenarios.

RESULTS

Accidents on European Roads (CARE analysis)

CARE has been analyzed towards accidents with fatal and/or seriously injured on urban and rural roads per intersection type based on accident years 2013-2015. Various differences were found comparing the information from the 24 countries for which data was available. For example, Ireland and Sweden reported a very high “unknown” rate regarding the crash location whereas countries such as Slovenia reported only a very few severe accidents at intersections and the United Kingdom a comparatively high rate. Germany reported no differentiation in the crash location. However, 11 countries were considered as providing reliable data for the purpose of this study. These 11 countries are: Austria, Croatia, Cyprus, Czech Republic, Denmark, France, Hungary, Luxembourg, Portugal, Spain and the United Kingdom. Figure 3 shows an overview about accidents with exact two collision partners involving at least one passenger car per intersection type. This analysis step revealed a share of accidents at intersections for all countries varying around 40-45%. “Crossroads” were reported most often followed by “T- or staggered junctions” and “roundabouts”.

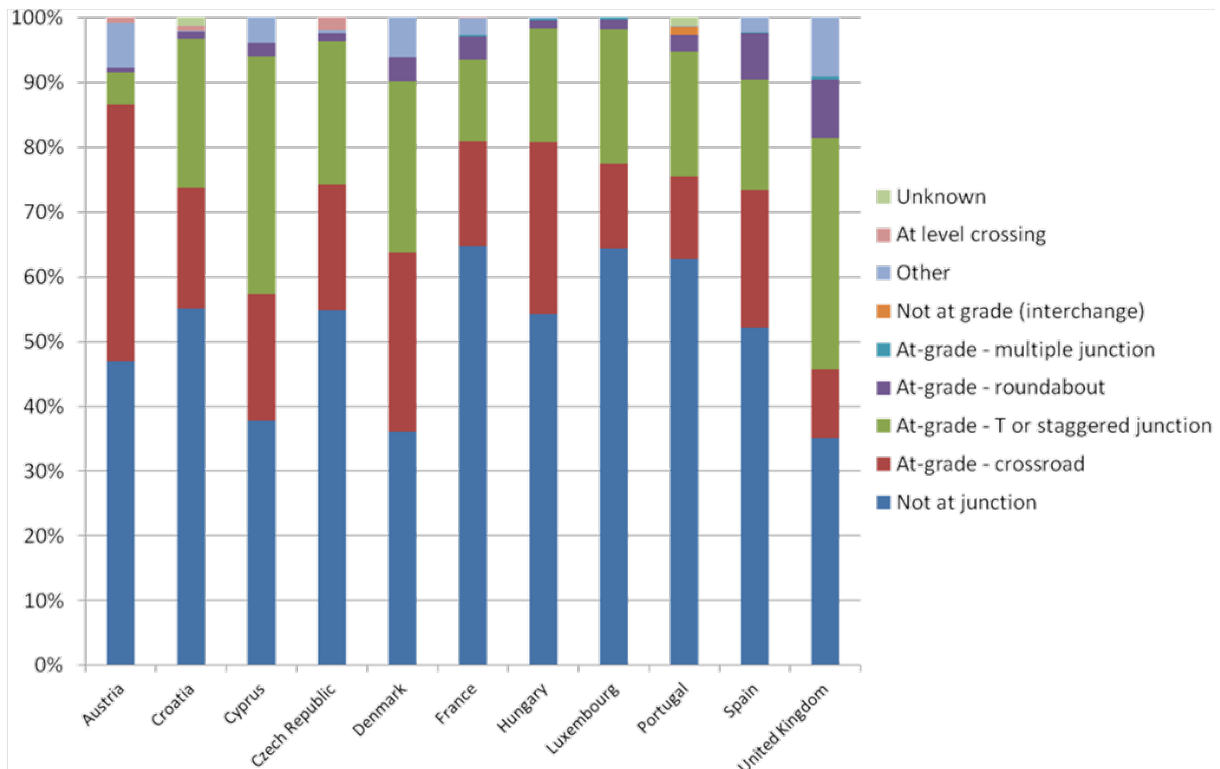


Figure 3: Accidents with fatal and/or seriously injured on urban and rural roads per intersection type, Two crash participants with at least one car, Country selection EU28, 2013-2015

The second analysis step based on CARE data from 2012-2015 and has looked for the number of KSI accidents (N=162,460) and corresponding fatalities (N=15,857) involving one passenger car (incl. taxis) and another road user (differentiating for accidents according to the configurations car-to-car, car-to-lorry, car-to-HeavyGoodsVehicle/Bus, car-to-PoweredTwoWheeler and car-to-RemainingRoadUsers). Omitting the “remaining road users”, it was found that car-to-PTW collisions (n=46,195) dominated the number of severe accidents, followed by car-to-car collisions (n=34,489). However, car-to-car collisions dominated the number of fatalities (n=4,236), followed by car-to-PTW collisions (n=2,992).

The numbers of accidents involving at least one passenger car and another road user and the corresponding figures on fatalities are shown per intersection type in Table 3 and Table 4, respectively. In both statistics, it was found that accidents at crossroads and T- or staggered junctions are of highest relevance. Focussing on accidents at intersections between one passenger car and another road user shows that around one-third of all accidents and related fatalities could have been assigned to car-to-PTW accidents and one-fifth of all accidents and fatalities to car-to-car accidents. “Car-to-remain” accidents involve accidents between cars and pedestrians/cyclists.

Table 3: Number of severe intersection accidents with involvement of one passenger car and another road user per intersection type (CARE, EU country selection, 2012-2015)

Number of KSI accidents and shares	Crossroad	Multiple junction	Roundabout	T- or staggered junction	Total
CAR-CAR	6,354 (9%)	102 (<1%)	908 (1%)	5,652 (8%)	13,016 (19%)
CAR-LORRY	934 (1%)	13 (<1%)	116 (<1%)	810 (1%)	1,873 (3%)
CAR-HGV/BUS	868 (1%)	19 (<1%)	174 (<1%)	931 (1%)	1,992 (3%)
CAR-PTW	8,797 (13%)	126 (<1%)	2,299 (3%)	11,209 (17%)	22,431 (33%)
CAR-REMAIN	8,888 (13%)	324 (<1%)	3,624 (5%)	15,013 (22%)	27,849 (41%)
TOTAL					67,161 (100%)

Table 4: Number of fatalities in severe intersection accidents with involvement of one passenger car and another road user per intersection type (CARE, EU country selection, 2012-2015)

Number of fatalities and shares	Crossroad	Multiple junction	Roundabout	T- or staggered junction	Total
CAR-CAR	396 (10%)	5 (<1%)	34 (1%)	321 (9%)	756 (20%)
CAR-LORRY	111 (3%)	0 (<1%)	7 (<1%)	75 (2%)	193 (5%)
CAR-HGV/BUS	156 (4%)	2 (<1%)	19 (1%)	158 (4%)	335 (9%)
CAR-PTW	464 (12%)	3 (<1%)	49 (1%)	605 (16%)	1,121 (30%)
CAR-REMAIN	508 (13%)	12 (<1%)	94 (2%)	758 (20%)	1,372 (36%)
TOTAL					3,777 (100%)

It has to be noted that the aforementioned (and also following) proportions per intersection type may reflect rather the frequency of these intersection types in Europe than certain associated risk factors.

Focusing on car-to-car intersection accidents, Figure 4 shows the distribution of the number of these accidents and fatalities per intersection type for urban and rural roads (without motorways). Considering all intersection types, around half of all related accidents happened in urban environments whereas this number decreases to one-third of all fatalities.

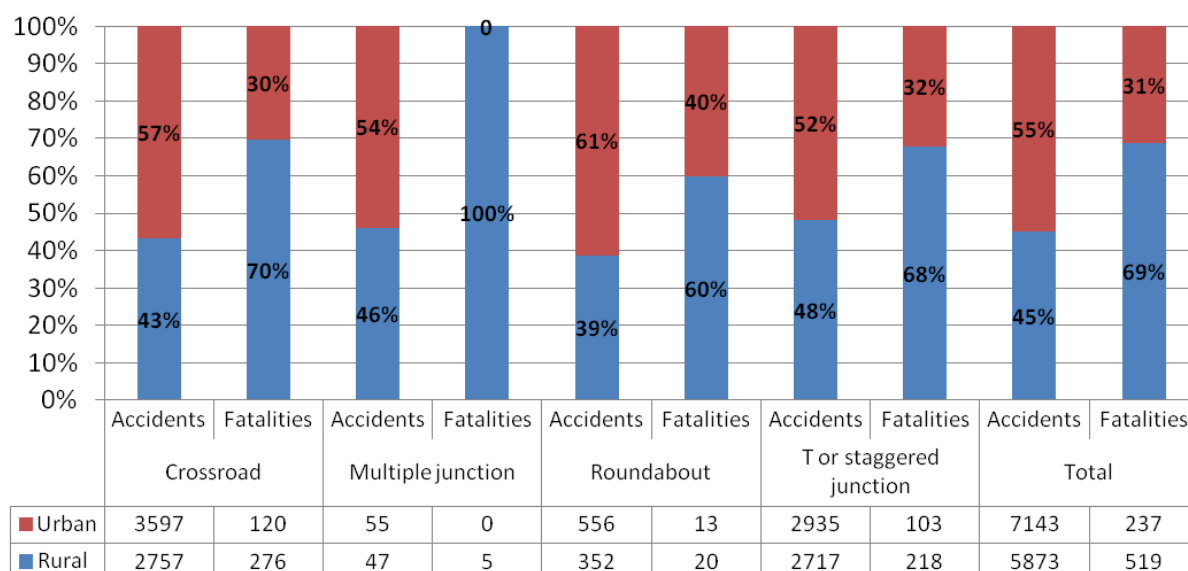


Figure 4: Shares of accidents and fatalities in car-to-car accidents per intersection type (CARE, EU country selection, 2012-2015), N(accidents)=13,016, N(fatalities)=756

Accidents on European Roads (selected countries)

Since the figures on seriously and slightly injured persons due to road traffic accidents are less reliable on a European level, further analyses of accidents involving exactly two passenger cars (incl. taxis) on urban and rural roads (without motorways) have been conducted accessing national statistics from France, the United Kingdom (UK) and Spain (note: Spain is not distinguishing for “multiple junctions”).

France, UK, Spain

The corresponding analyses concerning France, the UK and Spain are shown in Figure 5 - Figure 7, respectively. Overall, it can be seen that a severe injury outcome is linked with accidents on rural roads which is possibly connected to higher speeds. The proportion of rural environments is considerably higher in France and Spain compared to the UK. Comparing with the CARE analysis, the proportions of the intersection types crossroads and T- or staggered junctions against multiple junctions and roundabouts were confirmed; however, looking in greater depth shows that these proportions are varying a lot between the countries. For example, the shares of severe accidents at crossroads are 63% in France, but 28% in the UK and 50% in Spain and at T- or staggered junctions 30% in France, 66% in the UK and 36% in Spain.

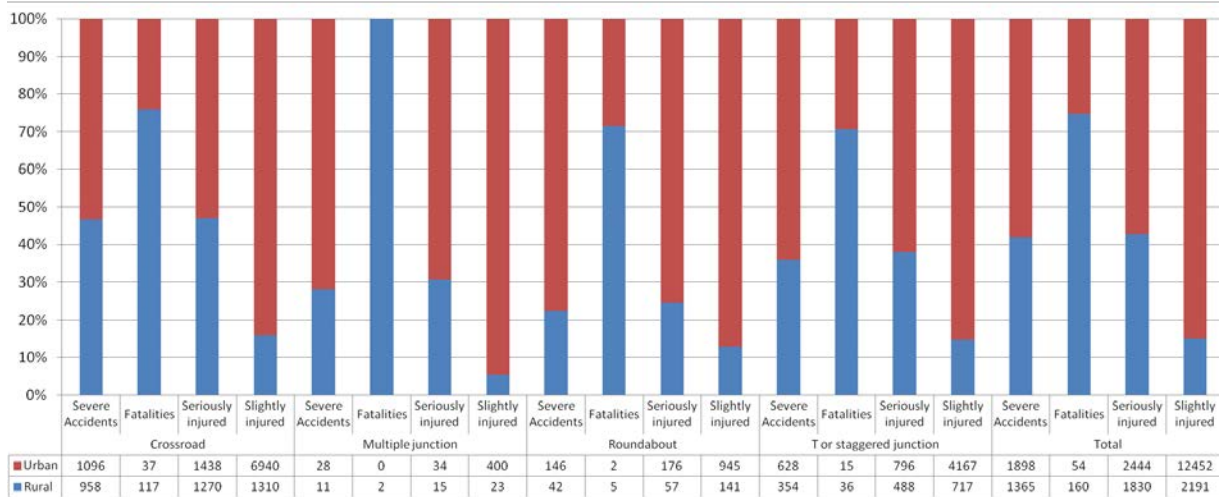


Figure 5: Shares of accidents and fatalities in collisions involving exactly two passenger cars per location and intersection type, excluding the intersection type "other" (BAAC, France, 2012-2015)

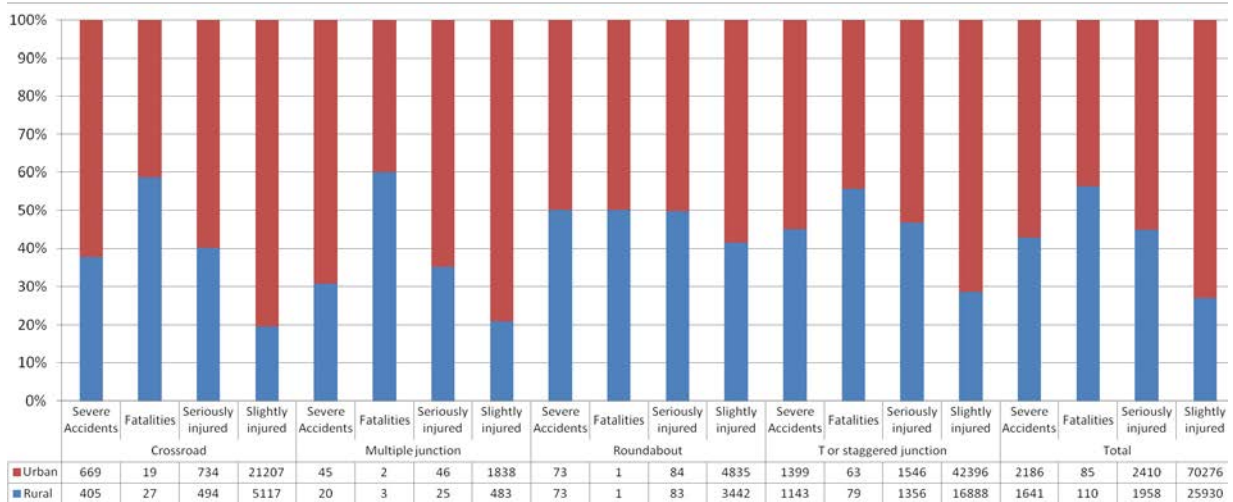


Figure 6: Shares of accidents and fatalities in collisions involving exactly two passenger cars per location and intersection type, excluding the intersection type "other" (STATS19, United Kingdom, 2012-2016)

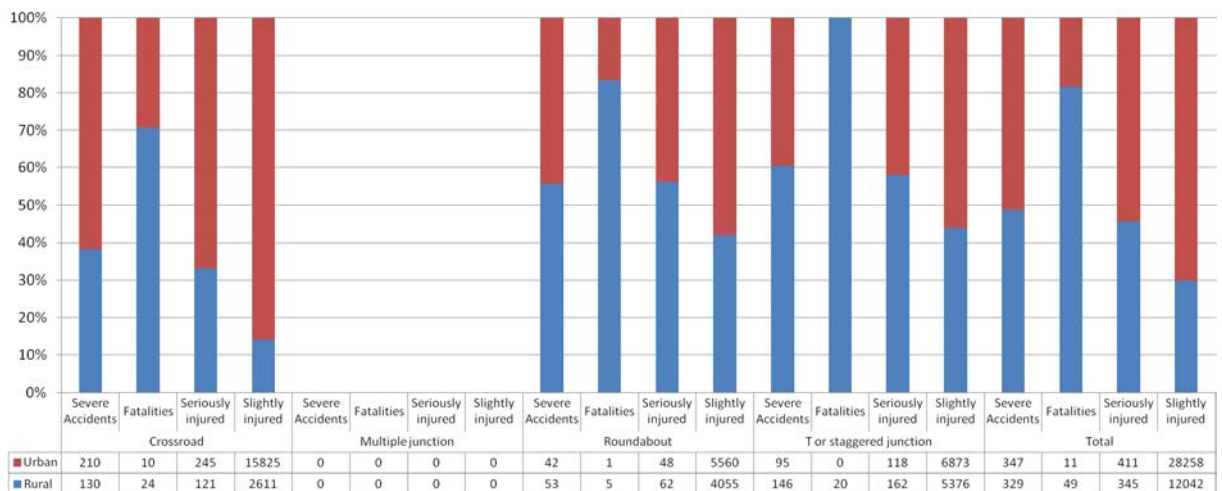


Figure 7: Shares of accidents and fatalities in collisions involving exactly two passenger cars per location and intersection type, excluding the intersection type "other" (DGT, Spain, 2013-2015)

Germany

Germany uses a different coding of road traffic accidents at intersections. The study by the Fraunhofer Institute found that more than 50% of all considered accidents have not been assigned any of the introduced seven pre-defined characteristics which means none of these characteristics was found relevant for / influencing remarkably the accidents. However, it was expected that a large amount of these accidents happened at an intersection (even though this was not seen as one of the primary contributing / influencing factors). Hence, the aim of the study was also to analyze as many accident locations as possible and if happened at an intersection, to classify the intersection type by the means of software (“analysis tool”) specialized for this purpose.

Concluding, the most common type of intersections is the crossroad with almost 48%, followed by the T-junction with nearly 25%. About 7% are multiple junctions and 6% are double crossroads (at least two lanes per driving direction). For almost 12% of all identified intersection accidents, the respective intersection type remained “unknown”. Accidents at roundabouts took place in 2.5% of the accidents. Though, it has to be mentioned that the tool still has limitations in classifying the intersections.

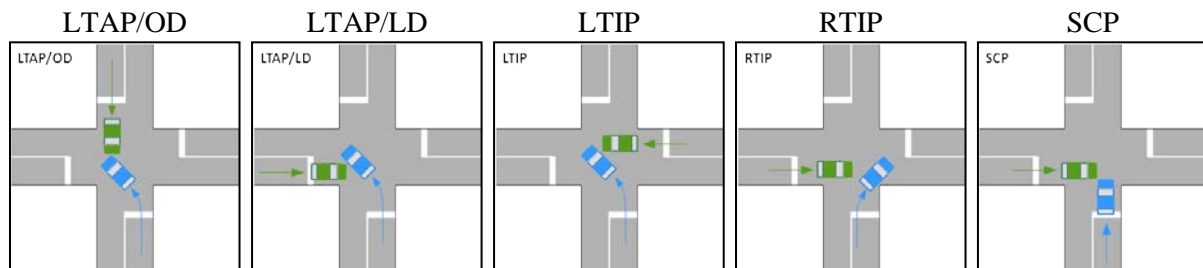
Accident Scenarios

Within Intersection 2020 seven AS were identified and considered for subsequent analyses. The following five AS were considered as being of highest interest, see also Table 5:

- Left Turn Across Path – Opposite Direction Conflict (LTAP/OD)
- Left Turn Across Path – Lateral Direction (LTAP/LD)
- Left Turn Into Path – Merge Conflict (LTIP)
- Right Turn Into Path – Merge Conflict (RTIP)
- Straight Crossing Paths (SCP)

In addition, the AS “Parking / Reversing” (P/R) and the AS “NA” were created. The latter AS comprises situations covered by current AEB systems, situations not addressed by intersection AEB systems or unclear accident courses of events. The assignment of “accident types” to these AS is summarized in the Appendix.

Table 5: Accident Scenarios of highest interest



To quantify the relevance of the particular AS considering all injury severity groups (fatally, seriously and slightly injured) an analysis of the subsample of the German national road accident statistics (data from five federal states) was performed and took 8,114 severe car-to-car accidents (at least one seriously injured person) at intersections with 168 fatalities, 10,728 seriously and 7,600 slightly injured casualties into account. To gain a ranking, the numbers of injured casualties were summed up and multiplied with weighting factors established in the European FP7 project ASSESS considering the average casualty injury costs as collected for different European countries [18]. Basically, the approach is based on the Equation 1:

$$\text{Analytical sum (per scenario)} = 1 * \text{number of killed} + 0.11 * \text{number of seriously injured} + 0.011 * \text{number of slightly injured} \quad (\text{Eq. 1})$$

Accordingly, applying the formula to all available data resulted into the figures and ranking summarized in Table 6. It can be seen that the highest ranked AS is SCP, followed by LTAP/OD and LTAP/LD.

Table 6: Analytical sum of ASSESS approach and ranking of severe car-to-car intersection accidents in Germany (sub-sample) per Accident Scenario

Ranking	AS	Analytical sum of ASSESS approach	Proportion (cumulative)
1	SCP	511.178	35,7%
2	LTAP/OD	391.423	27,3%
3	LTAP/LD	286.256	20,0%
4	NA	161.398	11,3%
5	LTIP	39.770	2,8%
6	RTIP	38.619	2,7%
7	P/R	3.036	0,2%
-	Total	1,431.680	100%

In-depth accident data analysis (GIDAS)

Table 7 shows the number of crashes and involved passenger cars per Accident Scenario for both injury severity groups: “slightly, seriously and fatally injured” (ALL) and “seriously and fatally injured” (KSI), for which similar shares were found. Overall, SCP reached highest shares around 40-43%, followed by LTAP/OD (~29-35%) and LTAP/LD (~21-23%). It has to be noted that at this analysis stage, SCP was not split into opposing vehicles approaching from left or right. Comparing the GIDAS figures on severe accidents with those presented in Table 6 by neglecting the additional AS “NA” shows comparable proportions of the AS. It has been concluded that the GIDAS figures represent satisfyingly Germany in this study and thus, no weighting factors are required.

The following results are focusing on the KSI accidents.

Table 7: Number of accidents (involving each two passenger cars) per Accident Scenario for the injury severity groups “slightly, seriously and fatally injured” (ALL) and “seriously and fatally injured” (KSI), highest shares were highlighted in grey, GIDAS 2005-2016, data not weighted

		LTAP/OD	LTAP/LD	LTIP	RTIP	SCP	P/R	Σ
KSI	Accidents	76	49	2	2	86	0	215
	%	35.3	22.8	0.9	0.9	40.0	0	100
All	Accidents	464	336	43	44	680	10	1,577
	%	29.4	21.3	2.7	2.8	43.1	0.6	100

LTAP/OD

According to the assignment of accident types to the AS, see Appendix, all LTAP/OD relevant GIDAS cases were grouped leading to 76 KSI and 464 ALL accidents. An overview of the associated accident types showed that for KSI and ALL accidents, accident types 211 and 281 emerged most frequently and covered at least ~95% of all LTAP/OD cases. Accidents assigned to 281 differ to 211 accidents by the existence of a traffic light only.

Hence, all LTAP/OD KSI accidents assigned to accident types 211 or 281 have been analyzed towards the reconstructed driving and collision speeds of both crash participants. The average speeds are shown in Figure 8.

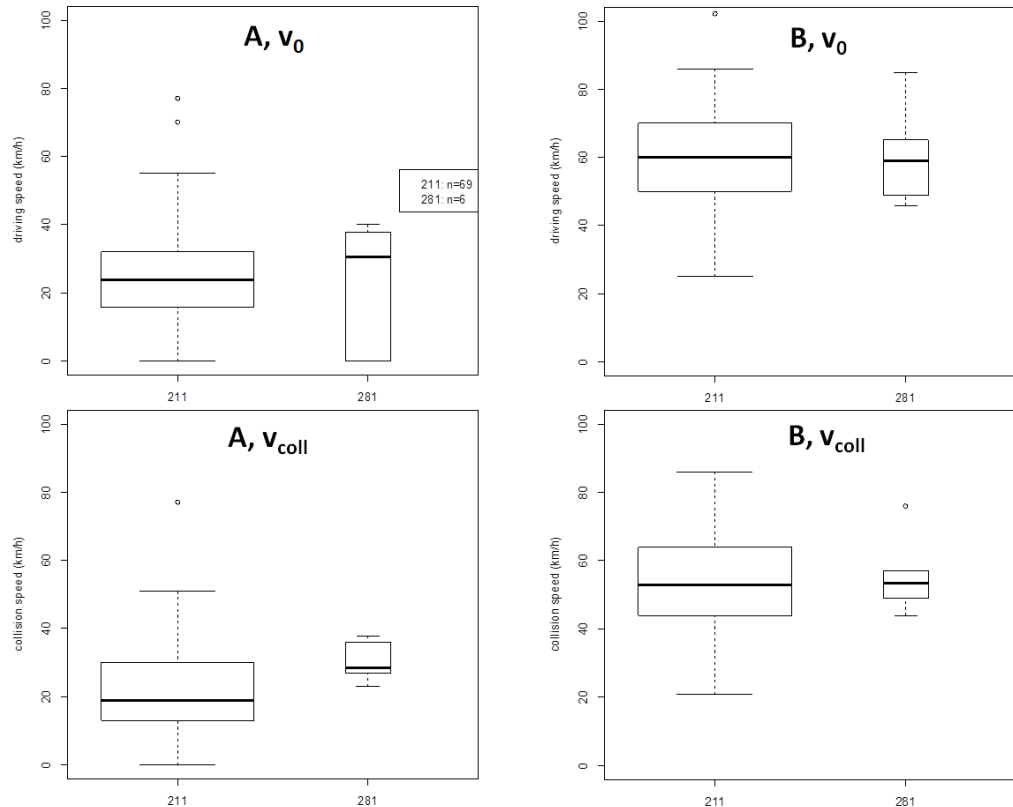
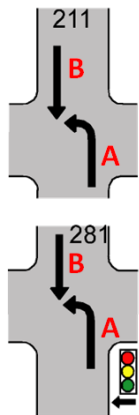


Figure 8: Boxplots of the driving (v_0) and collision (v_{coll}) speeds in LTAP/OD, KSI (N=76)

Table 8 summarizes these speeds approximately regarding their mean 50% (box without whisker), i.e., 50% of the accidents were within the specified speed ranges.

Table 8: Approximated mean 50% driving (v_0) and collision speeds (v_{coll}) of LTAP/OD and LTAP/LD KSI accidents for turning vehicle A and straight going vehicle B as well as of SCP KSI accidents for the entering, not-privileged vehicle A and the crossing privileged vehicle B

	A, v_0	B, v_0	A, v_{coll}	B, v_{coll}
LTAP/OD - KSI	15-35 km/h	50-70 km/h	15-30 km/h	45-65 km/h
LTAP/LD - KSI	05-25 km/h	50-75 km/h	10-20 km/h	40-65 km/h
SCP - KSI	20-50 km/h	30-60 km/h	20-45 km/h	30-60 km/h

However, to specify appropriate test speeds for this AS LTAP/OD a comparison of pairwise speeds was required, i.e., pairs of speeds of vehicles A and B, both involved in the same accident, see Figure 9.

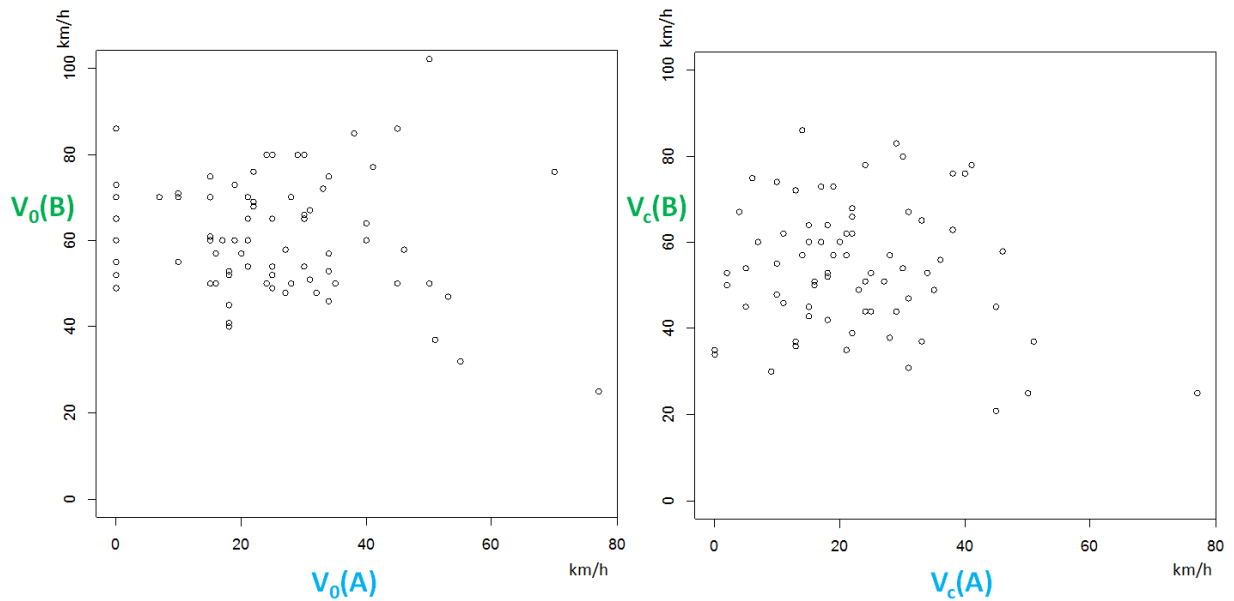


Figure 9: Pairwise driving (v_0) and collision (v_{coll}) speeds in LTAP/OD, KSI (N=76)

In addition, Figure 10 shows the speed change (here difference of a passenger car's driving and collision speed) to identify the basic patterns of accelerations and decelerations in LTAP/OD KSI accidents. Note: visible accelerations and decelerations do not necessarily correlate with initiated accelerating or braking of the driver. Further, the speed changes might have led to smaller or bigger changes in movement as the driving speeds could have been low or high. This is also true for the related figures on the AS LTAP/LD and SCP, see Figure 13 and Figure 16, respectively.

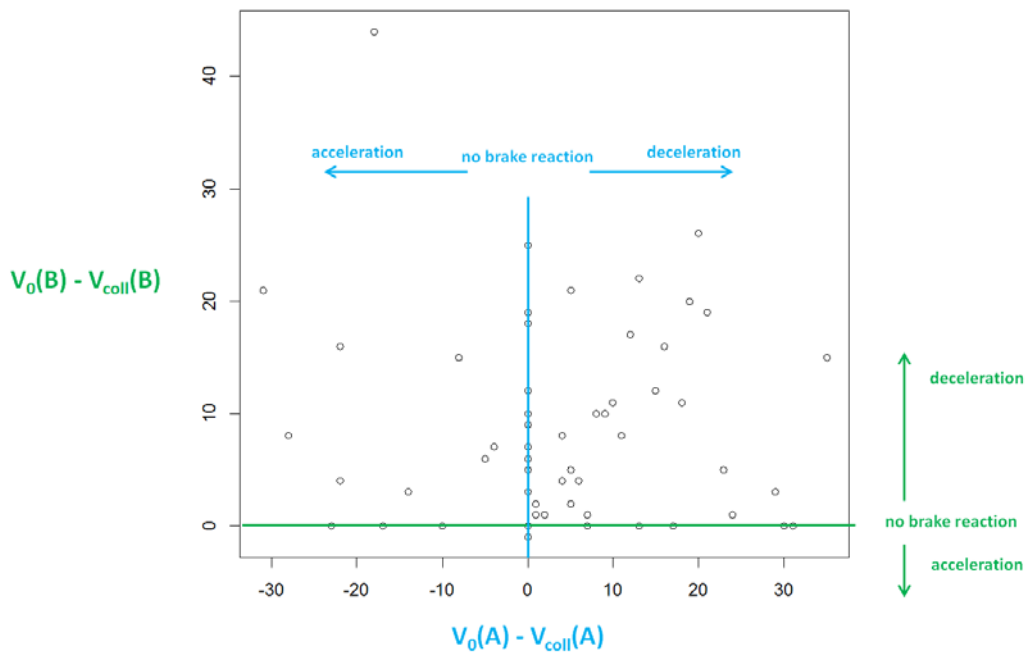


Figure 10: Pairwise speeds - accelerations and decelerations, LTAP/OD, KSI (N=76)

LTAP/LD

According to the assignment of accident types to the AS, see Appendix, all LTAP/LD relevant GIDAS cases were grouped leading to 49 KSI and 336 ALL accidents. An overview of the associated accident types showed that for KSI and ALL accidents, the accident type 302 emerged most frequently and covered at least ~94% of all LTAP/LD cases. Accidents assigned to 312 differ to 302 (accounting for remaining cases) accidents by the driving of another vehicle parallel to the vehicle with right of way.

Hence, all LTAP/LD KSI accidents assigned to accident types 302 or 312 have been analyzed towards the reconstructed driving and collision speeds of both crash participants. The average speeds are shown in Figure 11.

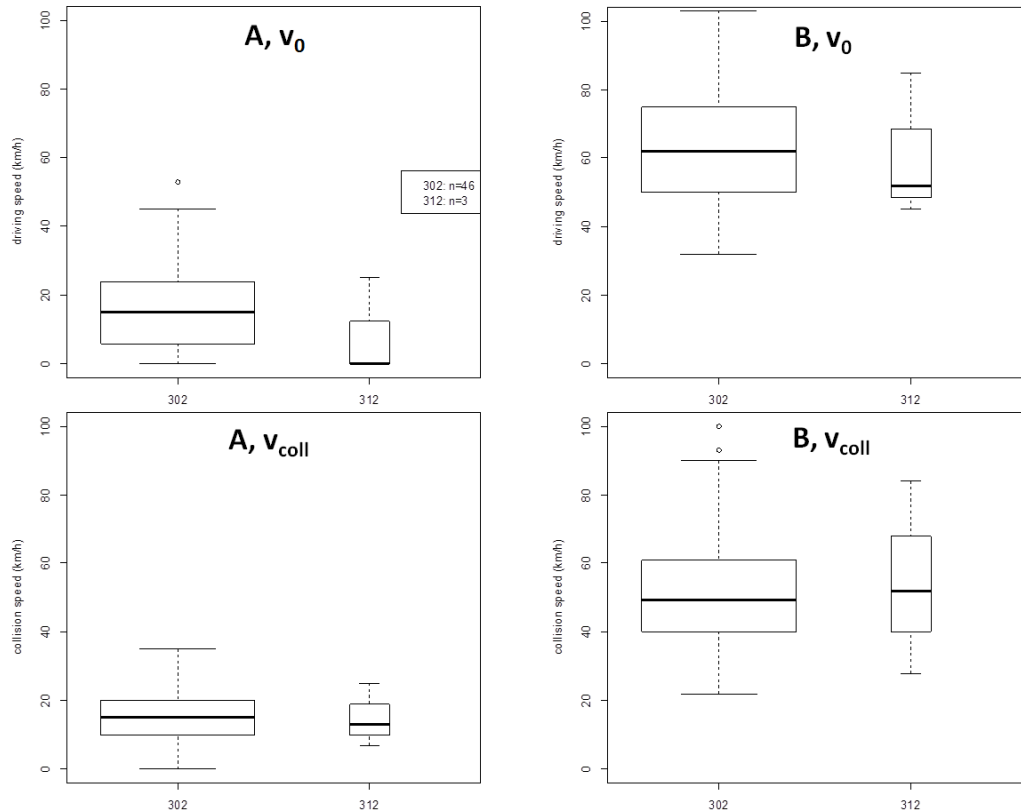
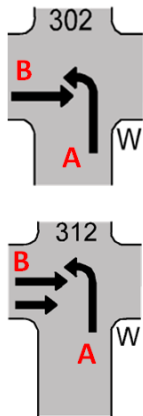


Figure 11: Boxplots of the driving (v_0) and collision (v_{coll}) speeds in LTAP/LD, KSI (N=49)

Table 8 summarizes these speeds approximately regarding their mean 50% (box without whisker), i.e., 50% of the accidents were within the specified speed ranges.

To specify appropriate test speeds for this AS LTAP/LD a comparison of pairwise speeds was required, i.e., pairs of speeds of vehicles A and B, both involved in the same accident, see Figure 12.

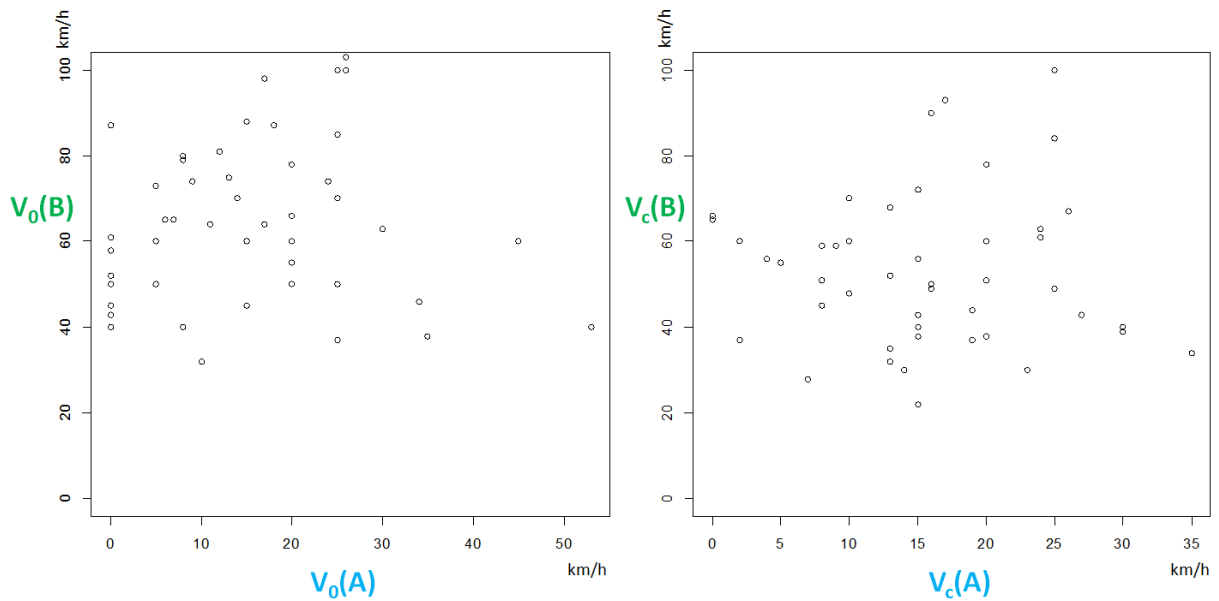


Figure 12: Pairwise driving (v_0) and collision (v_{coll}) speeds in LTAP/LD, KSI (N=49)

Additionally, Figure 13 shows the speed change (here difference of a passenger car's driving and collision speed) to identify the basic patterns of accelerations and decelerations in LTAP/LD KSI accidents.

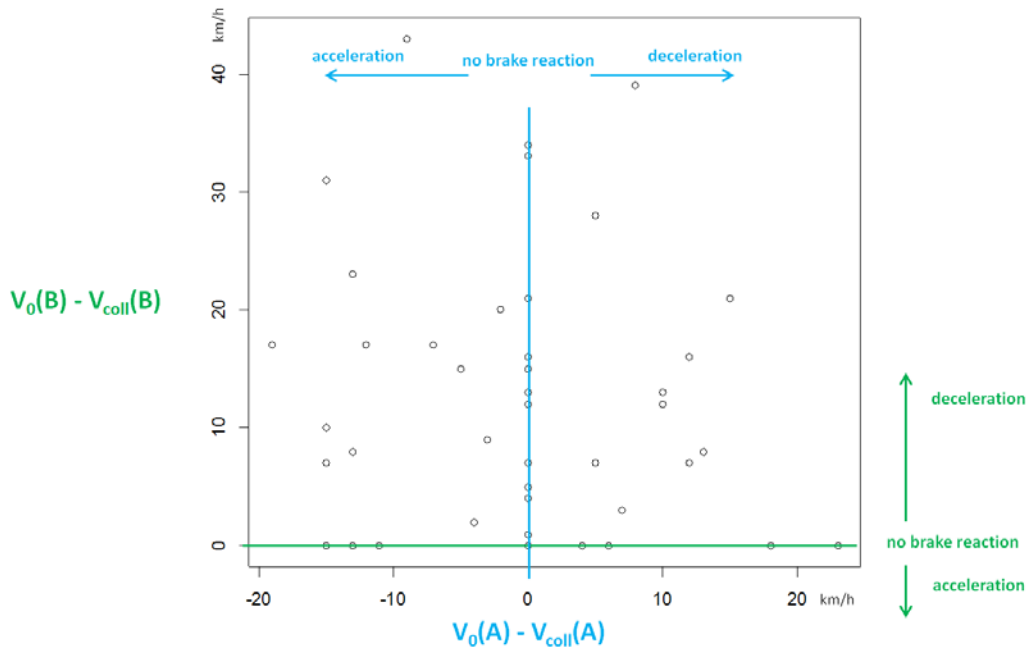


Figure 13: Pairwise speeds - accelerations and decelerations, LTAP/LD, KSI (N=49)

SCP

According to the assignment of accident types to the AS, see Appendix, all SCP relevant GIDAS cases were grouped leading to 86 KSI and 680 ALL accidents. An overview of the associated accident types showed that for KSI and ALL accidents, the accident types 301 and 321 emerged most frequently and covered at least ~92% of all SCP cases. Accidents assigned to 301 differ to 321 accidents by the direction of the privileged vehicle, either approaching from left or right.

Hence, all SCP KSI accidents assigned to accident types 301 or 321 have been analyzed towards the reconstructed driving and collision speeds of both crash participants. The average speeds are shown in Figure 14.

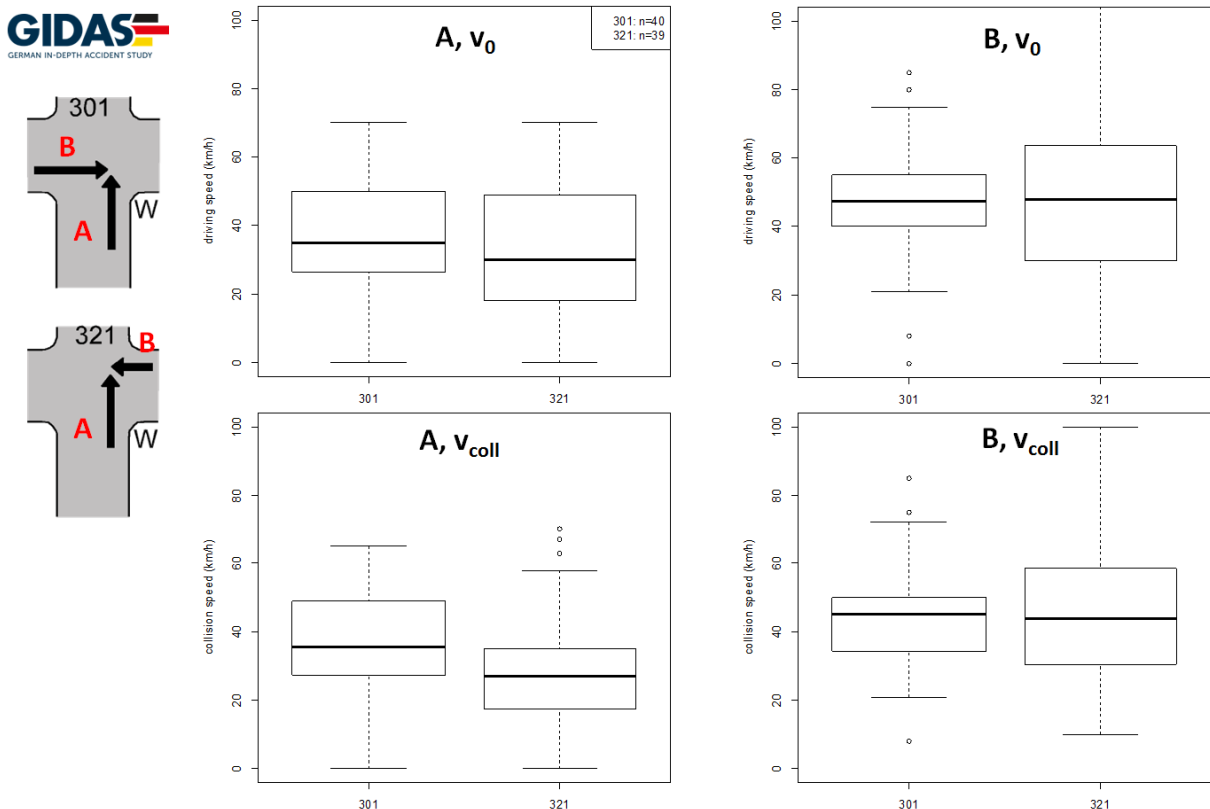


Figure 14: Boxplots of the driving (v_0) and collision (v_{coll}) speeds in SCP, KSI (N=86)

Table 8 summarizes these speeds approximately regarding their mean 50% (box without whisker), i.e., 50% of the accidents were within the specified speed ranges.

To specify appropriate test speeds for this AS SCP a comparison of pairwise speeds was required, i.e., pairs of speeds of vehicles A and B, both involved in the same accident, see Figure 15.

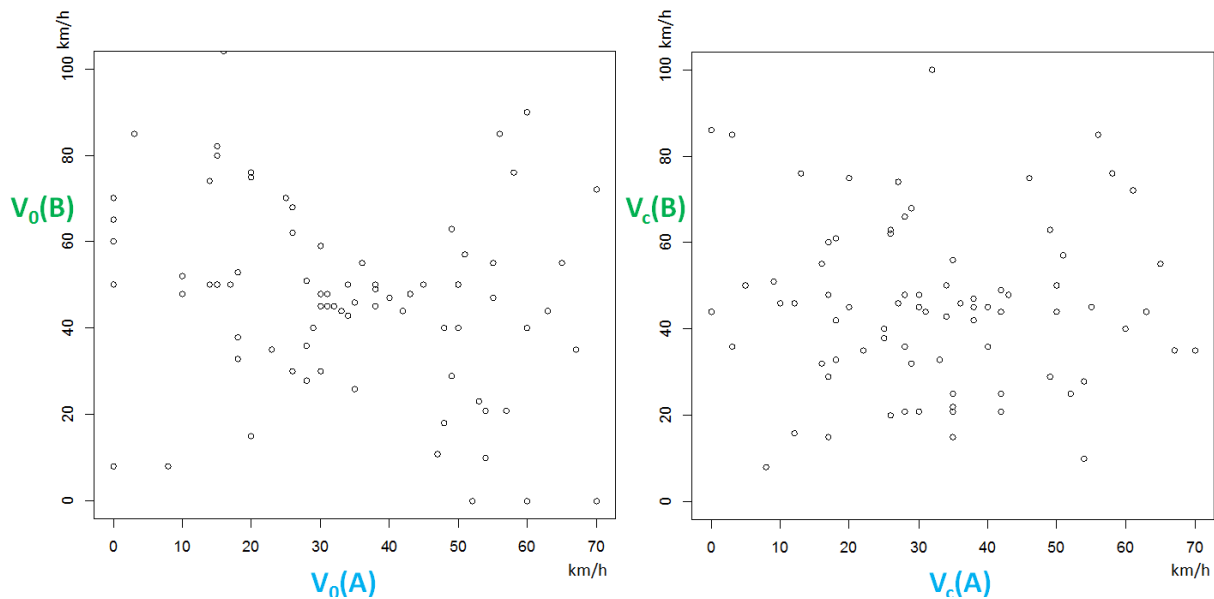


Figure 15: Pairwise driving (v_0) and collision (v_{coll}) speeds in SCP, KSI (N=86)

Additionally, Figure 16 shows the speed change (here difference of a passenger car's driving and collision speed) to identify the basic patterns of accelerations and decelerations in SCP KSI accidents.

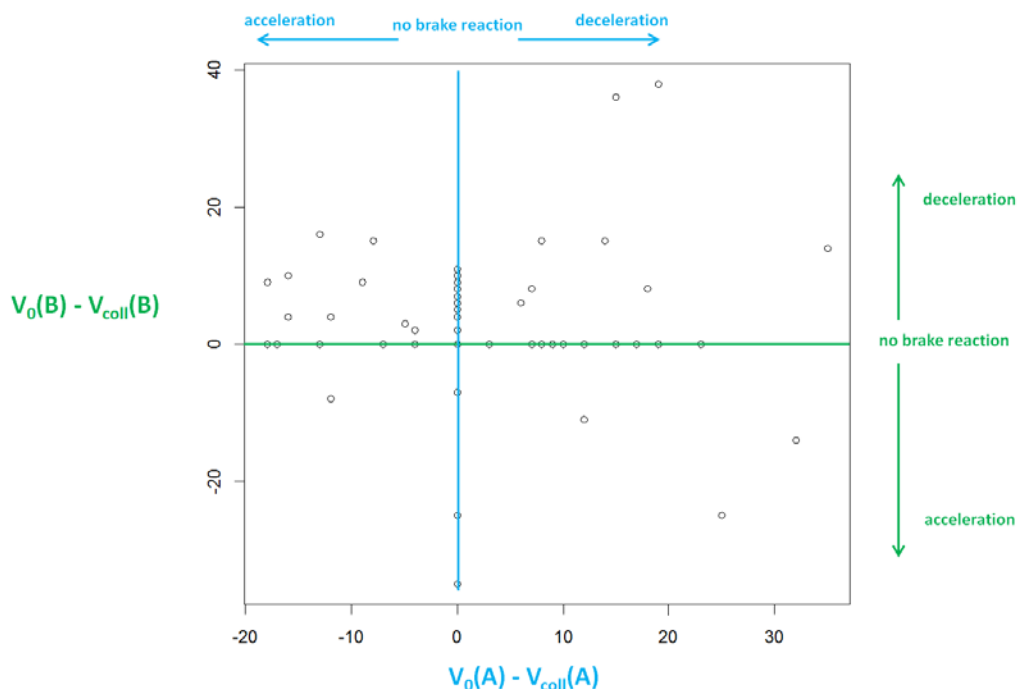


Figure 16: Pairwise speeds - accelerations and decelerations, SCP, KSI (N=86)

Use Cases

Required Parameters

Up to the level of Accident Scenarios, a rather abstract description of the basic movements of the vehicles is given. At the same time, the most important conflict situations at intersections to be addressed by corresponding AEB systems are known. However, when it comes to testing of such systems, scenarios should be representative

with regard to the crucial parameters. The selected parameters for further investigations are listed in Table 9. The principles of the analysis are provided for LTAP/OD in this paper. Analogue gained results for LTAP/LD and SCP were summarized below.

Table 9: Parameters under investigation using the GIDAS-based PCM to derive Use Cases

Parameter	Description / Main reason for consideration
Intersection type	Basic layout of an intersection (crossroad, t-junction etc.)
Right-of-Way	Driving behavior might be affected by the kind of road/traffic regulation
Angles between road arms	To estimate more exactly the relative direction of approach of the collision partners.
Lateral Offset between accident participants	Regarding a turning vehicle, the lateral distance to an oncoming crash opponent before initiating the turn maneuver is of interest. Defining this parameter is required to enable the initial positioning of the two vehicles.
Speed Profiles	To estimate the initial and collision velocities of both collision partners. Initial velocity means the speed at the point in time when the driver recognized the situation to be critical and thus, started a braking or evasive maneuver. In addition, data about the longitudinal acceleration and deceleration is of interest.
Collision Angle	Represents the orientation of two colliding vehicles to each other at the time of the crash. It can be related to the longitudinal axes or to the velocity vectors of the colliding vehicles.
Impact Points/Overlap	To determine the overlap by comparing the impact points for each of the colliding vehicles pair wise.
Turning Radius/Curvature	Relevant for turning vehicles

LTAP/OD - Lateral Offset

The lateral offset of both vehicles in the LTAP/OD could not be extracted automatically from GIDAS. Therefore, the sketches of the corresponding accident sites have been analyzed case-by-case to extract at least the relative positions of the lanes used by the accident participants. In general, the evaluation was performed regarding ALL LTAP/OD accidents; however, if classified as significant during the analysis of certain further parameters, the results for KSI accidents were reported separately. Additionally, the dataset was reduced to those cases that are included in the PCM (version 2016/2), as the associated subset was used in particular to determine the turning radii. Also, only those cases were evaluated where driver of the turning car had to give way to the oncoming traffic, which represented 88 % of all LTAP/OD cases.

Finally, three simplified intersection layouts were identified, see Figure 17. Layout 1 represents a rather clean layout, containing only two lanes in sum (one lane per direction of travel). The lanes are not separated by any other road elements. Layout 2 contains specific lanes (at least for the left turning car). However, as with layout 1, the lanes used by the accident participants are not separated by any other road elements. Layout 3 represents a rather complex geometry, containing a separation between the lanes used by the accident participants due to road elements such as traffic islands or additional lanes, for instance. Compared to layouts 1 and 2, this leads to an additional offset.

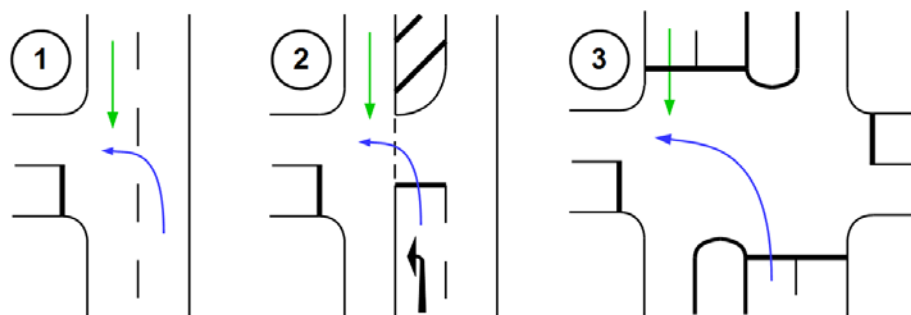


Figure 17: Simplified layouts for the LTAP/OD scenario

The spread of the lane widths and offsets with regard to the layouts 1 and 2 is relatively low. Regarding the offset, the mean 50% is in a range of approximately 3.2 to 3.5 m. It is worth noting that the lane widths also match the most relevant left turn types described in the German recommendations for the construction of rural roads [19].

However, the aforementioned determination of the lateral offset between the vehicles' centers followed the assumption that drivers are using exactly the middle of their lanes. In this context, the actual positions of the

vehicles within the used lanes was checked, finding that drivers tend to use the area facing away from the oncoming traffic. Thus, it was agreed on a lateral offset of 3.7 m for layout 1 and 2.

Looking at layout 3, the lane widths are smaller compared to layouts 1 and 2 which is possibly due to their high relevance in urban areas. On the other hand, the spread of offsets is much higher and also the mean 50 % (approx. 9.5 to 15.5 m). The presence of additional lanes between the accident participants, other road elements like traffic islands as well as tram tracks is a possible reason. Even though the significance is limited considering the small number of 15 cases, the results indicate that the variety of possible road dimensions increases with the complexity of layouts. Thus, the median of the distribution provides at least a minimum of representativeness, which means a lateral offset of around 11.5 m for layout 3, see Figure 18.

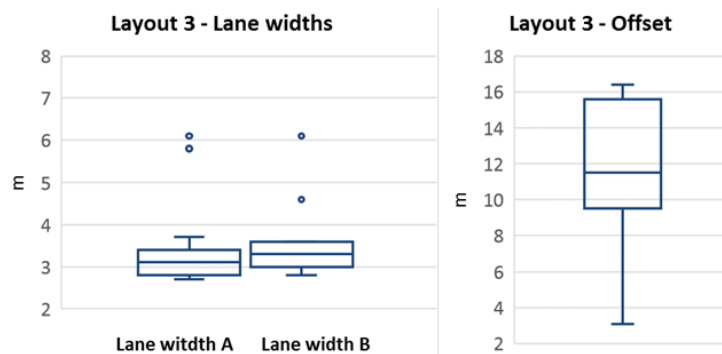


Figure 18: Boxplots of the lane widths of vehicle A (turning vehicle) and B (oncoming vehicle) and the resulting lateral offset for layout 3 (n=15) in LTAP/OD

LTAP/OD - Turning Radius

The dimension of a circle and thus, the radius can be derived by the positions of three points on an associated circular arc. It was considered to cover the arc as completely as possible by choosing the point where the turning maneuver is initiated, the collision point and the point in the middle between the aforementioned points.

Point 1 was identified by evaluating the time to collision (TTC) where the yaw rate ($d\phi/dt$) of the turning car exceeds a threshold of $5^\circ/s$. Note: $5^\circ/s$ is a value that cannot count as disturbance but as a deliberate action from the driver to change his way of travel. The $5^\circ/s$ were derived from the $4^\circ/s$ found in the literature as a tolerated disturbance from the perspective of a driver, see e.g., [20] and [21].

The TTC of the collision point (point 2) is equal to zero. The TTC related to point 3 is given by the half of the TTC of point 1. Finally, the x and y coordinates for each of the evaluated points in time is given in the PCM, so that the radius (r) can be determined by calculating the center of the circle (O) the three given points have in common. Note: TTC in the context of PCM does not represent the theoretically remaining time before a collision under the assumption of a constant speed, but the actual time lag prior to the crash resulting from the PCM simulation.

Since it was assumed that the radius chosen by turning drivers is also dependent on the presence of certain road elements (especially islands) in the area of the exit roadway, the defined layouts 1-3 were extended. Two additional subcategories (a and b) were defined, distinguishing between such exit road arms with an island in the middle of the roadway and those without, see Figure 19.

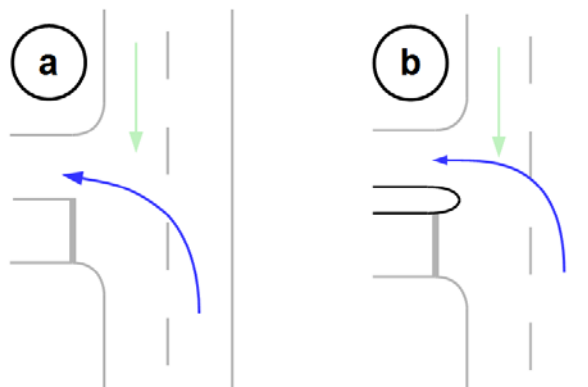


Figure 19: Distinction related to the presence of an island in the middle of the exit roadway

For the evaluation of the turning radii, six clusters (labeled as I-VI) were defined based on the layouts 1-3 and the subgroups a and b. On the one hand, the layouts 1 and 2 were merged, still distinguishing between the location of the accident site (urban/rural) and the presence of islands in the middle of the exit roadway. On the other hand, the distinction in terms of road elements was no longer pursued for layout 3. The resulting clusters and the associated turning radii are given in Table 10.

Table 10: Turning radii for different layout clusters

Cluster	Description	Area	No. of cases	Median radius
I	Layout 1a + 2a	urban	71	20.57
II	Layout 1b + 2b		24	25.41
III	Layout 3		68	19.64
IV	Layout 1a + 2a	rural	7	28.00
V	Layout 1b + 2b		65	21.87
VI	Layout 3		5	21.07

Regarding the urban clusters I and II, it is noticeable that the absence of a traffic island in the exit roadway does not lead to higher turning radii, even though this was expected before (assuming that the curve is cut more often in this case). An explanation might be that within urban areas the roadway width of the exit road arms as such is possibly rather narrow. With regard to the rural clusters IV and V, the results are in line with the expectations, although it has to be mentioned that the number of cases in cluster IV is rather low. Another interesting fact is that the turning radii related to the complex layouts (cluster III and cluster VI) have the lowest values. This leads to the conclusion that separations between the lanes used by the accident participants (like traffic islands for instance) prevent drivers from cutting the curve to a noticeable extent. Overall, it can be stated that across all the clusters there are no particular abnormalities.

LTAP/OD – Speed Profiles

The speed distribution of the turning vehicle for certain points in time prior to/at the collision ($TTC=0\dots5$ s) has been analyzed using the GIDAS-based PCM data. Table 11 shows the results for speeds at $TTC=5$ s and $TTC=0$ s and the longitudinal accelerations at the time of collision. Due to the small number of cases with regard to cluster IV and cluster VI, only the results of clusters I-III and cluster V are given.

The figures show that there are no particular abnormalities regarding the different clusters/layouts. In nearly all cases the turning vehicle is continuously moving with a speed higher than 5 km/h. Thus, turning vehicles involved in a crash do not seem to stand/wait before initiating the turning manoeuvre. Furthermore, the figures representing the acceleration at the time of collision show that constant speed during the crash is the most relevant situation. The number of cases with a turning vehicle accelerating during the collision is negligible. The remaining share of braking vehicles can have different reasons. Lower absolute values are possibly rather caused by a normal braking behaviour while turning, whereas the higher absolute values might represent emergency braking manoeuvres.

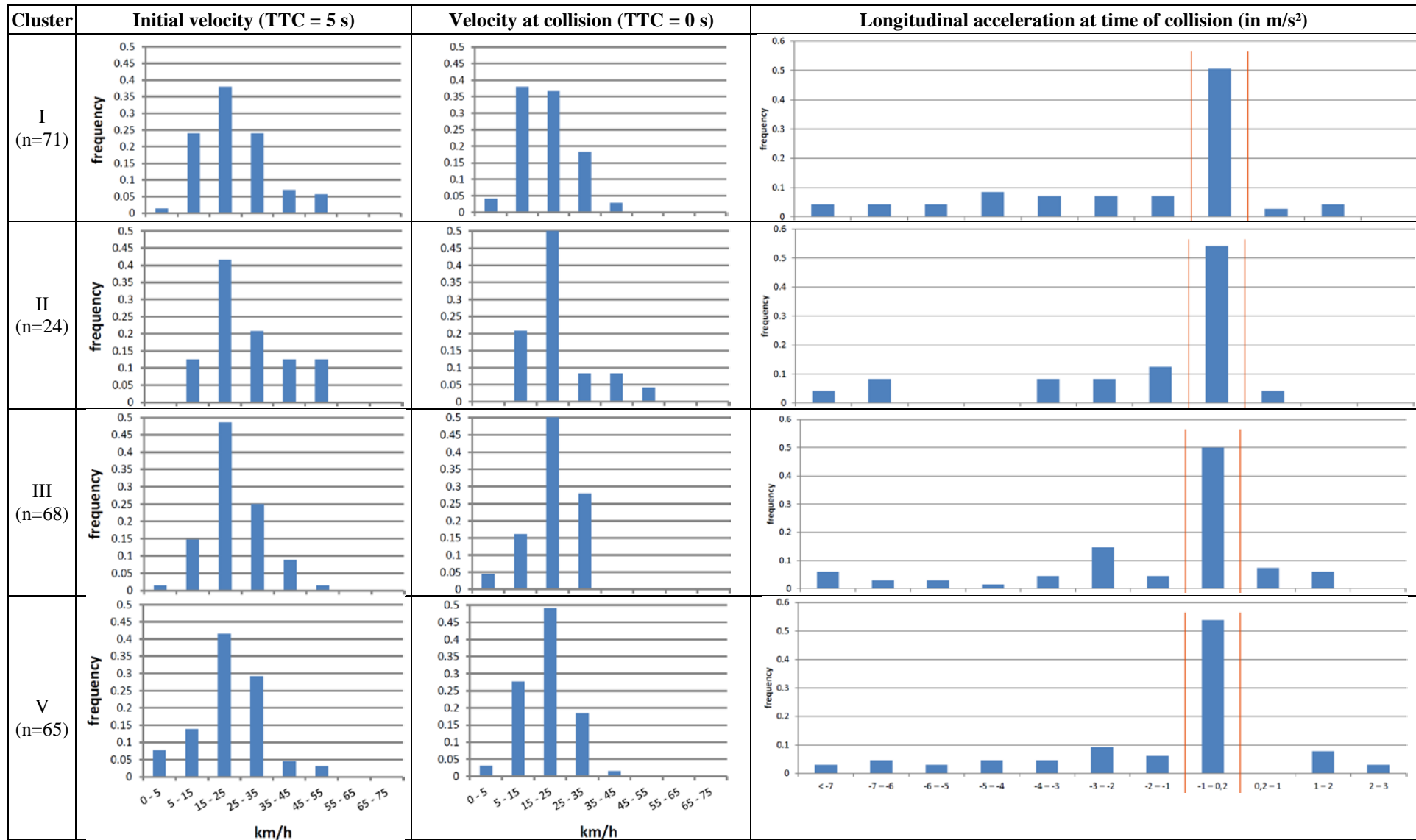
LTAP/OD - Impact Points / Overlap

The location of the main damage on a vehicle can be extracted from GIDAS; however, it does not necessarily describe satisfyingly the collision constellation at the time of collision. Therefore, a pairwise analysis of the impact points of the collision partners was performed enabling an approximation of the vehicles' overlap at the time of collision. In GIDAS the impact point is described by three variables: x_{impact} (distance to the foremost point of the vehicle in the direction of the vehicle's longitudinal axis), y_{impact} (distance to the longitudinal axis of the vehicle in the direction of the vehicle's lateral axis) and z_{impact} (vertical distance to the street surface).

To determine the frequencies of the impact points, a grid with regard to the vehicle contour was defined for the x- and y-directions as shown in Figure 20. The vehicle width was divided into three equal sections, while the vehicle length was divided into parts each of 12.5 % at the front and the rear and three sections each of 25 % for the remaining part. Depending on their location, the sections were labeled with a two digit number (from 11 to 53). In this context, the first digit represents the longitudinal location of the section, while the second digit represents the lateral location. Subsequently, each impact point could be assigned to the respective section.

As a next step, the bivariate frequency distribution with regard to the impact points of the two vehicles involved in the crash can be displayed by drawing a respective table. This makes it possible to identify the most relevant combinations of impact point sections and thus, the approximation of the corresponding overlap between two colliding vehicles.

Table 11: Distributions for speeds and longitudinal accelerations at time of collision for different layout clusters, LTAP/OD



Note: GIDAS also records the point of first contact for each of the colliding vehicles, which could have been a potential variable to be evaluated alternatively. However, small variations of the collision angle might lead to big changes of the contact point. Thus, it was considered that the evaluation of the impact point provides more significant results.

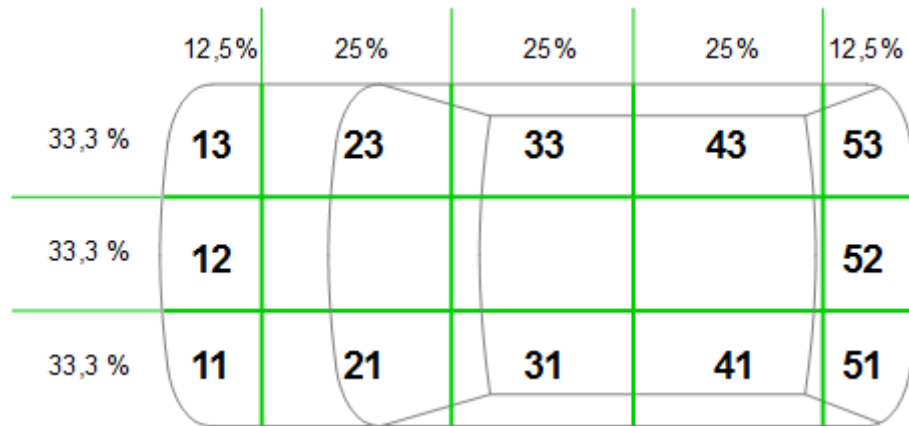


Figure 20: Definition of impact point sections

The notation “section A/section B” is used to address the respective combination of impact sections. For instance, the peak of pairwise impact points can be found at 13/11, representing 32 cases. It should be noted that some of the adjacent entries on the diagonals of the table are related to each other. Figure 21 gives an example: Regarding the initial overlap of both vehicles, combination 11/13 is comparable to combination 12/12, depending on intrusions during the crash phase and varying collision angles.

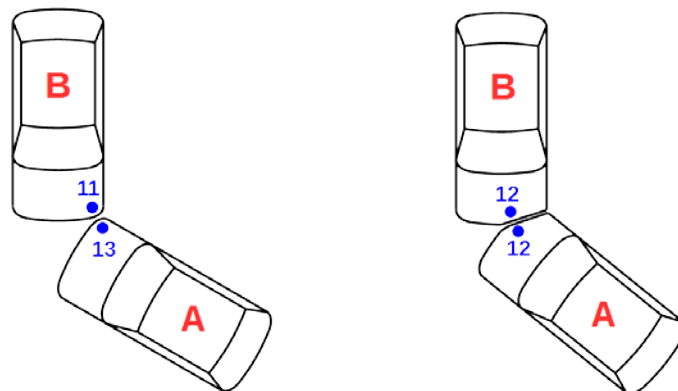


Figure 21: Similar impact point combinations regarding the initial overlap

Evaluations of the frequencies of the impact sections have been performed for “ALL LTAP/OD cases”, “KSI LTAP/OD cases” and “ALL LTAP/OD layout 1+2 cases”. The combinations of impact sections for ALL cases tend to be normally distributed around the above mentioned peak 13/11. Regarding KSI cases, no significant difference to ALL cases could be identified, also due to the small number of cases. Thus, the decision was taken to focus on ALL LTAP/OD cases and on the both most important intersection layouts 1 and 2, see Figure 22 for the respective impact section distribution.

		Vehicle B												
LTAP/OD Layout 1+2 (ALL)		left				front			right					
		Section	51	41	31	21	11	12	13	23	33	43	53	Total
Vehicle A	right	53												0
		43									1			1
		33						1	6					7
		23					1	5	9	2				17
	front	13				1	17	19	7	1				45
		12				5	23	5	2					35
		11		1	1	11	18	1						32
		21		1		3	1							5
	left	31												0
		41												0
		51												0
		Total		0	2	1	20	60	31	24	4	0	0	0

Figure 22: Impact points of LTAP/OD for layout 1 and 2, ALL cases

To identify the most relevant combinations of impact sections, a ranking was performed, see Table 12. In this context, the values of the aforementioned similar combinations of impact sections are summed up. All combinations of impact sections which represent at least 50 % of the evaluated cases (indicated by the column “cumulated shares”) were considered to be transferred into Use Cases.

Table 12: Ranking of impact point sections for layouts 1 and 2, LTAP/OD

Section combination (veh A/veh B)	Similar section combination (veh A/veh B)	No. of cases	Total	Relative share	Cumulated shares
12/11	11/12, 13/21	23+1+1	25	17.6 %	17.6 %
11/11	12/21	18+5	23	16.2 %	33.8 %
13/11	12/12	17+5	22	15.5 %	49.3 %
13/12	12/13, 23/11	19+2+1	22	15.5 %	64.8 %

Use Cases for LTAP/OD

Branching all LTAP/OD cases as previously described led to the corresponding Use Cases given in Table 13. Note: The mentioned speed ranges represent the middle 50% of the respective distributions, also referred to as interquartile range (IQR). To provide a potential link between the basic shares and the results of high-level accident data, the distributions of intersection types (crossing, t-junction and other types) is given, too. Apart from the possibility of testing several speeds, the combinations of the two layout groups and nine pairwise impact sections already leads to a number of 18 Use Cases.

Table 13: Use Cases for LTAP/OD

Inters. type	Layout 1+2				Layout 3				
	Crossing	T-junction	Other		Crossing	T-junction	Other		
Shares (in %)	56.0	40.7	3.3		74.0	24.7	1.3		
Lateral offset	≈ 3.7 m				≈ 11.5 m				
Shares (in %)	70 %				30%				
Speed profiles	Vehicle A		Vehicle B		Vehicle A			Vehicle B	
$v_{initial}$ (IQR)	16-30 km/h		47-65 km/h		20-33 km/h			45-53 km/h	
$v_{collision}$ (IQR)	12-25 km/h		38-55 km/h		16-27 km/h			33-50 km/h	
a_x (at collision)	Constant speed		Constant speed		Constant speed			Constant speed	
Impact sections	12/11	13/11	13/11	13/12	13/11	23/13	12/11	11/11	23/12
Shares (in %)	17.6	16.2	15.5	15.5	21.5	12.7	11.4	10.1	10.1

Use Cases for LTAP/LD

Similar to LTAP/OD scenario evaluation, simplified intersection layouts have been defined with regard to the LTAP/LD scenario, resulting in three groups (from a rather clean layout 1 up to a rather complex layout 3). The evaluation of approaching angles as well as turning radii showed that the layouts 1 and 2 are quite similar (median turning radius: ≈ 25 m). In addition, these two layouts represented 89 % of all LTAP/LD cases. Thus, layout 3 was found to be less relevant.

Regarding the speed profiles and accelerations, it was found that vehicle A is driving with low speed (< 5 km/h) in a significant number of cases (about 15 %) compared to the other scenarios. Accordingly, deceleration is not relevant with regard to vehicle A. Looking at vehicle B, constant speed at the time of collision took place in about 34 % of all cases, whereas a braking maneuver was initiated in about 66 % of all cases. The most relevant impact point combinations for the merged layouts 1 and 2 were identified, resulting in four crash constellations.

Branching all LTAP/LD cases finally led to the corresponding Use Cases given in Table 14. The speed ranges represent the middle 50% of the respective distributions (IQR). Apart from the possibility of testing several speeds, the combinations of all identified parameter groups (acceleration and pairwise impact sections) already leads to a number of 24 Use Cases.

Table 14: Use Cases for LTAP/LD

	Layout 1+2 (89 % of all LTAP/LD cases)				
Inters. type	Crossing		T-junction		Other
Shares (in %)	18.5		60.5		21.0
Speed profiles	Vehicle A			Vehicle B	
v_{initial} (IQR)	8-19 km/h			45-61 km/h	
$v_{\text{collision}}$ (IQR)	9-16 km/h			37-50 km/h	
a_x (at collision)	Const.	Accel.	Braking	Const.	Braking
Shares (in %)	47.0	32.0	21.0	33.8	66.2
Impact sections	11/13		21/12		11/12
Shares (in %)	22.4		14.4		11.2
					10.4

Use Cases for SCP

First, all SCP cases have been split into two sub-scenarios based on the direction of approach of the prioritized vehicle (from left or right). With regard to the angle of approach, no particular abnormalities were found. Thus, test scenarios with an orthogonal orientation of the vehicles during the entire pre-crash phase can be seen as sufficiently representative for the SCP cases.

Regarding the initial and collision speeds, no significant differences were identified between the sub-scenarios SCP/L and SCP/R. However, looking at the acceleration at the time of collision, specific characteristics have to be taken into account. Significant shares of vehicle A and vehicle B are performing braking manoeuvres in both sub-scenarios. Finally, the most relevant impact point combinations were identified, resulting in four crash constellations for each of the two sub-scenarios.

Branching all SCP cases led to the corresponding Use Cases given in Table 15. The speed ranges represent the middle 50 % of the respective distributions (IQR). Apart from the possibility of testing several speeds, the combinations of the sub-scenarios and the further parameter groups (acceleration and pairwise impact sections) already leads to a number of 32 Use Cases.

Table 15: Use Cases for SCP

	SCP/L				SCP/R			
Inters. type	Crossing		T-junction		Crossing		T-junction	
Shares (in %)	92.0		6.6		91.8		7.7	
Speed profiles	Vehicle A		Vehicle B		Vehicle A		Vehicle B	
v_{initial} (IQR)	19-44 km/h		37-52 km/h		25-46 km/h		30-50 km/h	
$v_{\text{collision}}$ (IQR)	19-40 km/h		33-48 km/h		21-40 km/h		26-46 km/h	
a_x (at collision)	Const.	Braking	Const.	Braking	Const.	Braking	Const.	Braking
Shares (in %)	75	25	50	50	50	50	50	50
Impact sections	11/13	31/12	21/13	21/12	33/12	23/12	13/11	23/11
Shares (in %)	15.7	15.7	13.6	11.4	14.8	13.9	12.2	11.8

SUMMARY

The Intersection 2020 project was initiated to develop a test procedure for Automatic Emergency Braking systems in intersection car-to-car scenarios to be transferred to Euro NCAP. The project aims to address current road traffic accidents on European roads and therefore sets a priority of the identification of the most important car-to-car accidents and Use Cases. In a later stage taking into account technological and practical limitations, Test Scenarios are derived from the Use Cases.

This report provides an overview of common car-to-vehicle(at least four wheels) collision types at junctions in Europe, specifies seven Accident Scenarios from which the three scenarios “Straight Crossing Paths (SCP)”, “Left Turn Across Path – Opposite Direction Conflict (LTAP/OD)” and “Left Turn Across Path – Lateral Direction (LTAP/LD)” are most important due to their high frequencies of severe car-to-car accidents. Technical details about crash parameters such as collision and initial speeds are delivered. The analysis work performed is input for the definition and selection of the Use Cases as well as for the project’s benefit estimation.

Various accident datasets from Europe have been analyzed. Two major injury severity groups have been investigated: killed and seriously injured (KSI) and killed, seriously and slightly injured (ALL).

Most countries in Europe distinguish between intersection layouts; however, the comparability among each other is limited. The lowest common denominator was found in the categorization based on an initiative by the EU. However, although these definitions are widely accepted and applied, only a few countries work accordingly.

The numbers of accidents and fatalities in accidents at intersections involving a passenger car were shown per intersection type. In both statistics, it was found that accidents at crossroads and T- or staggered junctions are of highest relevance, followed by roundabouts. Focusing on accidents at intersections between one passenger car and another road user showed that around one-third of all accidents and related fatalities could have been assigned to car-to-PTW accidents and one-fifth of all accidents and fatalities to car-to-car accidents.

Regarding severe car-to-car accidents 38% out of 34,489 car-to-car accidents in Europe happened at intersections. These figures correspond to 18% of the fatalities (4,236 fatalities in total). Considering all intersection types, around half of all related accidents happened in urban environments whereas this number decreased to one-third of all fatalities. It has to be noted that the aforementioned proportions of the number of accidents and fatalities per intersection type may reflect rather the frequency of these intersection types in Europe than certain associated risk factors.

Further results based on the CARE analysis comprised that the proportion of road fatalities per country occurring at intersections varies widely across the EU and that there are proportionately more fatalities in daylight/twilight.

In addition, latest national accident statistics from France, the United Kingdom, Spain and Germany have been analyzed regarding road traffic accidents at intersections. Overall, the results were similar to the ones obtained from the CARE analysis. The shares of accidents in urban areas differed considerably between the countries. Severe car-to-car accidents occurred most often on crossroads and T- or staggered junctions. Contrarily, two-thirds of these accidents were assigned to crossroads in France, but to T- or staggered junctions in the UK and around half of these accidents each to crossroads and T- or staggered junctions in Germany. In Spain, half of the severe accidents occurred on crossroads and one-third on T-or staggered junctions. At roundabouts, severe accidents were similarly proportioned in urban and rural areas. Fatal crashes happened most often in rural areas.

Germany uses a different coding of road traffic accidents at intersections. Also, accidents at roundabouts were coded as accidents at intersections until the year 2015. Since 2016, accidents at roundabouts are coded separately in the national statistics. However, to provide possibilities for direct comparisons with other countries different approaches were considered. The most promising approach was found in a work by the Fraunhofer Institute IVI which developed a tool (commissioned by Toyota Motor Europe) being able to distinguish between different intersection types. Relevant results were kindly provided to the Intersection 2020 project.

Use Cases are supposed to be derived from Accident Scenarios and by adding detailed information for example about the road layout, right-of-way and the vehicle trajectories prior to the collision. A first attempt to generate a proper list of Use Cases based on the available collision data, using clustering algorithms and having the principal goals of the project in mind failed as the application of the statistical models to the data directed quickly into various issues and uncertainties but also similar results as presented in literature. Further, it became clear that vehicles’ trajectories are important but could not be derived from GIDAS and various parameters (e.g., varying lane width, view obstructions), identified as being meaningful, could not be transferred to any Test Scenario for consumer programs in next years for which reasons a pragmatic approach was finally preferred. The principles of the Use Case analysis are provided for LTAP/OD in this paper. Analogue gained results for

LTAP/LD and SCP were summarized. Finally, 74 Use Cases were identified. This large number indicates the complexity of intersection crashes due to the combination of several parameters.

Regarding the scenario LTAP/OD two main groups were identified as suitable to assign further characteristics: intersections with adjacent lanes used by the accident participants (layout 1 and 2) as well as intersections with an additional lateral offset between the lanes (layout 3). For the first group, which represents approximately 70 % of all LTAP/OD cases, a lateral offset of 3.7 m was identified. The second group has a larger spread of lateral offsets with a median of around 11.5 m. For both groups the turning radii were analyzed, considering also the location of the accident site and road elements such as islands in the exit roadway. However, no significant differences between the several clusters could be identified. To a certain degree, the same applies to the investigated speed profiles with regard to the turning vehicle. Finally, the most relevant impact point combinations for the case groups could be identified, resulting in four crash constellations for layout 1 and 2 and five crash constellations for layout 3.

Regarding the LTAP/LD scenario, simplified intersection layouts have been defined resulting in three layouts. The evaluation of approaching angles as well as turning radii showed that the layouts 1 and 2 are quite similar (median turning radius around 25 m). In addition, these two layouts represented 89 % of all LTAP/LD cases. Thus, layout 3 was found to be less relevant. Regarding the speed profiles and accelerations, it could be found that vehicle A is driving with low speed (< 5 km/h) in a significant number of cases (about 15 %) compared to the other scenarios. Accordingly, deceleration was not found being relevant with regard to vehicle A. Looking at vehicle B, constant speed at the time of collision took place in about 34 % of all cases, whereas a braking maneuver was initiated in about 66 % of all cases. The most relevant impact point combinations for the merged layouts 1 and 2 were identified, resulting in four crash constellations.

Regarding the SCP scenario, firstly, all SCP cases have been split into two sub-scenarios based on the direction of approach of the prioritized vehicle (from left or right). There were no conspicuous findings with regard to the angle of approach. Thus, test scenarios with an orthogonal orientation of the vehicles during the entire pre-crash phase can be seen as sufficiently representative for the SCP cases. Regarding the initial and collision speeds, no significant differences were identified between the sub-scenarios SCP/L and SCP/R. However, looking at the acceleration at the time of collision, specific characteristics have to be taken into account. Significant shares of vehicles A and B are performing braking manoeuvres in both sub-scenarios. Finally, the most relevant impact point combinations were identified, resulting in four crash constellations for each of the two sub-scenarios.

CONCLUSION

An analysis of car-to-car accidents at intersections in Europe has been conducted based on various datasets. It has to be noted that there is no clear definition of an intersection in Europe. And although definitions for different intersection types were achieved in a European consortium, only a few countries deal with it in the intended manner. Nevertheless, the data quality was sufficient to generate basic results for different European countries. More specific analyses have been performed using data from the German national accident statistics and the German In-Depth Accident Study (GIDAS).

The accident data analysis revealed that three Accident Scenarios are key for further work steps within the Intersection 2020 project (due to their high frequency rates in accidents with severe injury outcome) which are accidents at 1) Straight Crossing Paths (SCP), 2) Left Turn Across Path – Opposite Direction Conflict (LTAP/OD) and 3) Left Turn Across Path – Lateral Direction (LTAP/LD). Most of these accidents occurred under daylight conditions.

For each of these Accident Scenarios, basic crash parameters including the cars' initial and collision speeds were provided supporting the work of selecting appropriate test speeds. The data is also supposed to support the activities around the benefit estimation work in the project.

The presented Use Cases are the basis for the development of Test Scenarios considering their relevance, the transferability to the test track, an economic test environment and the expected performance of the systems to be tested.

To accelerate the market penetration of innovative junction/crossing autonomous emergency functions in state-of-the-art vehicles the consumer protection organisation Euro NCAP will change the assessment for the year 2020 and launch an assessment for technology that addresses the above listed accident scenarios. As an example the announced "car-to-car front turn across path" (CCFtab) test for 2020 will address the LTAP/OD accident scenario and the test is derived from the Use Cases presented in the core of this work. An assessment that addresses the remaining Accident Scenarios is strongly considered or even already announced.

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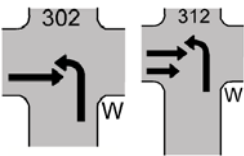
APPENDIX

Assignment of accident types [14] to Accident Scenarios

LTAP/OD



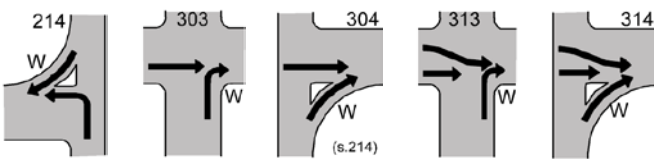
LTAP/LD



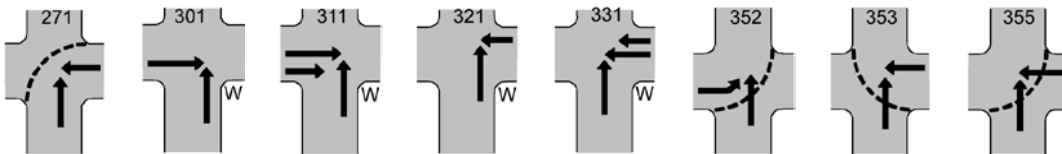
LTIP



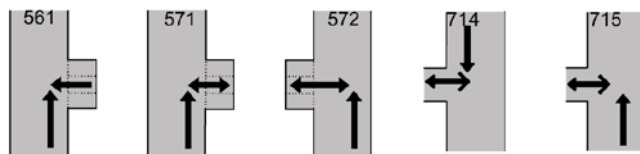
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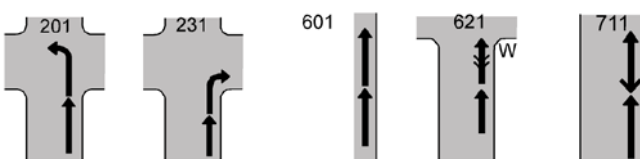
SCP



P/R



NA (Selection)



FUTURE POTENTIAL OF AUTOMATIC EMERGENCY BRAKING SYSTEMS FOR HEAVY TRUCKS

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ABSTRACT

The European Union requires an Automatic Emergency Braking System (AEBS) for all new heavy trucks (N3) since 2015. In case of an anticipated rear-end collision, the AEBS in accordance with EU regulation 347 – 2012 has to provide an adequate two-fold warning cascade and a subsequent emergency braking. After becoming a mandatory system, a strong increase of market penetration of AEBS has been established. However, first analyses in 2017 on German highways showed only minor impact of AEBS in the field [Petersen, E., “Wirksamkeit von Sicherheitssystemen im Straßengüterverkehr”, Zukunftskongress Nutzfahrzeuge, Berlin, 08. Nov. 2017]. Identified reasons for the minor impact are, amongst others, overruling of the AEBS by braking / accelerating, a probable system deactivation by the driver, and limited implications of an EU conform AEBS. Concerning the requirements, the EU conform system demands in its current level (effective November 2018), for instance, a deceleration of 20 km/h during an emergency braking on a highway approaching with 80 km/h a standing opponent at the end of a traffic jam– the collision may still occur with up to 60 km/h. Being aware of the limitations of AEBS requirements, BOSCH established top level requirements for a high-performance AEBS assumed to not only mitigate but to prevent most rear-end collisions of trucks.

The present study evaluates the benefit of Automatic Emergency Braking Systems exemplarily for German roads. It comprises of a thorough analysis of rear-end collisions involving N3-trucks, followed by stochastic simulations of a truck assumed to be equipped with either of the systems: the current EU-conform AEBS or a generic high-performance Automatic Emergency Braking System. In the first part of the study, the German in-depth accident study (GIDAS) was used to identify a potential field of effect for AEBS. In the second part, a simulation frame work specifically designed for the stochastic approach was established. It includes a sensor system, various road conditions from on-spot measured data and a simplified truck driver model accounting for driver reaction times and the specific kind of driver reaction.

About 2 300 N3-truck rear-end collisions with casualties per year in Germany can be positively influenced by an AEBS (field of effect for truck AEBS). In the second part of the study, after 2.5 mio stochastic simulations, avoidance potentials of at least 7% for the EU-conform minimum system and up to 84% for the high-performance AEBS were identified (assuming full AEBS penetration in N3 vehicles). These avoidance potentials could scale up to 1 900 collisions with casualties in Germany per year, if each truck would be equipped with the high-performance AEBS. For the remaining accidents the collision velocity would be significantly reduced, too.

In summary, this study reveals that an AEBS applied to and accounting for real-world accident situations can increase the effectivity of an Automatic Emergency Braking System preventing rear-end collisions of trucks

INTRODUCTION

One of the most feared situations for many car drivers is imagining an accident situations on motorways where a heavy truck crashes with almost no speed reduction into a standing car at the end of a traffic jam. This type of accident often results in severe or fatal injuries for the car occupants. At the same time, the car occupants, despite having identified the severity of the situation in advance, have to await their fate helplessly. Severe accidents involving heavy trucks in a front-to-rear-end situation are neither common nor occur often. However, if there is an accident of that type, damages might become catastrophic as well as the medial attention is huge. Furthermore, the motorway is often closed for several hours for rescuing and cleaning the road leading to long traffic jams and thereby to possibly additional economic impact.

To reduce such front-to-rear-end collisions, the European Union requires trucks to be equipped with an Automatic Emergency Braking System (AEBS) [1]. The EU regulation 347 – 2012 is mandatory for middle and heavy trucks (typically >3.5 t, for semi-trailers >8 t) with registration dates after November 2015 (1st level). Three years later, in November 2018, the 2nd level of the regulation became effective. In general, the AEBS should initiate an emergency braking protocol in case of an anticipated collision with a slower or standing vehicle in front of the truck to mitigate or even avoid the collision at all. While the regulation in detail specifies requirements for AEB systems admitted to the European market, the key requirements with respect to physical effectivity of such systems are the ones given in the following. Specifically, the AEBS has to be fully equipped to be able to prevent collisions of constantly moving opponents with velocities larger than 32 km/h (1st level) and 12 km/h (2nd level) being in an in-line constellation. Furthermore, anticipating a collision with a standing opponent, the AEBS has to reduce the truck velocity by at least 10 km/h and 20 km/h for 1st and 2nd level, respectively.

As commercial vehicles such as heavy trucks have small turn-over cycles, the hope was to reach a state where severe accidents caused by heavy trucks on motorways will significantly reduce. Now, some years later, the share of trucks on motorways equipped with an AEBS should have reached a reasonable level, and first impact of the legislation should be visible. Yet, the situation, especially on German motorways seems to be the contrary [2,3].

Here in this study, we will review the typical accident prior to the AEBS legislation and estimate the impact of a system as demanded by EU regulations, especially for the current 2nd level requirements. In our simulations, we will fully implement a generic three-fold warning cascade with acoustic warning first, followed by partial braking and, in its final stage, an automatic emergency braking. Additionally, we will introduce a generic AEBS based on a high performance system and estimate the maximum in avoidance and mitigation potentials. Based on a comparison with the current status, we will provide insights into how future automatic emergency braking systems could be designed to not only achieve the ambitious aim of EU legislations but also to come close to the maximum with respect to avoidance and mitigation potential of a future AEBS.

STATUS: HEAVY TRUCKS REAR-END COLLISIONS IN GERMANY

For 2017, the Federal Statistical Office of Germany (Destatis) presented in the annual German national accident report a total number of 302 656 accidents with casualties on German roads [4]. In 29 170 accidents of the same year (almost 10%), at least one truck was involved with a total of 32 234 participating trucks [5]. While the official report separates into light trucks (≤ 3.5 t), middle and heavy trucks (>3.5t) and semi-trailers, an individual reporting for heavy trucks (>12t) is not available. However, a trucks with mass >3.5t (middle and heavy trucks as well as semi-trailers) engaged in 15 805 accidents which serves as an upper bound for heavy trucks. Estimating the number of heavy trucks (>12t; N3) being involved in accidents with casualties on German roads will be a first step to assess the field of effect for a heavy truck AEBS.

Evaluating the effect of an AEBS for heavy trucks (>12t) requires a thorough analysis of the present status of the field of effect. For that purpose, the current study is based on in-depth accident data. A more than suitable database is the German in-depth accident study (GIDAS) recording detailed on-spot information about the accident, location and weather conditions, as well as all involved parties in more than 2 000 parameters per accident [6]. GIDAS is by now recording accidents for more than two decades. After recording the accidents, the course of events of each accident is reconstructed. Overall, GIDAS is a database with about 30 000 recorded and reconstructed accidents. By

weighting the distributions of accidents, locations and severity to the annual German national accident report, analysis of the GIDAS database is made representative for German roads. By construction, the GIDAS database records accidents with at least one injured occupant – consequently property-damages only incidents are not included in this study.

For the present study, we use a subsample of the GIDAS database containing the years 2005 to 2018 with a total of 28 225 accidents (Fig. 1). Thereof 933 accidents involved a heavy truck (>12t). Refining to an AEBS relevant scenario, defined by a collision of the truck’s front with the opponent’s rear-end in an in-line constellation, the GIDAS database provides 162 cases. Weighting these cases to German roads, a heavy truck is involved in about 12 500 accidents while the field of effect for an AEBS consists of a total of about 2 300 accidents in Germany.

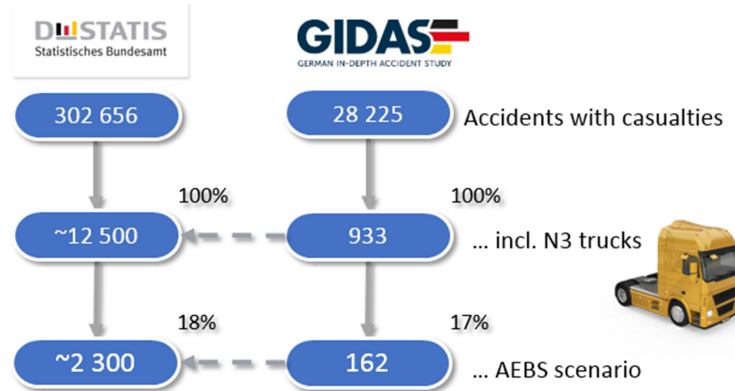


Figure 1: Case selection and basis for the present study, weighted for Germany 2017

In the following paragraphs, we present a thorough analysis of the 162 GIDAS cases – weighted to German roads. As a first result, the location of AEBS relevant crashes for heavy trucks is identified. Every second accident (48%) is found on a motorway, every fourth accident (21%) in rural areas and every third accident (31%) is found in urban areas (Fig 2a). Thereby, the typical road for front-to-rear-end collisions is a straight road – a relevant curve radius <500 m applies in only a marginal 2% of all cases.

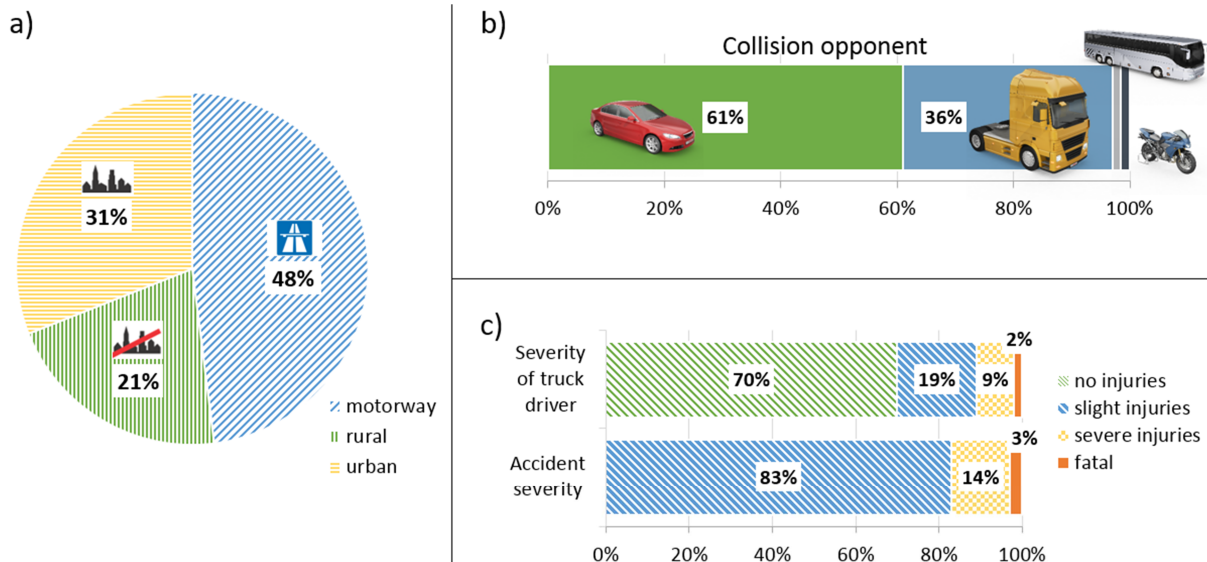


Figure 2: a) Share of collisions on motorways, in rural or urban environments. b) Type of collision opponent. c) Severity of truck driver in comparison to the accident severity. Please note: by construction of GIDAS the accident severity is at least “slight injuries”.

Next, collision participants and severity are characterized. In a vast majority of all cases, the collision opponent is a car (61%) or a truck (36%). In the remaining cases, the opponent was a motorcycle or a bus (Fig 2b). The age of the truck at the time of the collision follows approximately the age distribution of trucks in Germany with 80% being younger than nine years. Due to the huge momentum of a heavy truck and a seating position of the truck driver in a height of two and more meters above the road surface, for more than two of three cases (70%) the truck driver was not injured, while the opponent was at least slightly injured (Fig 2c). The truck driver was identified with light and severe injuries in 19% and 9% of all accidents, respectively. Despite the advantages of height and momentum, in 2% of the accidents, the truck driver died. However, one possible reason for the truck driver severity could be the fact that about every 10th truck driver was not belted. For the opponent, the accident severity is typically increased compared to the truck. Accordingly, the accident severity of all AEBS relevant accidents with casualties involving a heavy truck is categorized as “slight” in 83%, “severe” in 14% and “fatal” in 3%.

A closer look on typical velocities reflects the dynamics of a typical AEBS relevant heavy truck collision. The reconstructed initial velocity of the truck before the collision has an average of 61 ± 24 km/h (mean \pm one standard deviation, see Fig 3a). The initial state of the opponent was standing for 41% of all accidents (Fig 3b). In the other cases, the opponent was driving with an average of 45 ± 28 km/h, either moving with constant velocity (10%) or moving and braking before the collision (49%). The truck driver behavior prior to the front-to-rear-end collision concerning intensity of braking (with respect to the road condition) was in two of three cases classified as partial braking (66%). In only 10%, the truck driver was decelerating with full braking, while in 20% of all relevant accidents, the truck driver did not show any signs of braking (Fig 3a). The remaining cases (4%) are comprised of an accelerating truck, typically accelerating at traffic lights faster and/or earlier than the collision opponent in front of it.

The distribution of driver reactions prior to the collision reveals the true potential of an AEBS. A warning and subsequent automatic emergency braking could alert the 20% of drivers not braking and could support the 66% of drivers that were only partially braking. Moreover, the 10% of drivers that were fully braking could benefit from an early warning, too: applying the full brake load earlier could further reduce the collision velocity or possibly avoid the anticipated collision at all.

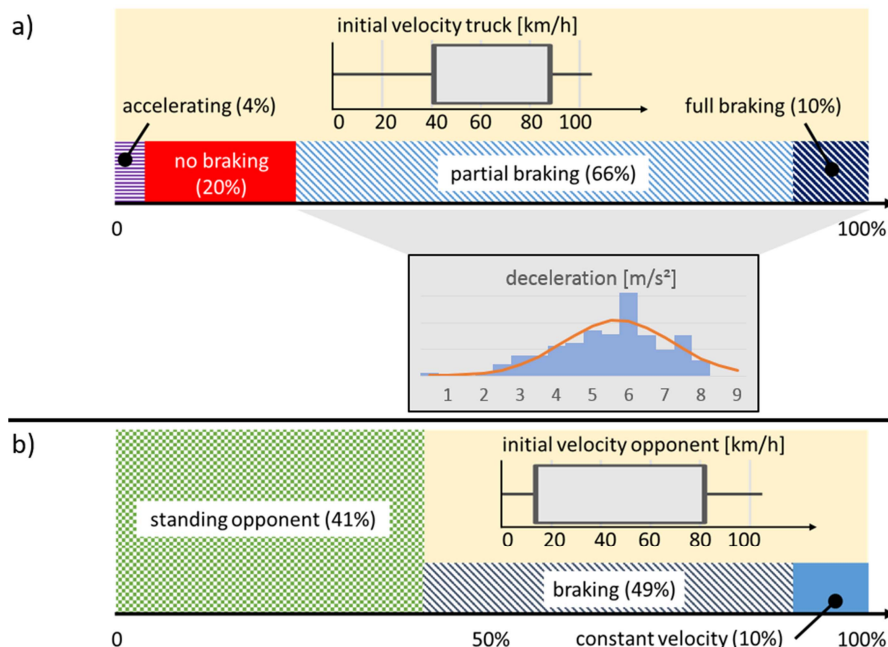


Figure 3: a) Initial truck velocities in a box plot (box equals to mean \pm one standard deviation) and type of driver reaction. Inset: reconstructed decelerations for a braking driver as distribution (blue bars) and its Gaussian approximation (orange line). b) Share of standing, constantly moving and braking opponents. The box plot depicts the initial velocity of the opponent.

As reported in the previous section, the GIDAS analysis shows that about 10% of all opponents move with a constant velocity. As an AEBS according to the EU regulation is required to avoid collisions only with constantly moving opponents, the minimal avoidance rates of all EU conform AEB systems is given by the share of accidents with a constantly moving opponent and an initial velocity above the given thresholds of 32 km/h and 12 km/h for 1st and 2nd level, respectively. However, only about 3% of all opponents move with constant velocity and are faster than 32 km/h, while for the 12 km/h threshold the share increases to 7% (data not shown).

In conclusion, our analysis of the status of front-to-rear-end collisions of heavy trucks shows three major results. First, for a vast majority of collisions, the collision opponent is a car or truck and is prior to the collision in an in-line constellation. Thus, detecting and classifying the anticipated collision becomes possible for most cases. Second, an AEBS could warn 20% of truck drivers not braking prior to the collision and support about 2 out of 3 drivers by applying the maximal brake force. Third, a current EU-conform AEBS avoids only at least 7% of all AEBS relevant collisions involving a heavy truck. Here, even at this stage of the study, a possible benefit of a system beyond EU regulations becomes obvious.

SIMULATION STUDY

Simulation layout

The overall simulation study aims to unravel three main questions:

- What is the avoidance potential of a warning only system in comparison to a high performance AEBS?
- Which share of accidents is mitigated and what is the benefit in reduced collision velocity?
- What is the main advantage of a high performance system compared to a minimal system?

The simulation is designed to fully image the pre-crash trajectory of both main participants in the front-to-rear-end collision. Out of 162 cases in GIDAS identified as AEBS relevant front-to-rear-end collisions involving a heavy truck, a total of 127 cases provide all information necessary to reconstruct the pre-crash trajectories. At the initial state, both participants approach the scene with their respective reconstructed initial velocities. Here, the initial state is assumed to be at least five seconds before the original collision. If applicable, the opponent starts braking as it was reconstructed from the original case. Thereby, we assure to challenge the generic AEBS in the simulations with an opponent behavior as close as possible to the original case. The original truck driver commands are removed and it is assumed the truck driver will only react to AEBS warnings. With these assumptions, the benefit of an AEBS to a cautious truck driver stays beyond the scope of this study. However, the main purpose of the present study is the assessment of the effectivity of an AEBS conform to current EU regulations (2nd level) and the differences between this minimal AEBS and a high performance system.

For each of the 127 GIDAS cases and both types of AEBS specifications, the simulation is performed in three scenarios: first, there is no AEBS present, second, the system generates only an acoustic warning with the truck driver braking and, third, the full AEBS procedure (with acoustic warning, partial braking and in the final step an emergency braking) is applied. The simulation itself is set up as a stochastic simulation with variations in the reaction of the truck driver. In contrast, the reactions of the AEBS are deterministically parametrized as described below. To maintain a statistically stable simulation, a total of 10 000 simulations per GIDAS case are performed. Consequently, for each system involving truck driver reactions, warning only system and full AEBS, a total of $127 \times 10\,000 = 1.27$ mio. runs is performed. The first system (re-simulating the original case without AEBS) is fully deterministic lacking the stochasticity of the other systems and, thereby, assures a proper foundation for a statistical analysis of the simulations.

The technical, yet generic design of the AEBS involves a threefold warning cascade. Upon detection of an AEBS relevant situation, an acoustic signal alerts the driver, followed by initiating a partial braking and finally establishing the emergency braking (see Fig. 4).



Figure 4: Schematic view of AEBS phases

The threefold warning cascade meets the EU regulations if the acoustic warning and the partial braking start at least 1.4 s and 0.8 s, respectively, before the emergency braking phase. While the acoustic warning in the simulation just alerts the truck driver to react and apply the brakes by himself, the partial braking follows a protocol simplified by three steps: (i) system reaction time (no braking), (ii) linear ramp up of the brake force up to the desired deceleration and (iii) holding the maximal constant deceleration of the partial braking phase. Typically, the partial braking phase reduces the velocity of the truck by only a few kilometers per hour and is subsequently followed by an emergency braking phase. After reaching the trigger level for the emergency braking phase, a brake protocol applies again with system reaction time, ramp up of brake force and constant deceleration – up until standstill if necessary. While following the same functional protocol, the individual parametrization is different for both phases. The overall AEBS system parameters are chosen as displayed in table 1, meeting a typical – yet generic – high performance parametrization specific to heavy trucks.

Table 1: Generic AEBS parameter specifications

Category	Value
Start warning phase before emergency braking	1.4 s
Start partial braking phase before emergency braking	0.8 s
System reaction time partial braking	0.4 s
Ramp up gradient partial braking	12.8 m/s ³
Maximal deceleration partial braking	3.5 m/s ²
System reaction time emergency braking	0.15 s
Ramp up gradient emergency braking	10.0 m/s ³
Maximal deceleration emergency braking	8.0 m/s ²

The AEBS reacts to an opponent, if a collision is anticipated. To detect the position and velocity of the opponent, the truck is equipped with a sensor module. In the case of AEBS relevant front-to-rear-end collisions, the opponent is typically in a straight line in front of the truck. Thus, the sensor consists of a list of ranges up to which opponents are detected depending on a generalized radar cross section for motorcycles, cars and trucks. The ranges were chosen to mimic a current state-of-the-art frontal long-range radar, independent of the manufacturer, ranging up to 200m.

For a simulation study of a driver assistance system, supporting the driver in his reactions, a truck driver model is needed. As a matter of fact, no released model for a truck driver is currently available. Thus, a generic model was set up. For the present comparative study, the truck driver is not initiating the emergency braking by himself but reacts only to an acoustic warning of the AEBS. The generic driver is modelled by a probability to react to the acoustic warning, a reaction time and a maximal deceleration. For this study the parameters were chosen as described in table 2 with reaction time and maximal deceleration being modelled as normal distributions with mean and standard deviation. Here, the probability to react to the acoustic signal is in accordance with recent finding [7] and mean and standard deviation for reaction time follow acknowledged data of the field [7-9]. In contrast, the maximal deceleration is motivated by the findings of the GIDAS analysis itself as presented in Fig. 3 a.

Table 2: Truck driver parameter specifications

Category	Value
Probability to react to acoustic warning	80%
Reaction time – mean	1.4 s
Reaction time – standard deviation	0.5 s
Maximal deceleration – mean (according to GIDAS)	5.7 m/s ²
Maximal deceleration – standard deviation (according to GIDAS)	1.5 m/s ²

In total, the simulation setup is well defined and allows for a stochastic simulation study of real-world accident data. Again, the driver assistance system AEBS is fully deterministic, while the truck driver is modelled by probability distributions for the main characteristic and, thereby, a stochastic approach is suitable.

Simulation results

An obvious parameter for an AEBS being of enormous interest is the avoidance potential. However, the simulation provides more than just the avoidance potential. First, the distances to the opponent at the time of initiating the emergency braking is analyzed. Second, avoidance potentials of the warning only and the full AEBS are highlighted. Here, an avoidance potential of an AEBS fulfilling the minimal EU requirements is estimated, too. Finally, the share of mitigated collisions and corresponding collision velocities as well as the velocity difference at the time of the collision is evaluated.

Analyzing the start of the emergency braking phase is most straight forward: given the AEBS parameters, as well as the position and velocities of both participants, the start of the emergency braking phase is calculated by the distance needed for braking the truck's velocity to the opponent's velocity. Here, the AEBS is neither triggered nor limited by thresholds of the variable "time to collision". In contrast, the chosen procedure to determine the start of emergency braking allows for a target braking. At the start of the emergency braking phase, the truck has a distance of 20.0 ± 12.8 m (mean \pm standard deviation) to its opponent with larger distances in cases of a standing opponent. These distances correspond to times of 1.8 ± 1.1 s before the collision (for a detailed distribution see Fig 5a). For acoustic warning and partial braking, the respective phase is initiated 1.4 s and 0.8 s earlier, as required by EU regulation 347 – 2012.

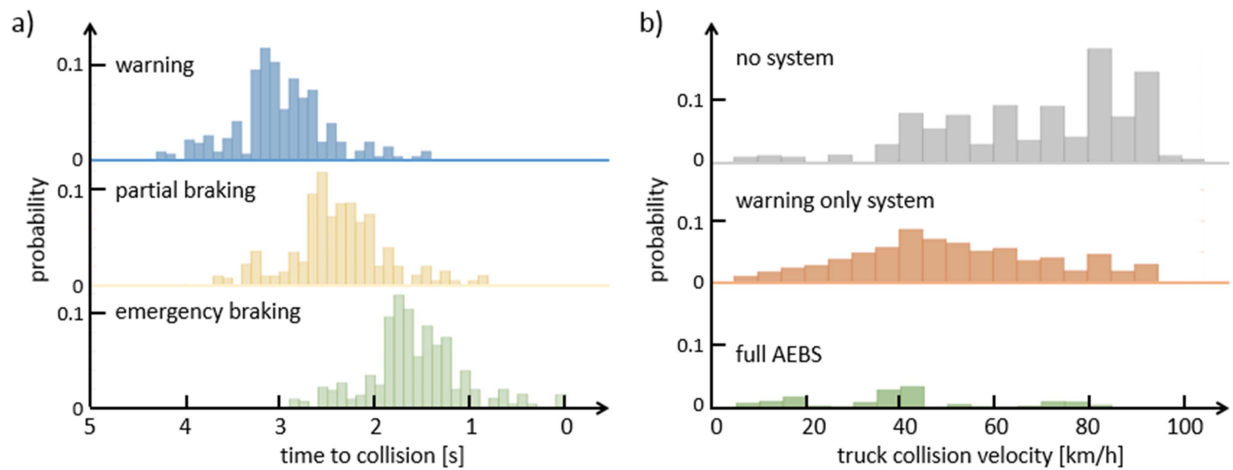


Figure 5: Simulation results: a) start of warning phase (top), partial braking phase (middle) and emergency braking phase (bottom) b) Truck collision velocities.

The most desired effect of an AEBS is its ability to avoid collisions. Given by the EU regulations effective since November 2018, an AEBS has to avoid a collision with an opponent moving with a constant velocity above 12 km/h. Thus, the minimal avoidance potential for any AEBS operating within the EU is given by the 7% of cases where the opponent fulfills the given requirement. However, there are three additional categories of opponent behavior: (i) standing opponent (41%), (ii) constantly moving opponent with $v < 12$ km/h (3%), and (iii) moving but braking opponent (49%). While an advanced high performance AEBS would avoid collisions with any standing or constantly moving opponent (together 51% within the field of effect), a braking opponent is challenging as the opponent is actively decreasing the remaining distance between truck and opponent. In cases where a truck equipped with a high performance AEBS is approaching a braking opponent, two out of three collisions could be avoided (66%). Given the large share of 49% of all cases involving a braking opponent, the maximal share of avoided collisions for a high performance AEBS sums up to $41\% + 10\% + 66\% \times 49\% = 84\%$ for a standing, a constantly moving and a braking opponent, respectively (Figure 6). In contrast, the minimal avoidance potential for a minimal AEBS is estimated by the share of accidents with a constantly moving opponent with velocity above 12 km/h, i.e.,

7%. Under the assumption, the minimal AEBS is performing equal or worse than the high performance system if the opponent is braking, the upper bound for the avoidance potential of a minimal AEBS is set by $7\% + 66\% \times 49\% = 40\%$. Compared to the maximal avoidance potential of 84% of a high performance system, a substantial increase in avoidance potential is still possible.

After analyzing the benefit of a full AEBS system, the avoidance potential of a warning only system is addressed. Here, the simulations show an avoidance potential of about 23%. However, the avoidance potential for this system is strongly dependent on the particular truck driver parametrization and large deviations become possible by changing the driver parametrization. For a rough estimate, we identify about one out of four collisions avoided by a warning only system, while more than four out of five collisions could be avoided by an advanced high performance system.

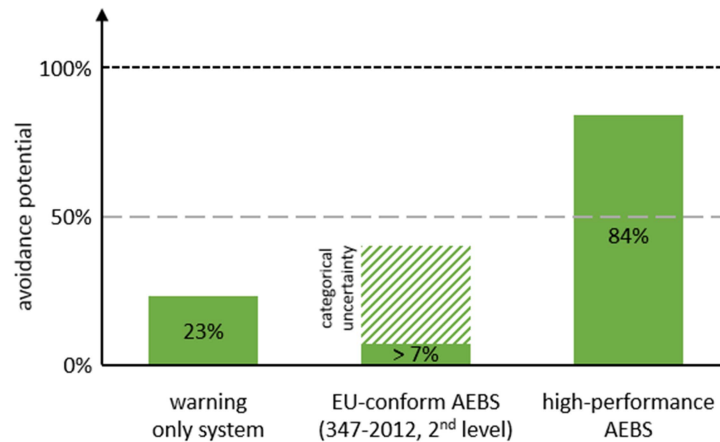


Figure 6: Simulation results: avoidance potentials for a warning only system vs EU-conform AEBS vs high-performance AEBS

In cases where avoidance stays out of reach, the collision velocity and the difference in velocities at the time of collision become important. Here, we compare three systems as described earlier: (i) cases without any intervention, (ii) warning only system and (iii) full AEBS. A weighted distribution of the truck collision velocities for the respective system is shown in Fig. 5b. Obviously, braking reduces the collision velocity drastically. In terms of means and standard deviations, for a warning only system the collision velocity is about 52 ± 22 km/h, while for the full system the mean becomes 43 ± 22 km/h. However, especially for the full AEBS, most cases are avoided and the reported mean and standard deviations of collision velocities are comprised of only few cases.

While for the EU conform AEBS (2nd level) the minimal avoidance rate is at least 7% for the collision velocity an upper bound is found: for all standing opponents, the collision velocity is reduced by at least 20 km/h. This results in a weighted mean collision velocity of maximal 53 km/h. Due to a further reduction of velocity of individual systems prior to a collision with a standing opponent or reducing the collision velocity with a braking opponent, the mean collision velocity of a current EU conform system is assumed to be reasonably smaller than 53 km/h.

Whether limitations of the sensor restrict the avoidance potential is another question that was addressed by the simulations. Here, we analyzed additional to the finite sensor ranges discussed above the avoidance potential of a system with a sensor of infinite range. However, the improvement of avoidance potentials by an infinite sensor is virtually not present: the avoidance potential with an infinite sensor is at the same rate as with the finite sensor. The reason is mainly that a combination of the generic sensor set with ranges up to 200 m with the restricted velocities of a truck is sufficient to not restrict avoidance potentials of an AEBS.

CONCLUSIONS

The present study reveals various insights of front-to-rear-end collisions in an in-line constellation for heavy trucks. First, an AEBS could address up to annually 2 300 accidents on German roads. More than every second collision was found on a motorway with typical opponents being other trucks or cars. Due to the large share of motorway incidents, the initial velocity of trucks is rather large with 61 ± 24 km/h. Additionally, due to heavy masses of large trucks and often very demanding conditions for truck drivers, 3% of all AEBS relevant accidents were fatal, and in an additional 18% the accident was classified as severe. Consequently, to avoid collisions with standing opponents, a large reduction in velocity is necessary which – in turn – demands highest requirements for such a system. On the other hand, the analysis showed the true potential of advanced automatic emergency braking systems: in two out of three reconstructed collisions, the truck driver was only partially braking before the collision. Here, an AEBS could support the driver and further reduce the collision velocity.

Our stochastic simulations estimated minimal and maximal benefits of AEB systems. For an AEBS conform to current EU regulation 347 – 2012 (2nd level) the benefit was estimated to:

- minimal avoidance rate of at least 7%
- reduced collision velocity for all mitigated collisions smaller than 53 km/h

For a high performance, yet generic AEBS the benefit could become:

- maximal avoidance rate up to 84%
- reduced collision velocity for the few remaining mitigated collisions 43 ± 22 km/h

The main limitations of the EU conform AEBS are given by requiring only for avoidance with constantly moving opponents faster than 12 km/h. For standing opponents, a speed reduction of at least 20 km/h is requested. Including full avoidance of all constantly moving as well as all standing opponents could boost the effectivity of truck AEBS with respect to avoidance from at least 7% up to 51% and more. Yet, improving sensor quality to secure a reliable detection of standing opponents is a key challenge for further improving future automatic emergency braking systems.

Given the enormous avoidance potentials of up to 84% within the field of effect, a strong decline in front-to-rear collisions of heavy trucks should be visible soon – even with only few systems on the street. However, recent studies on German motorways were yet not able to detect any decline in accident numbers at all [2,3]. Mostly a combination of AEBS penetration rates in truck stock and low avoidance rates required by the EU regulation could explain why a study of 2017 was not able to detect any impact of AEBS. On the other hand, the expected decline in accident numbers could result from small datasets and statistical outliers: with a hypothetical assumption of a market penetration of 50% only a little more than one year after AEBS became mandatory, an AEBS would address little above 500 accidents with casualties on German motorways (field of effect: 2 300 accidents with casualties in Germany; hypothetical market penetration: 50%, share of all accidents on motorways: 48%). Assuming the minimal avoidance potential (7%) for the 2nd level of EU regulation the system would avoid only less than 50 accidents with casualties on German motorways. Thus, from a statistical point of view, it is very challenging to detect effects due to AEBS. Nevertheless, often attributed and partially speculated reasons [2,3], e.g., truck drivers manually overriding the AEBS, could still play a role for explaining not-declining front-to-rear accident numbers involving heavy trucks and casualties.

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HOW CLOSE TO ZERO CAN VOLVO CARS GET BY 2020? AN ANALYSIS OF FATAL CRASHES WITH MODERN VOLVO PASSENGER CARS IN SWEDEN

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ABSTRACT

In 2008 Volvo Cars set out its vision - by 2020 no one should be killed or seriously injured in or by a new Volvo car. Today, 2020 is very close and it is possible to assume most of the safety technologies that will likely be fitted in Volvo cars by then. The objective of the present study was to estimate how close to zero fatalities Volvo Cars can get in Sweden by 2020.

The Swedish Transport Administration (STA) carries out in-depth studies of all road fatalities in Sweden. Cases involving at least one modern Volvo car were extracted for the period 2010-2017 (MY 2010 and onwards, excluding the C30, S40 and V50 models) and analyzed retrospectively (n=62). The yearly average number of fatalities in Sweden during 2010-2017 was 2.8 for occupants in Volvo cars and 5.0 for either occupants in other vehicles or VRUs impacted by Volvo cars, respectively.

The actual fitment of safety technologies was investigated among the Volvo cars involved in these crashes. The basic assumption was that by 2020 the boundary conditions in each crash would be unchanged, but the Volvo car would be a MY 2020 and therefore would be fitted with the same safety technologies as the V60 MY 2019. An assessment was then made of whether a certain technology could have prevented the crash or substantially reduced the crash severity in 2020. Cases involving extreme violations such as excessive speeding, were included in the analysis but presented separately. It was also assumed that no major improvements in crashworthiness would be introduced between the analyzed Volvo models and Volvo cars MY 2020.

The analysis showed that almost half of the fatalities in and by Volvo cars could have been prevented with the safety technologies fitted on the V60 MY 2019. It was also found that most of the fatalities that could not be prevented with a V60 MY 2019, occurred in crash scenarios where at least one safety technology was relevant, although the current performance was estimated not to be sufficient to prevent the fatality. Only three cases occurred in crash scenarios without any relevant existing safety technology.

It should be kept in mind that these results were based on retrospectively upgrading already relatively safe cars to the following generation. This suggests that reducing fatalities by almost 50% through the introduction of only one new car generation would be a very impressive achievement. It is also important to note that these results were based on the assumption that the road infrastructure, speed limit and crash opponents would be unchanged. Clearly, taking safety improvements in the road infrastructure and other vehicles into account would result in an even higher reduction of fatalities in and by Volvo cars by 2020.

In conclusion, regardless of whether Volvo's vision will be achieved by 2020 or not, it is very important to set road safety targets, develop new solutions and follow up the results, also for a car manufacturer.

INTRODUCTION

Setting targets for the number of fatalities and serious injuries in road traffic crashes has been a tradition for jurisdictions, regions and even globally. Since some years, starting in Sweden in 1997, long-term targets have been set based on Vision Zero. In this vision, the ultimate objective is to develop the entire road transport system to be forgiving, by adopting the principle of the failing and fragile human. The design philosophy is to reduce human mistakes, but if they still occur, the system is forgiving. Several layers of technology must be in place to bring driving back to normal, or prepare for a crash that is survivable and not causing long-term injury. To develop a safe road transport system is a matter of merging a number of factors and components of the system together to act in a way that protects the road users. In particular the amount of kinetic energy, i.e. speed, must be limited to the inherent safety of the protective systems.

Vision Zero, sometimes called Safe System, has been adopted by many stakeholders across the world. Individual countries, the EU, the UN, the US, and many cities nowadays develop their transport systems according to the policy, and for example the EU has even set a year for reaching "close to zero deaths" (2050; EC, 2011). Already in 2008, Volvo Cars set a Vision Zero target, and also set a date for when it should be reached (model year 2020; Volvo Cars, 2009). In doing so, Volvo was the first car manufacturer to set a target of this kind, and still seems to be alone in having a target year for its completion. Therefore, it is of great interest to estimate how close to zero Volvo Cars will be in 2020. From the issue of automated cars it is also of great interest to study the latest safety systems, although a manually driven car is far from automated driving when it comes to the "freedom" of the driver to drive the car outside its design envelope including basic traffic rules.

The target by Volvo Cars does not seem to be set with any restrictions concerning risk factors, when and where it applies. In some of the communication it has even been expressed in a way that it also includes road users outside the Volvo car, i.e. "seriously injured or killed in or by a new Volvo" (Volvo Cars, 2009). In a broader context, the value of the vehicle to solve almost the entire road safety problem is at stake, and therefore needs to be studied carefully as it would have a massive impact on the choice, investments and management of safety countermeasures.

OBJECTIVE

The objective of the present study was to estimate how close to zero fatalities Volvo Cars can get in Sweden by 2020.

DATA SOURCE

The Swedish Transport Administration (STA) has been carrying out in-depth studies of all road fatalities since 1997. Crash investigators at the STA systematically inspect the vehicles involved and record direction of impact, vehicular intrusion, seat belt and helmet use, airbag deployment, tyre properties, etc. The crash site is also inspected to investigate road characteristics, collision objects, etc. Further information is provided by forensic examinations, witness statements from the police and reports from the emergency services (STA 2005). Collision speeds are generally derived by vehicular deformation, and the initial driving speed is mostly based on eye-witness accounts, brake skids, etc. Pre-crash braking is also coded based on eye-witness accounts, brake and skid marks. The final results of each investigation are normally presented in a report. Because all fatal crashes are included in the sampling criterion, the material can be considered fully representative for Swedish road fatalities and possibly even for Northern Europe at large.

MATERIAL AND METHODS

Fatal crashes involving at least one Volvo car of model year (MY) 2010 and onwards were extracted for the period 2010-2017. The C30, S40 and V50 models were excluded as they were based on older platforms with limited safety technologies. This selection process resulted in a total of 57 cases: 18 fatal crashes with 22 fatally injured occupants in modern Volvo cars were found. Further 39 fatal crashes with 40 fatally injured occupants in other motor vehicles or vulnerable road users (VRU) were identified (see Table 1). The yearly average number of fatalities in Sweden during 2010-2017 was 2.8 for occupants in Volvo cars and 5.0 for either occupants in other vehicles or VRUs impacted by Volvo cars, respectively.

Table 1.
Number of fatalities in and by Volvo cars MY \geq 2010 in Sweden during 2010-2017. C30, S40/ V50 models excluded

road user type	fatalities <u>in</u> Volvo cars	fatalities <u>by</u> Volvo cars
car drivers	16	17
car passengers	6	1
pedestrians		12
PTW riders		6
cyclists		2
electric wheelchairs		1
HGV occupants		1
Total	22	40
average per year (2010-2017)	2.8	5.0

The actual fitment of safety technologies (for instance rear-end Autonomous Emergency Braking, Lane Departure Warning etc.) for each of the Volvo cars involved in these 57 crashes was investigated and retrospectively upgraded to the equipment of the V60 MY 2019. In other words, the analysis was based on the assumption that by 2020 the boundary conditions in each crash would be unchanged (i.e. the road infrastructure, speed limit and crash opponents would be the same). However, the Volvo car would be a MY 2020 and therefore would be fitted with the same safety technologies as the V60 MY 2019. These are as follows (Volvo Cars 2019a):

- Active Bending Lights
- Adaptive Cruise Control (ACC)
- Autonomous Emergency Braking (AEB)
 - Low-speed rear-end
 - Left-turn crossing with oncoming traffic
 - Head-on
 - Large animal detection
 - Pedestrian and cyclist detection
 - Post-crash
- Blind Spot Detection
- Cross Traffic Alert with AEB
- Driver Alert Control
- E-call
- Electronic Stability Control (ESC)
- Emergency Steering Support (individually brakes one or two wheels to reinforce the steering wheel input in an evasive maneuver)
- Forward Collision Warning (FCW)
- Lane Support (Oncoming Lane Mitigation and Lane Keeping Aid)
- Rear Collision Warning
- Run-Off road Mitigation
- Seat Belt Reminder (SBR)
- Tire Pressure Monitoring System

An assessment was then made of whether at least one of the above technologies could have prevented the crash or substantially reduced the crash severity. To handle the issue of subjectivity in such assessments, each case was discussed in a group of at least three road safety analysts until consensus was reached. Cases involving extreme violations were included in the analysis but analyzed separately. In the present study, extreme violations were defined as clear and intentional violations of basic traffic rules, for instance extreme speeding or unbelted occupants despite SBRs. It was also assumed that no major improvements in crashworthiness would be introduced between the analyzed Volvo models and Volvo cars MY 2020.

RESULTS

The majority of the fatal crashes involved the S80/V70/XC70 models (60%, see Table 2). All of the analyzed cars were fitted with ESC and SBR in the front seats. While 65% were fitted with low-speed AEB for rear-end

collisions (City Safety), only 13% had the optional Driver Support safety package including a number of technologies such as ACC, Lane Departure Warning (LDW) and/or Lane Keeping Assist (LKA), Driver Alert Control, Pedestrian Detection and Blind Spot Detection (see Table 3). The V40s were fitted with pedestrian airbag.

Table 2.
Number of Volvo car models MY ≥ 2010 included in the analysis

Volvo model	fatalities <i>in</i> Volvo cars	fatalities <i>by</i> Volvo cars
S60/V60	7	5
S80/V70/XC70	14	23
V40	1	5
XC60		6
XC90 MY 2016		1
Total	22	40

Table 3.
Fitment of safety technologies among the Volvo cars included in the analysis

Safety technology	fatalities <i>in</i> Volvo cars	fatalities <i>by</i> Volvo cars	% fitment
ESC	22	40	100%
SBR front seats	22	40	100%
City Safety (AEB low-speed rear-end)	13	27	65%
Driver Support Package	1	7	13%

It was also found that 37% of the Volvo cars were privately owned. Further 57% were either company cars, leased cars or rental cars. Information on ownership was missing in 6% of cases.

The analysis showed that 16 of the 22 fatalities in Volvo cars occurred under normal driving conditions (73%), see Figure 1. The remaining six cases involved clear violations, mostly excessive speeding. It was assessed that a total of ten fatalities (45%) could have been prevented with a Volvo V60 MY 2019 safety equipped vehicle (9 of these occurred under normal driving conditions). In one case, this assessment was not possible due to partly missing information.

With regard to the fatalities by Volvo cars, similar results were found: 34 fatalities occurred under normal driving conditions (85%, see Figure 2). A total of 17 fatalities (42%) were assessed to be potentially prevented by a Volvo V60 MY 2019 (16 of these occurred under normal driving conditions). In two cases, the available information was not sufficient to make such an assessment.

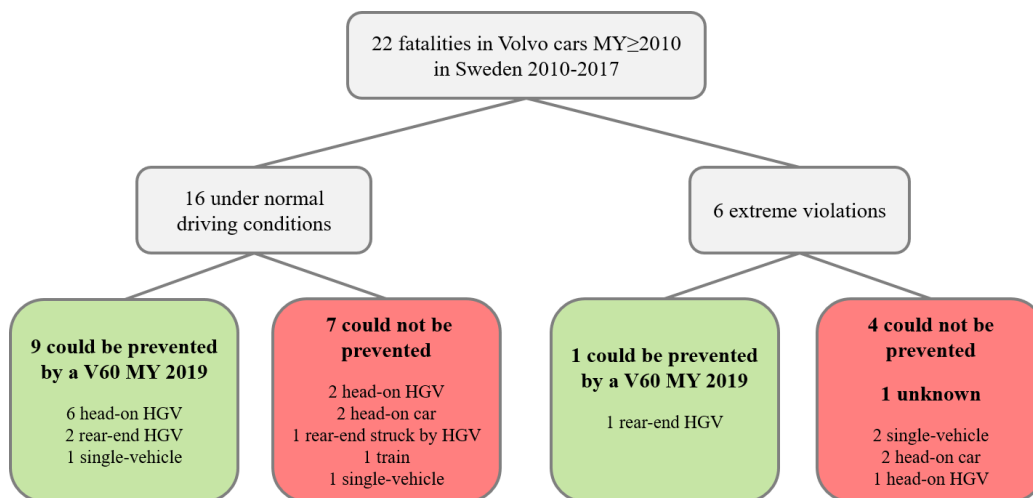


Figure 1. Number of fatalities *in* Volvo cars MY ≥ 2010 in Sweden during 2010-2017 that could have been prevented in a V60 MY 2019.

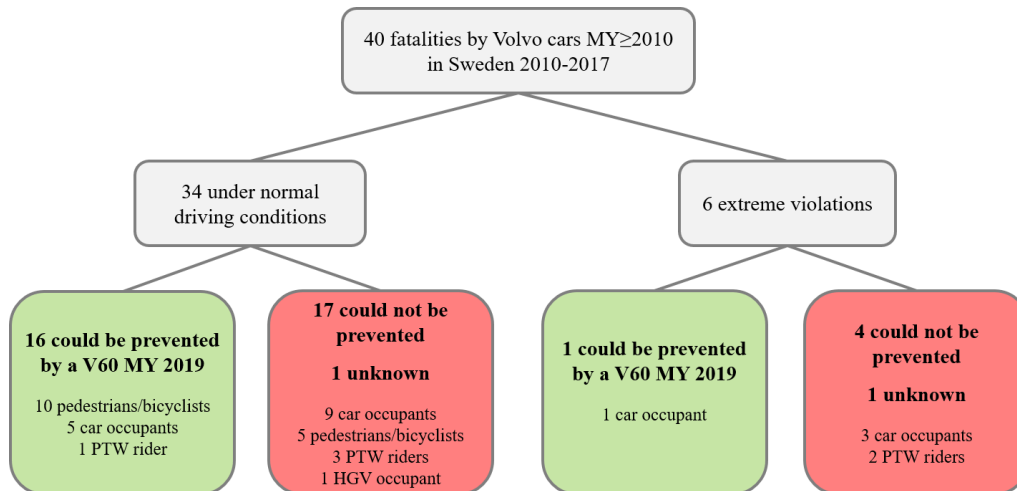


Figure 2. Number of fatalities by Volvo cars MY ≥ 2010 in Sweden during 2010-2017 that could have been prevented by a V60 MY 2019.

The reductions shown in Figure 1 and 2 would correspond to approximately 1.4 fatalities in Volvo cars and 2.6 by Volvo cars per year in Sweden. The technologies that could have prevented the fatalities in and by Volvo cars are listed in Table 4. Among fatalities in Volvo cars, the most effective technology was Lane Support (n=7), followed by ACC and Driver Alert Control (n=3, respectively). However, it is important to note that several crashes could have been prevented by more than one technology, which explains why the sum of the individually prevented fatalities shown in Table 3 is higher than 10.

Among fatalities by Volvo cars, the most effective technology was estimated to be AEB with pedestrian and cyclist detection (n=10), followed by AEB head-on (n=5). In two cases, it was estimated that the combination of AEB with pedestrian detection and improved crashworthiness could have prevented the fatality, at least theoretically. However, such assessment was considered too uncertain to be included among the prevented fatalities.

Table 4. Number of fatalities that could have been prevented by different technologies

	fatalities <i>in</i> Volvo cars	fatalities <i>by</i> Volvo cars
ACC	3	
AEB head-on	2	5
AEB post-crash		1
AEB with large animal detection		1
AEB with pedestrian and cyclist detection		10
Driver Alert Control	3	
Emergency Steering Support	2	1
Lane Support	7	
<i>Not prevented</i>	<i>11</i>	<i>21</i>
<i>Unknown</i>	<i>1</i>	<i>2</i>
Total without double counting	22	40

As shown in Figures 1 and 2, it was assessed that a total of 32 fatalities in and by Volvo cars could not be prevented with a V60 MY 2019. Among these 32 fatalities, it was found that 20 (16 under normal driving conditions) occurred in crash scenarios where at least one safety technology was relevant, although the current performance was estimated not to be sufficient to prevent the fatality. The most common ones were AEB head-on (n=10) and AEB with pedestrian and bicyclist detection (n=3), in cases where detection was highly likely but impact speeds were too high to be reduced to survivable levels with the current levels of autonomous emergency braking. In further six cases (five under normal driving conditions) the Volvo driver did brake and/or swerve to such an extent that the potential of AEB or Emergency Steering Support was considered to be minimal. In further three cases no technologies were estimated to be effective to any great extent due to extreme violations. Finally, the remaining three cases occurred in crash scenarios without any relevant safety technology. These

were a rear-end collision where a Volvo car was struck from behind by a PTW, a collision with a train at a railway crossing and a single-vehicle crash involving understeering in very slippery road surface conditions.

As shown in Table 3, eight fatalities (six under normal driving conditions) involved a Volvo car fitted with the optional Driver Support safety package. It was found that seven crashes occurred in crash scenarios where no relevant safety technologies were included in such safety package. These were:

- three unintentional lane drifting by an oncoming car, resulting in head-on collisions
- one intentional overtaking by the Volvo car, resulting in a head-on collision
- one reversing collision with a pedestrian
- one collision with a moose, resulting in the moose being ejected into an oncoming vehicle
- one single-vehicle crash involving understeering in very slippery road surface conditions

In one case, a pedestrian was killed by a Volvo car fitted with AEB with pedestrian detection. However, loss-of-control due to very slippery conditions had occurred prior to the collision with the pedestrian, which made the AEB detection and activation impossible.

Finally, it was also found that if the passenger car opponent had been fitted with ESC and Lane Support, further three fatalities in Volvo and six fatalities by Volvo cars could have been prevented, respectively. This would correspond to approximately 58-59% reduction of fatalities in and by Volvo cars. It should be also noted that most HGV in this study lacked all sorts of relevant safety technologies, and that ESC and ACC on HGV could potentially prevent further two fatalities in Volvo cars (for a grand total of 68% reduction, if combined with ESC and Lane Support on the passenger car opponents).

DISCUSSION

The present paper analyzed Swedish in-depth data from fatal crashes involving modern Volvo cars (MY \geq 2010) to understand how close to zero fatalities Volvo cars can get in Sweden by 2020. It was estimated that almost half of the current fatalities in and by Volvo cars could be prevented with a V60 MY 2019 safety equipped vehicle, which suggests that Volvo's vision will not be achieved in Sweden by 2020. However, it should be kept in mind that these results were based on retrospectively upgrading already relatively safe cars to the following generation. When this aspect is taken into account, it could be argued that reducing fatalities in and by a car by almost 50% through the introduction of only one new generation would be a very impressive achievement.

The present study has a number of limitations that need to be discussed. First of all, it should be clear that the results were based on two main assumptions. Firstly, Volvo cars MY 2020 would be fitted with the same safety technologies as the V60 MY 2019, and secondly, no major improvements in crashworthiness would be introduced between the analyzed Volvo models and Volvo cars MY 2020. While these assumptions do not seem unreasonable, it is evident that they directly affect the results.

STA in-depth studies are fully representative for Sweden, and possibly for Northern Europe at large. However, it is important to note that Swedish conditions may differ from other regions of the world. The Swedish market accounts for approximately 10% of Volvo's global market (Volvo Cars 2019b; Bil Sweden 2019). Therefore, caution should be used before generalizing the present results to a global level. Another limitation is that in this kind of retrospective analyses it is difficult to take into account any behavioral effects that may possibly follow from some technologies. On the other hand, analysis of the eight fatalities involving the Driver Support Package did not suggest any clear behavioral adaptation due to the presence of optional safety technologies. Clearly, it will be essential to follow up the real-life safety performance of the V60 model to understand how accurate the present results are.

Another important point to discuss is that the present paper exclusively analyzed the potential benefits of safety improvement in Volvo cars. In other words, no improvements among other vehicles, mostly passenger cars, but also in the road infrastructure were taken into account. This aspect can be seen as both a strength and a limitation at the same time. It is well-understood that the general car development is towards safer and safer cars, and that new cars from other manufacturers than Volvo are also fitted with several safety technologies, as shown in the latest Euro NCAP test results (Euro NCAP 2018). Some of these technologies could contribute to avoid fatalities in and by Volvo cars as well. For instance, unintentional lane drifting by oncoming vehicles could be prevented with Lane Support, thus preventing head-on collisions where the crash severity is too high for the current AEB head-on. At the same time, it could also be argued that the safety standards of Swedish roads are being constantly revised and that a portion of such head-on collisions with high crash severity will be progressively addressed by safer road infrastructure. All of these aspects suggest that the present results may be an

underestimation, at least in the long-term Swedish prospective. On the other hand, from a more global prospective it could be more difficult to achieve Volvo's vision by relying on a high market penetration of new safety technologies in other vehicles, and/or on a significant safety improvement of the road infrastructure. Therefore, it may be also a strength to focus on the potential benefits in Volvo cars to provide better guidance for future safety development.

It is also important to briefly discuss the relevance of different types and degrees of violations for the future development of vehicles. In the present study, 20% of the fatalities involved extreme violations, which is in line with previous findings on the frequency of extreme violations in all fatal crashes in Sweden (Lie et al 2001). In the present material, the majority of such extreme violations were excessive speeding. It seems reasonable to argue that in the future extreme violations will account for an increasingly proportion of all car fatalities, since crashes under normal driving conditions can be expected to be reduced to a larger degree by vehicle and infrastructural safety improvements. Therefore, it will probably become even more important in the future to detect and properly address reckless driving. Also, the potential of addressing milder (or even tolerated) violations such as driving at 90 km/h in an 80 km/h speed area should not be underestimated.

The present results are also relevant for the issue of automated driving. While such a vehicle implicitly does not drive recklessly, drivers of other vehicles might do, thus creating a problem for the automated car. It is also obvious that the automated car, if driven as the cars involved in the current study, would not be able to eliminate all fatalities with vulnerable road users. Obstructed pedestrians are a challenge also for automated cars. This could potentially partly be solved by cautious driving by the automated cars. The way the automated car is driven is therefore crucial for the performance of the safety technology.

Concerning the issue of safety management, it seems like a very good idea to set targets, develop technologies and follow up the results also for a car manufacturer. This gives opportunities for the outside community to monitor the progress and to understand what is needed from the rest of the community to act. This is well in line with both the road safety management system ISO 39001 (STA, 2015) as well as the Sustainable Development Goals (SDG) in the 2030 Agenda (UN, 2015). Communicating targets and outcome is a fundamental piece in both these instruments.

Conclusions

In summary, by analyzing Swedish in-depth data from fatal crashes involving modern Volvo cars (MY \geq 2010), it was found that:

- The yearly average number of fatalities in Sweden during 2010-2017 was 2.8 for occupants in Volvo cars and 5.0 for either occupants in other vehicles or VRUs impacted by Volvo cars, respectively.
- It was estimated that these fatalities could be almost halved with the safety technologies fitted on the following car generation, the V60 MY 2019. This would correspond to approximately 1.4 fatalities in Volvo cars and 2.6 by Volvo cars per year in Sweden.
- It was also found that most of the fatalities that could not be prevented with a V60 MY 2019, occurred in crash scenarios where at least one safety technology was relevant, although the current performance was estimated not to be sufficient to prevent the fatality.
- Only three cases occurred in crash scenarios without any relevant existing safety technology.
- These results are based on the assumption that the road infrastructure, speed limit and crash opponents would be unchanged. Clearly, taking safety improvements in the road infrastructure and other vehicles into account would result in an even higher reduction of fatalities in and by Volvo cars by 2020.
- In conclusion, regardless of whether Volvo's vision will be achieved by 2020 or not, it is very important to set road safety targets, develop new solutions and follow up the results, also for a car manufacturer.

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HYDROPLANING AVOIDANCE – A HOLISTIC SYSTEM APPROACH

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ABSTRACT

Accidents in severe weather mainly arise due to a drastic loss of friction between the tires and the road surface unexpected by the driver. Beside all kinds of slippery winter conditions hydroplaning situations are even more dangerous not just for manually driven vehicles but also for automated vehicles when cruising at speeds above 80 to 100 km/h. This paper describes the Continental approach for a cascaded holistic safety system in imminent hydroplaning situations independent of the degree of automation. First, to reduce the overall hydroplaning risk a continuous tire tread depth monitoring function is integrated to trigger a timely replacement of worn-out tires. Second, a surround view camera and new tire-sensor-based early hydroplaning risk recognition allows an in-time driver warning or a system-initiated speed adaptation in case of automated vehicles. Especially for Automated Driving (AD) vehicles it is of major importance to avoid hydroplaning before it happens. Third, this information is send to the cloud-based eHorizon service so that also other traffic participants can be informed before entering a hydroplaning risk area. In case hydroplaning cannot be avoided a control system is designed and tested to evaluate an innovative assistance strategy in hydroplaning situations. The test cases demonstrate the suitability of this assistance concept.

1. INTRODUCTION

Heavy rain and bad weather conditions involving reduced traction because of wet, snowy and icy surfaces have been major contributory factors to traffic accidents in general. Extreme weather conditions are responsible for 39% of all accidents in Germany, [2]. One of the most dangerous driving situations is hydroplaning, which is difficult to predict and almost impossible to manage for the driver but also for automated vehicles. The hydroplaning situation depends on both vehicle and tire conditions as well as on environmental parameters such as water film thickness on the road. During hydroplane steering generally is not possible, because tire-road friction is completely lost at the front axle and therefore any transfer of lateral and longitudinal forces is not possible by the front tires anymore. Today's measures to avoid the risk of hydroplaning are almost exclusively infrastructure-based such as roadway draining and/or speed limits.

The Continental AG is developing a cross-divisional bundle of vehicle-based solutions proposing a cascaded holistic approach. This holistic approach is based on the four following cornerstones:

- Avoid
- Predict
- Warn
- Assist

Beside the proposal to analyze vehicle dynamics and controllability in hydroplaning situations and sketch an active safety system to assist the driver safely through this dangerous situation the main scope of this paper is to avoid the hydroplaning danger by a continuous tire tread depth monitoring system and the integration of two complimentary sensor-based systems to detect the imminent hydroplaning risk in an early pre-hydroplane phase before hydroplaning occurs. This information is used to warn the driver or to actively control the speed of an automated vehicle in imminent hydroplaning risk situations. Additionally, in such cases the potential risk to other vehicles on the road can be mitigated by an early communication via V2X technology and eHorizon, facilitating

a network of solidarity where one vehicle acts as a safety sensor for all other vehicles and not just those in its direct vicinity. eHorizon can provide this information to vehicles that could potentially be affected, so they are able to adjust their routing and driving functions to the risky weather conditions.

2. HYDROPLANING THEORY

A hydroplaning imminent situation can be explained by the following three-phase tire zone model concept in figure 1.

Exemplarily at a vehicle speed of 100 km/h a discrete element of the tire tread (P1) has a total contact duration with the surface and its top water layer of only 5 msec, where the three phases as displayed in the figure are passed through. In phase 1 the tread element is touching the water surface and displacing the water into the void volume of the tire's tread pattern. In phase 2, when the void is filled with water, the tire is analogously acting as a slick tire and more water cannot be absorbed by the void volume any more. This is the reason why the excessive water must be displaced to the front and to the sides underneath the tire.

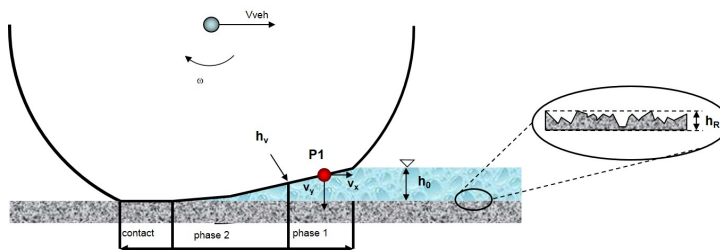


Figure 1. Three-Zone model concept for hydroplaning: separation zone (phase1), intermediate zone (phase2) and contact zone

As long as the tire's inside pressure is higher than the water pressure generated by the water wedge in front of the tire, the tire is successful in displacing the water to keep its road surface contact in the runout of the footprint. Just if the pressure relation changes and

the pressure of the water wedge in front gets higher than the tire's inside pressure the tire will swim up. This water displacement phase before it comes to hydroplaning is used to be detected by the systems for an early hydroplaning warning. This physics are the reason why there is a reasonable good chance to warn the driver up-front before the tires will completely hydroplane.

The critical vehicle speed is calculated as the averaged footprint length (L_m) divided by the touch down time (t_A) for a discrete tread element (P1), where the touch down time depends on the water height (h_0), the surface roughness (h_R) and the radius (R) for a circular tread bar, [1].

$$v_{\text{krit}} = \frac{L_m}{t_A} \quad (\text{Equation 1})$$

$$t_A = \frac{R/2}{2\sqrt{\frac{p_m}{\rho}}} \cdot \ln \frac{1 + \sqrt{1 - h_R/h_0}}{1 - \sqrt{1 - h_R/h_0}} \quad (\text{Equation 2})$$

With a mean support pressure (p_m) of 0,3 MPa, a density (ρ) for water of 1000 kg/m³, a water height (h_0) of 8mm and a surface roughness (h_R) of 1mm the characteristic squeeze-out velocity for the water is approximately 35 m/sec. This results in considerably splash and spray water as a physical principal effect before it comes to hydroplaning. This splash water effect together with the oscillation caused by the water wedge in front of the tire's footprint is used by the system to detect the hydroplane risk in the pre-hydroplane phase.

3. TIRE TREAD DEPTH MONITORING

A critical factor in the context of hydroplaning is the residual tread depth of each tire. While periodic checks are sometimes done when changing from summer to winter tires (and back), there is no permanent monitoring of the tread depth. When using all season

tires, or in regions where the local climate does not require a seasonal change of the tires, the only tread depth monitoring relies on the user. Continental's TreadDepthMonitoring function continuously estimates the tread depth of each tire and can provide a timely recommendation for a tire change. Based on the tire mounted sensor eTIS (electronic Tire Information System) which was launched for the European tire pressure monitoring aftermarket in 2014, the system can now access not only the tire Pressure P and temperature T , but also the acceleration of the tire itself – not only the RIM. This allows for several new features (see also the direct indication of hydroplaning in chapter 5.2). It is clear, that by means of the tire acceleration, it is possible to measure the footprint length, which combined with the tire pressure provides the tire load L . Similarly, it is possible to accurately measure the impact factors influencing the dynamical tire radius R_{Dyn} . The dynamical tire radius itself can accurately be obtained by utilizing the wheel speed sensors ω in context with a GPS reference velocity V^{GPS} (see fig. 2) and state of the art methods dealing with the geometric impact of curves and situations that produce slip. Given that the tread of a tire is a rather slowly varying parameter, unsuitable situation (e.g. high tire slip) can be discarded and the remaining measurements can be filtered appropriately to deal with remaining measurement noise and effects like tire belt expansion in the beginning of a tire life.

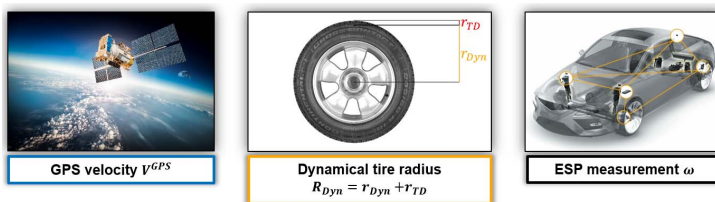


Figure 2. Dynamical tire radius R_{Dyn} separated into two contributions 1) Dynamical tire radius up to the tread r_{Dyn} and 2) Dynamical tire radius from tread r_{TD}

This accurately determined dynamical tire radius is impacted by the tire velocity V , tire pressure P , tire load L , tire temperature T and finally the tire tread depth r_{TD} .

$$V^{GPS} = R_{dyn} \times \omega = [r_{dyn}(P, T, V, L) + r_{TD}] \times \omega \quad (\text{Equation 3})$$

Common to all the impact factors is that their impact depends on measurable noise factors. Here eTIS is an integral component for the tire pressure, load, and temperature, while the velocity V can be obtained from ω . After compensating for the noise factors and employing state of the art learning techniques to deal with manufacturing tolerances, the remaining impact on the tires dynamical radius is its tread depth which can be extracted by proper algorithms from r_{TD} . Based on this tread depth the following information (see figure 3) can be communicated to the driver in context with a specific tire type (e.g. summer vs. winter tire):

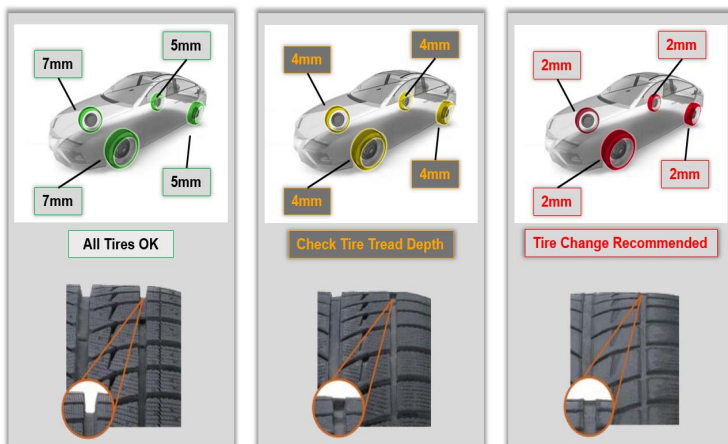


Figure 3. Information strategy for timely tire replacement

This provides ample time for an upcoming necessary tire replacement. Additionally, suboptimal tread depth levels (like the ones indicated in orange and red can be treated by the vehicle in context with the current velocity and information from the other

systems presented in this paper. This can then lead to a speed warning to the driver or a direct reduction of velocity via autonomous driving systems. In the following figure results are shown where the system was installed after some 8.000km into tires which were subsequently driven for another 40.000km on the front axle before they needed replacement, while the tires on the rear axle lasted a total of 60.000km. The vehicle has a front wheel drive architecture. The green lines indicate reference measurements together with min / max values (indicated by the bars). The black line is the output of the systems algorithm, while the red lines indicate the algorithms own error estimation. After carrying out several fleet campaigns with different vehicles and mission profiles, the overall accuracy of the algorithm was found to be +/-1mm, which is clearly achieved for the specific tire life on the vehicle in figure 3.

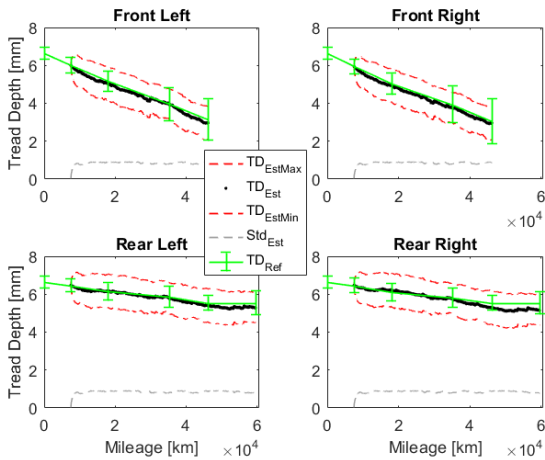


Figure 4. Results of TreadDepthMonitoring for the 4 tires of a front wheel drive vehicle driving a total of 60.000km

The front tires have been replaced after some 47.000km. The solid black line is the output of the algorithm with the red dashed lines being an error estimation. The green lines are reference measurements with corresponding uncertainties (bars).

4. LEVERAGING eHORIZON SERVICES

Weather has a strong impact on the road friction and thus the driver safety. For instance, after a long period without rain, a lot of particles and oils percolate through the road surface. Thus, at the beginning of rainfall, those oils ascend on the top of the road, resulting in a reduced friction potential.

Precisely predicting rainfall and especially friction related weather conditions is a major requirement for the future of Automated Driving solutions. This precision must not only boil down to temporal and spatial but to a strong reflection of the weather phenomena.

Nevertheless, forecasts delivered by the Weather Forecast Providers (WFP) are not sufficient in both spatial and temporal resolution. Actually, those forecasts might be sufficient at the city level (1 km square grid and hourly update) but not for Automated Driving (A.D.) and Advanced Driver Assistance Systems (A.D.A.S.) purposes: for which less than 100 meters of precision and below 5 minutes of frequency update are required. Figure 5 shows 4 weather cells near Frankfurt-City, WFP weather cell size is 1/100 of degree (in both longitude and latitude).

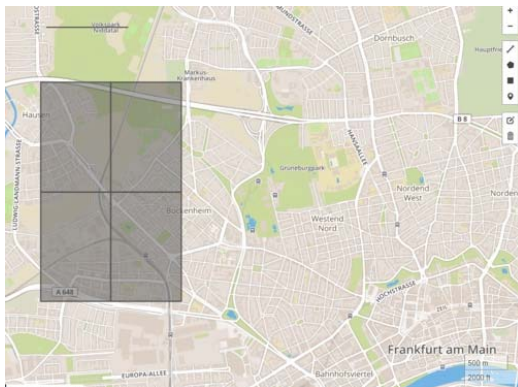


Figure 5. Example of weather cells in Frankfurt a. M.

Relying on vehicles as IoT weather stations, is a way to overcome this precision drawback. Vehicles are constantly collecting a large amount of weather related data and producing real-time weather-related observation system (*i.e.* activation of wiper, lights, and user or automated actuators as well as the information from temperature, hygrometry and pressure sensors). At a local level, vehicle data can be used to enhance weather forecast data. For instance, when a driver encounters a rainfall, either he activates the wipers, or the rain sensor is enabled. Those events are uploaded to the cloud where they are used to update short term weather forecasts. Wiper activation at the vehicle level increases the probability of precipitation at the cell level and thus each car contributes to changing the probability of the weather phenomenon. Figure 6 illustrates this behaviour. Thus, from local information, *eHorizon* produces a high accuracy map from both WFP and vehicle data.

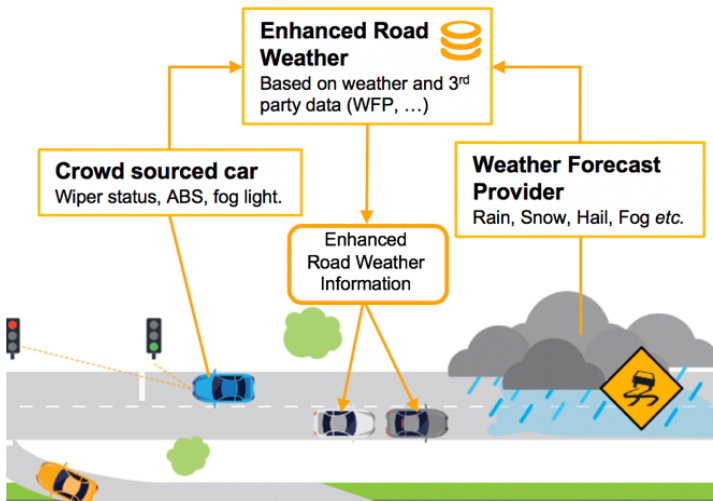


Figure 6. Road Weather Enhancement using vehicle data

The confusion matrix below compares results on rain detection for a Weather Forecast Provider (WFP) and our Road Weather (RW) service for a trip of 20 minutes with rain by only one vehicle. As the

matrix shows, the WFP does not predict rain for the whole trip (only 69%). RW, with only one vehicle, increases the precision by 30% (90% of good classifications).

Table 1.
Confusion Matrix for rain weather

	% False Predictions	% True Predictions
Rain : WFP	31%	69%
Rain : RW	10%	90%

With eHorizon Road Surface Condition services as an extension of eHorizon Road Weather it becomes possible to predict weather related situations and their impact on the road conditions and tire/road friction for the road ahead. Machine Learning approaches facilitate training of personalized road models to detect friction related hazardous weather situations such as hydroplaning or black ice. This method allows an accurate and fast prediction for a single road segment. eHorizon supports driving functions by delivering required information along the vehicle path in advance, before sensors can detect dangerous situations in immediate surroundings.

Adverse weather with heavy rain and exceptionally when first vehicles have already experienced and detected pre-hydroplane or even (full) hydroplane the information about the potential hydroplane risk for a specific weather cell is send to eHorizon. eHorizon services again will provide this information to other vehicles that could potentially be affected, so that they are able to adjust their driving functions to the risky weather conditions.

5. PREDICTIVE HYDROPLANING RISK RECOGNITION

5.1. Water Spray Recognition by surround view cameras

The approach to integrate surrounding sensors for early hydroplaning risk detection is because emerging of hydroplaning goes along with increasing water pressure between the tire's

footprint and the road surface which generates the above-mentioned splash water and spray in all directions (see chapter 2). The physical effect of the squeezed-out water is used to be detected and classified by an intelligent surround view camera system.



Figure 7. Water spray detected by surround view cameras for vehicle near field sensing

Surround view systems are based on four miniaturized wide-angle cameras, one front, one rear and two side cameras integrated in the base of the two exterior mirrors. These systems provide a 360° panorama view as well as single images from all four cameras in the near-field of the vehicle's environment. Additionally, to the sole imaging functionalities a bundle of different functionalities based on computer vision algorithms can be offered to the customer. Main use cases are parking functionalities with scalable level of automation.

The main goal of the surround view camera approach for this application is to use computer vision and machine learning methods to discriminate between different road conditions and to detect the imminent risk of hydroplaning. Figure 8 shows an example image of

the right-side mirror-integrated camera for the hydroplane risk recognition and the relevant region of interest (ROI) in red to be evaluated.

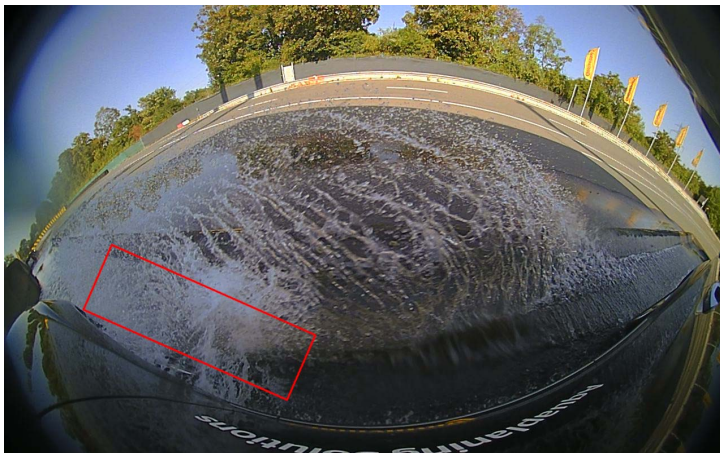


Figure 8. An example of the ROI for the Hydroplane (risk) class

To automatically distinguish between different road conditions, a classification framework based on Fisher Vector Encoding [14], which has become the state-of-the-art approach for a variety of image classification tasks, is proposed. In a pre-processing step, a Region Of Interest (ROI) is extracted from the original surround view image (see figure 9). The determination of its location, shape, and size is a crucial aspect for robust classification. On the one hand, the ROI must provide sufficient information to allow for the separation of the different classes. On the other hand, however, the ROI should only cover as few as possible information of the environment, since characteristics, which are not related to the actual road condition, might cause overfitting, especially in the case of limited training data. Once an appropriate ROI is defined, a compact and generic representation of the image is computed.

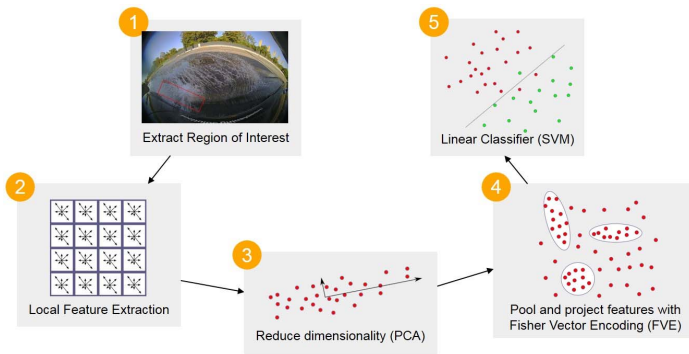


Figure 9. Typical pipeline for digital image processing

For this purpose, a set of local image features are extracted on a regular dense grid. For instance, the frequently used Histograms of Oriented Gradients (HOG) [12] feature descriptors can be applied to obtain a compact feature vector for each grid cell by computing a histogram of occurrences of image gradient orientations. In a further step, it is possible to reduce the dimensionality of the feature space by applying Principal Component Analysis (PCA) [13] and discarding the dimensions that contain the least information. Finally, the set of feature vectors are embedded into one global representation per image using Fisher Vector Encoding (FVE) [14]. In the training phase, a Gaussian mixture model is fitted to the training data. During encoding, the gradient of the log-likelihood with respect to the model parameters are determined based on the soft assignments of every local descriptor to each Gaussian distribution of the mixture model. Those gradients can be understood as adjustments to the parameters of the trained model with respect to a given image which results in a generic and unique representation. The gradients of individual model parameters are finally concatenated into a single global feature vector for each image. In the last step of the proposed framework, a classifier is trained to obtain a mapping from global feature vectors to road condition classes. As suggested by the authors of FVE [14], a linear Support Vector Machine (SVM) [15] is applied, where the feature

space is separated by a hyperplane which is determined during training. Thereby, the hyperplane is defined by a small set of training examples located at the class boundaries which are referred to as support vectors. Furthermore, a probabilistic output can be achieved by applying logistic regression.

The avoidance of overfitting poses a challenge in the particular case of hydroplane. Overfitting means the memorization of the training data, rather than understanding the concepts of the classes. As it is extremely dangerous to drive in hydroplaning situations in “real-world situations” on public roads the training data for this class can only be generated in a safe proving ground environment. The state-of-the-art test site of Continental is called “Contidrom”. Here are different water basins for tire tests available that can be filled up to a specified water depth to create different reproducible hydroplaning situations in a safe vehicle test environment. So far there are no examples of hydroplaning from real world situations available for training. Therefore, special precautions must be taken to learn the typical characteristics of hydroplane. In this paper, the results of two different basic experiments are presented. For the experiment “only Contidrom”, the system is trained and tested on images for all three classes (dry, wet & hydroplane risk) generated just at the safe proving ground environment. In the experiment “all Data” the system is trained and tested on images from the “Contidrom” proving ground (all three classes) as well as from “real-world situations” on public roads for dry and wet conditions only. Furthermore, hydroplaning situations only from the “Contidrom” are provided, as no real-world data can be generated safely for this class. In both experiments 50% of the data is used for training and the remaining 50% for testing, then the sets are switched in a second run.

Table 2 shows the first results of the experiments for both cases. The Overall Recognition Rate (ORR) describes the ratio of correct classifications to the number of samples, whereas Average Recognition Rate (ARR) calculates this ratio per class, averaged over classes. The “Contidrom” tests form the baseline for the experiments, as no real-world influences are present. Hydroplaning risk is detected correctly in 97.4% of the cases.

Table 2.
Results of the experiments: ORR (Overall Recognition Rate;
ARR (Average Recognition Rate) per class

Experiment	ORR	ARR	Dry	Wet	Hydroplane
only „Contidrom“	95.6%	95.0%	93.3 %	94.4 %	97.4%
all Data	98.5%	96.0%	99.0 %	100 %	89.2%

The experiment “all Data” shows, that the system can learn the real-world situation well and even exceeds the “Contidrom” results for both ORR and ARR. However, a decreasing detection rate for hydroplaning is apparent in this setting. This suggests that the system has not only learned hydroplaning features but has also taken features of the test site environment into account. Since there is a much higher variability in the road characteristics for “real-world”, the classification of hydroplaning is a much more difficult task.

More experiments were carried out, where the system was only trained on “Contidrom” data and tested on a mixture of “Contidrom” and “real-world” data. In these settings, system performance decreased for wet and dry roads. This shows that the classifier trained only on the “Contidrom” data is prone to overfitting on the training environment and is not able to generalize very well.

Since no large data set of real-world hydroplaning data can be generated safely, potential overfitting on the test site environment has to be prevented in a different way. The biggest improvements can be achieved by generating more data for the case of hydroplaning by a wide variation of surrounding influences, e.g., different road surfaces, perturbations, and illumination situations. Additionally, methods of data augmentation to artificially generate more variability in the training data can be applied.

The first experiments clearly show that the discrimination between the different road conditions by surround view cameras is possible and on a good way. In particular, also the combination with feature

detection by a front camera and the enhancement by Deep Learning algorithms shows to be very promising.

5.2. Water Pressure Recognition by new Tire Sensors

Beside the usage of the eTIS Sensor for tire tread depth estimation, information about the interaction between the tire footprint region and the road when water is present is specifically of high interest. A model is outlined that explains a unique signature of hydroplaning in the radial acceleration that is measured by the sensors inbuilt accelerometer. The intended target is the detection of the very first manifestations of hydroplaning before the tire has lost a substantial amount of grip. Such an approach allows an early warning at vehicle speeds lower than the speed that ultimately results in full hydroplaning. With such an approach many of the driving situations that gradually lead to hydroplaning can be detected and by means of a driver warning or a more direct velocity reduction full hydroplaning can be avoided altogether.

For a constant water film covering a road, it is well known [11] that increasing the vehicle velocity when driving on a wet road causes the tire road interaction to change through different stages. At low velocities, where the water can fully be absorbed by the tire's void volume of the tread, the tire road interaction is characterized by its "normal" wet grip behavior. When increasing the velocity, at some point the tire's tread is not able any longer to fully absorb the water (ref. also Chapter 2). There will be a water wedge build-up in front of the tire, which partially penetrates underneath the forward-facing section of the footprint region, while the rest of the footprint region still has full & partly wet grip on the road. Consequently, the tire has lost only a fraction of its contact area and still enables vehicle control for most practical purposes. This state is of special interest for the detection with the eTIS sensor. When increasing the vehicle velocity even more, at some point the water wedge will fully penetrate between the footprint of the tire and the road. At this point, the tire has lost its contact to the road and there is no more grip at all. This state can be labelled as full hydroplaning.

5.2.1. Model for radial acceleration measured by eTIS

A model is presented explaining the radial accelerations seen by the eTIS sensor during the three different stages (wet grip, pre-hydroplaning, full hydroplaning). It explains how the concept introduced in Chapter 2 (ref. also Fig. 1) is sensed by the accelerometer in the eTIS Module.

In Fig. 10d) the radial acceleration a_R measured by eTIS as a function of the rotation angle ϕ is plotted. This acceleration data is based on an interpolation between different acceleration values derived from the corresponding curvature experienced on the path that eTIS moves along. Assuming that the longitudinal velocity V is constant along the circumference of the tire, the radial acceleration at a given rotation angle ϕ is given by,

$$a_R = V^2 / r(\phi) \quad (\text{Equation 4})$$

where $r(\phi)$ is the radius of the circle locally converging to the path of the eTIS. The left part (Figs. 8a and 8d) shows the case of wet grip. At 0° the radial acceleration is defined by the radius of curvature of the tire r_0 , i.e. by V^2 / r_0 . When the sensor enters the footprint region, the radius of curvature decreases to smaller values. The largest acceleration corresponds to the smallest radius r_1 , i.e. V^2 / r_1 . Inside the footprint area the path is nearly flat, i.e. the corresponding radius of curvature is very large which produces a measured acceleration of roughly 0. When leaving the footprint, the acceleration overshoot is approximately the same as when entering, i.e. V^2 / r_1 . Finally, eTIS experiences the radial acceleration corresponding to the radius r_0 , i.e. V^2 / r_0 at 360° .

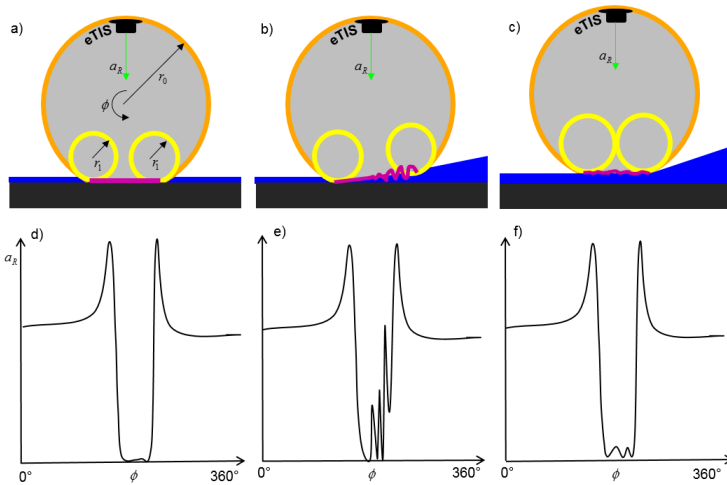


Figure 10. eTIS radial Acceleration as a function of the tire rotation angle. a), d): wet grip. b), e): pre-hydroplaning. c), f): full hydroplaning. a), b), c): Radius of curvature corresponding to top position (orange), entering/leaving the footprint (yellow), inside the footprint (magenta). d), e), f): Radial acceleration model output for eTIS position

In the case of pre-hydroplaning (Fig. 10b and 10e), this picture changes uniquely in the footprint region. Due to the penetration of the water wedge at the leading footprint edge, the small radius r_1 does not directly go to large values but shows oscillations during this transition phase. These oscillations originate from the expulsion of the water at the leading footprint edge. They are much less present at the trailing edge. Consequently, a unique asymmetry between trailing and leading edge in the case of pre-hydroplaning can be expected.

In the case of full hydroplaning (Fig. 10c and 10f) the tire slides virtually frictionless over the water. In this case, the oscillations are expected to be of much smaller amplitude since the contact to the road is completely lost.

5.2.2. Hydroplaning tests with eTIS

To test the model, a vehicle was equipped with eTIS samples that specifically focus on measuring the radial acceleration around and in the footprint region. This vehicle has been driven on a test track into a water basin with approximately 10-20 mm of water. The vehicle was fitted with new “Continental Viking Contact 205/55R16” tires with full tread depth. In a first test run the vehicle was driven with 60km/h over a wet road. In this case, the shape of the measurement resembles the expectation for the wet grip case (Fig. 10d).

In a second test run attention towards the radial acceleration when driving with 60km/h inside the water basin was paid, where the full hydroplaning threshold was ~75km/h. This pre-hydroplaning situation was analyzed in the time domain and also by means of a spectrogram in the following figure:

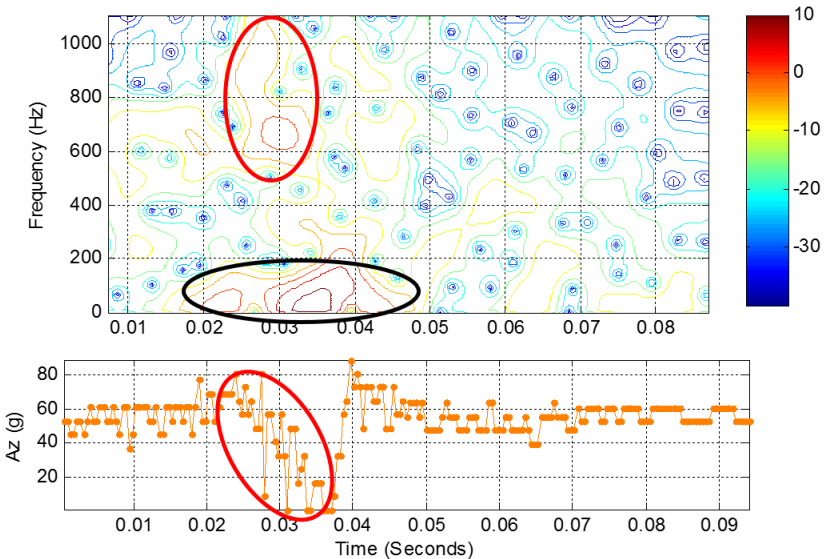


Figure 11. eTIS radial acceleration and spectral density

At the bottom of the figure, the eTIS radial acceleration signal as a function of time for this typical pre-hydroplaning situation is

plotted. It is important to note that when plotting against the time, the leading edge occurs before the trailing edge. In Fig. 10, the acceleration curve was plotted as a function of the counterclockwise defined rotation angle ϕ . The leading edge displayed exactly the oscillations expected from the expulsion of the water (red diagonal oval). These oscillations are not visible at the trailing edge. Consequently, the expected strong asymmetry was fully visible in the time-domain.

At the top of the figure, the spectral density (color coded) as a function of the same time axis and also the frequency (y-axis) is displayed. One can clearly see an increased spectral density of rather low frequencies (0...200Hz) that is distributed somewhat symmetrically over the entire footprint area (indicated by a black oval). Additionally, an increased spectral density is also clearly visible at higher frequencies (500-1100Hz), but only around the leading edge (indicated by red oval). This analysis reveals an asymmetry between the leading and the trailing edge of the footprint. The spectrogram confirms the higher frequency oscillations associated with the leading edge of the footprint, visible on the time signal, while also evaluating quantitatively the frequency range of the oscillations - roughly 500 Hz to 1100 Hz.

Theory and measurements show promising potential for the detection of pre-hydroplaning. A unique asymmetric signature in the radial acceleration measurement has been identified. The corresponding eTIS based detection is able to trigger the prevention of full hydroplaning.

6. HYDROPLANING ASSISTANCE BY BRAKE INTERVENTION AT THE REAR AXLE

6.1. Active Safety Assistance

In a hydroplaning situation the driver needs assistance in two distinct ways: firstly, to stabilize the vehicle in case of disturbances and secondly, to guide the vehicle safely along the course of the road. For control design a linear single-track model is used, in which

the front tire forces are neglected due to the hydroplaning behavior. The state vector \mathbf{x} contains yaw rate and side slip angle as state variables. Control input \mathbf{u} is the rear axle longitudinal force difference. This control action can be provided e.g. by torque vectoring based on rear wheel individual braking. The disturbance input s is an unknown yaw torque M_z , caused e.g. by not homogeneous water film thickness at the front left and right wheels.

The assistance is triggered by evaluating wheel slip and other signals provided by a standard ESC (Electronic Stability Control) system. The controller is designed as a state feedback in combination with feed-forward of the driver steering input w and disturbance compensation, i.e. the control law is given by

$$\mathbf{u} = -\mathbf{K}_x \mathbf{x} - \mathbf{K}_s \hat{\mathbf{x}}_s + \mathbf{K}_w w \quad (\text{Equation 5})$$

The control structure is further extended by an inner-loop longitudinal slip control described in [4] to access the full control potential whilst ensuring that the rear axle will not be destabilized during the intervention. The sign of the control variable \mathbf{u} determines which rear wheel is in slip control mode. The overall control structure of the hydroplaning active safety assistance is shown in Figure 12. Details of the design of the controller are given in [3].

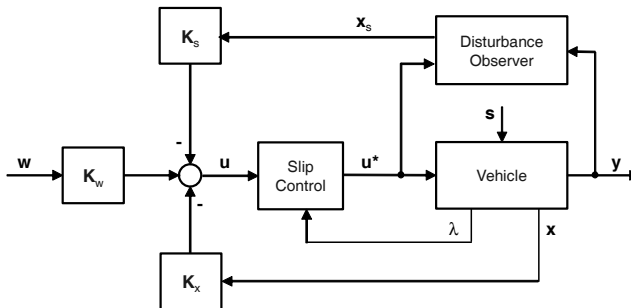


Figure 12. Control structure of the hydroplaning active safety assistance system with inner-loop slip control and outer-loop yaw rate control

6.2. Vehicle test results

Figure 13 illustrates the hydroplaning tests with a rear-drive vehicle at the “Contidrom” proving ground. The hydroplaning basin is 100 m long and 6 m wide. The water film thickness is approx..10 – 20 mm.



Figure 13. Hydroplaning assistance vehicle test at the “Contidrom” proving ground with front wheels floating. The vehicle is controllable by rear wheel brake torque vectoring

The following figure illustrates the assistance principal as well as typical vehicle dynamics signals.

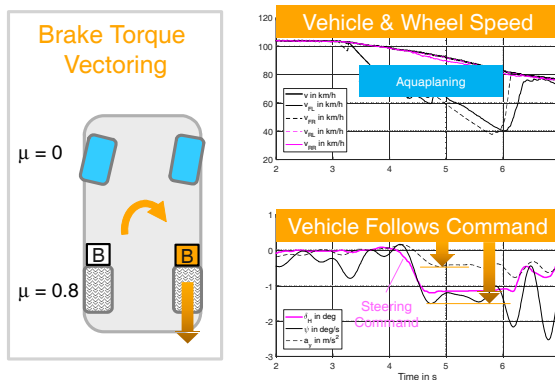


Figure 14. Hydroplaning vehicle tests at the “Contidrom” proving ground. (Left): Assistance principle: vehicle is controllable by torque vectoring at the rear axle. (Right):

Vehicle dynamics showing that vehicle is following driver steering command during hydroplaning phase

Figure 14 illustrates the performance of the hydroplaning assistance. The driver initiated a steering wheel angle ramp-step during floating phase of the front wheels. With the assistance system active the vehicle is controllable and follows the driver commands by building up sufficient yaw rate and lateral acceleration. Without assistance the vehicle is moving uncontrollable in straight direction despite driver steering command.

7. CONCLUSIONS

The integration of the eTIS-based TreadDepthMonitoring function is intended to avoid driving with too low tire tread depth during heavy rain and adverse weather situations in the first place. A surround view camera and tire sensor (eTIS) based system for early hydroplaning risk detection has been proposed to recognize the imminent hydroplane risk and to warn the driver or to intervene in the case for an automated vehicle in an early phase before (full) hydroplaning occurs. Based on outdoor vehicle tests in real hydroplaning situations feasibility studies have been carried out where both systems demonstrate the potential and ability for a proof of concept and further base development.

After adverse weather and pre-hydroplane events have been detected the cloud-based eHorizon services will be updated and provides services to inform other vehicles that could be affected before entering the hydroplane risk area.

Further-on a simulation environment has been designed to study an active safety system with the purpose to assist within the physical limits when the vehicle already hydroplanes (full). An extended tire model reproduces the effect of the surface water leading to a complete loss of grip at the front wheels. The proposed assistance strategy is based on a state feedback and feed-forward control torque vectoring actuating the rear brakes. The system enables an adequate amount of yaw damping as well as a minimum guidance capability. Vehicle tests have shown significant benefit of the assistance.

The hydroplaning assistance as proposed in this paper is the next

step to strongly support Continental's long-term strategy "Vision Zero" leading to zero traffic-related fatalities, injuries and road accidents in future.

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SAFETY EVALUATION OF AUTOMATED VEHICLES THROUGH ACTUAL VEHICLE TESTS IN CUT-IN AND OFFSET CUT-IN SITUATIONS.

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ABSTRACT

This paper describes the safety assessment results of level 2 automated vehicles in cut-in and overlap cut-in collision situations. The test results were compared with typical rear-end and 50% overlap rear-end collisions. From analysis of NASS CDS data, cut-in rear-end accidents occur at a rate of 25% out of rear-end accidents. The cut-in and 50% overlap cut-in situation were tested for the evaluation of level-2 automated vehicles. Main parameters of the cut-in scenario are speed of vehicles, TTC(Time to collision) and TLC(Time to lane changing). The speed of vehicles for scenario composition was selected from NASS CDS data analysis. The speed of the vehicle target was selected at 20km/h. The speed of the VUT(Vehicle Under Test) consisted of 5 types: 30, 40, 50,60 and 70 km/h.

Cut-in scenarios were designed with TTC 4 seconds and the target vehicle changes the lane to the front of the test vehicle at each TTC. The target vehicle's TLC was set to 2 seconds at all scenarios. For comparison, rear-end collision and 50%-offset rear-end collision scenarios suggested by EuroNCAP 2018 were also tested. A low platform robot vehicle target was utilized for all test scenarios. The low platform robot vehicle and a balloon dummy were used to imitating the causative vehicle in the accident and reproduce the accident situation. The robot vehicle target and the VUT were communicated with their position, speed, and acceleration data from GPS INS data. The data were recorded for further analysis.

OVERVIEW

The driver had to take risks such as personal and financial damages while driving the car. Various legal, institutional, and technical measures have been put in place to reduce the risk, and now it is possible to use safe and convenient vehicles based on the development and dissemination of autonomous vehicles.

In particular, the development and emergence of autonomous vehicles and assistive technologies are expected to prevent or reduce the risk of automotive crashes occurring at present. As a result, the demand for the development and distribution of safer autonomous vehicles is getting lighter, and the interest of the users is increasing. In response to this trend, the New Car Assessment Program (NCAP) urged developers of autonomous vehicles to upgrade their safety in accident situations.

However, the current NCAP standards are not a standard for dealing with various accidents that may occur on the current roads. In particular, among the functions of the autonomous vehicle, the evaluation criteria of AEB, which plays the most role in avoiding accidents in sudden accident situations, has a limitation that can be confirmed only for simple rearward collision situations. As the function of the autonomous vehicle increases, it is expected that the users will use the technologies more actively. Therefore, more rigorous safety of the autonomous vehicle is required and safety verification in various accident situations is required.

This paper identifies some of the AEB protocols provided by the NCAP, and develops real-world test scenarios for interrupt situations as a result of classifying dangerous accident situations that often occur on the roads. The AEB performance of the autonomous vehicle is conducted the actual vehicle experiment for the safety evaluation safety.

METHODS

Building of Scenario

Accident data analysing: NASS CDS data was analyzed for five years from 2100 to 2015. 2,633 cases in 2015, 2,896 cases in 2014, 3,385 cases in 2013, 3,581 cases in 2012, and 4,278 cases in 2011. The data were classified and analyzed according to the type of accident. More than 40 types of accidents type was classified by NASS CDS. It was classified into single vehicle accident, rear-end collision, cut-in rear-end collision, frontal collision and side collision..... As a result, shown in the Fig.1, the ratio of single vehicle accident was the highest at 36%, side collision was the second at 31%, rear-end collision and head on collision occupied at the third and fourth, with 5% of ratio.

Especially, when the type of accident was classified as rear-end collision, cut-in collision accounted for about 22% of the total rear collision. As a result of checking the ratio of AIS injuries according to the accident situation, the ratio of injury severity of simple collision accident to intervention collision was similar.

Through the results of the accident DB analysis, it can be seen that the rear-end collision is the most important accident type, which is the type of accident that is already evaluated through the NCAP protocol. However, the NASS CDS DB analysis shows that the rate of interruption in the collision is about 1/4, and the degree of injury in the case of interruption shows a similar tendency to the general collision.

Therefore, it is necessary to confirm the AEB performance not only in a simple rear-end collision situation but also in a cut-in rear-end collision situation. Considering the AEB test Protocol proposed by 2018 Euro NCAP, the cut-in collision scenario and 50% offset cut-in collision scenario were constructed according to the following procedure.

Set parameters for scenario configuration: Main parameters of the cut-in scenario are speed of vehicles, TTC(Time to collision) and TLC(Time to lane change). The parameters were determined by analyzing the results when an accident occurred. The speed of each vehicle was selected by referring to the results of NASS CDS accident database. TTC and TLC were selected by analyzing images acquired from dashboard camera image.

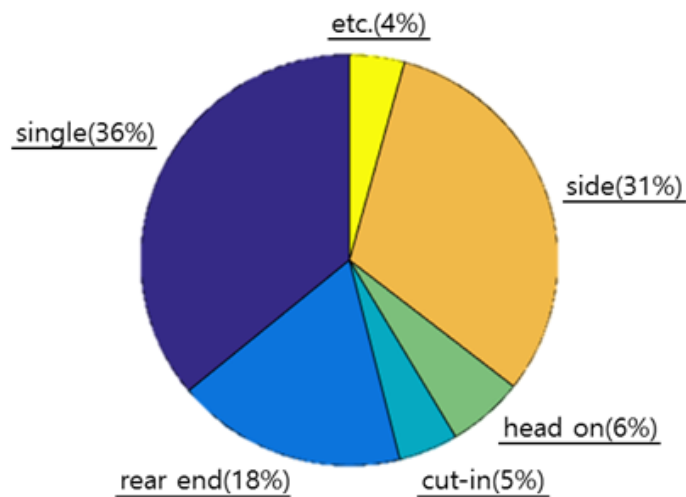


Figure 1. The frequency by accident type.

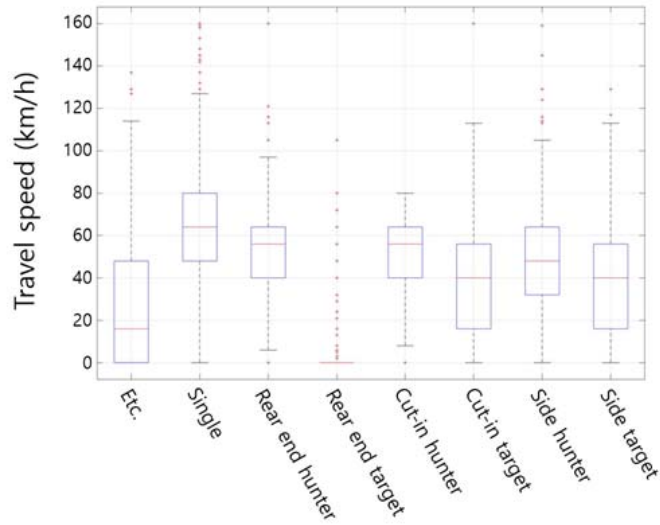


Figure 2. Velocity distribution by accident type (Public roads:Speed limit less than 80 km/h)

In the case of the target vehicle, 50% of the vehicles are present in the range of 20 to 50 km/h and the median value is 40 km / h. The speed of the target vehicles are present in the range of 20 to 40 km/h and the median value is 40km/h. TLC is selected by dashboard camera images in Korean intervention situation. In a total of 63 dashboard camera image data, it was confirmed that the average TLC in an accident situation was 1.85 seconds. It is difficult to determine when to start a cut-in from the black box images or accident DB analysis results. Therefore, the time to start cut-in was arbitrarily selected. Based on the results of the pre-test in one vehicle, the time to start cut-in was selected as TTC 4 seconds. That is, according to the constructed scenario, the time remains 2 seconds for the VUT to collide with the target vehicle when the cut-in complete. Based on these analyzed parameters, the following scenario table is constructed.

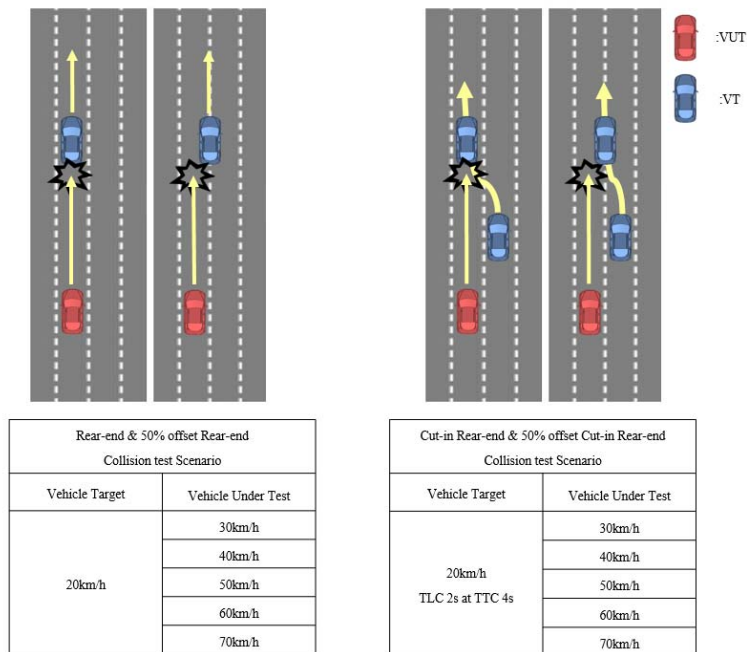


Figure 3. Scenario Table for AEB collision test

Development of Testbed

Low-platform robot vehicle target: In the Euro NCAP protocol, the EVT(Euro NCAP Vehicle Target) used for the AEB test is a pile that shapes the rear-end collision of the vehicle, and serves as a forward vehicle in test such as rear-end collision. In case of EVT, it is not suitable for scenario that requires path following function because it is mounted on a rail or connected with a preceding vehicle. Therefore, a robot vehicle target capable of performing in various scenarios was designed.

In the case of robot vehicle target, it is necessary to be able to perform not only the rear collision test used in the existing NCAP test but also the forementioned cut-in scenario. In addition, in order to be able to repeat the experiment, the robot vehicle was designed so that the equipment, the VUT, and the experimenter would not be damaged or injured in the event of a collision due to the VUT not responding to the accident situation.

RVT (Low-Platform Robot Vehicle Target) was designed as a robot vehicle target. From the developed scenario, the maximum relative speed of VUT and RVT is 50km / h. It should be designed so that the test system is not damaged even if it collides at this speed. The height of the lower part of the vehicle differs by vehicle type, but the legal minimum ground height in Korea is 110mm. As a result, the height of the RVT is limited to 90 mm. In order to carry out the scenario, The RVT equipped with a dummy model is designed to be able to travel at a maximum speed of 40 km/h and change lanes 3.5m within 2 seconds. The RVT and the VUT had configured communication systems to accurately measure each position and transmit data to each other. The type of data to be transmitted is the position, speed, and acceleration information of the vehicle. These data are also the main analytical elements obtained from the experimental results. It is confirmed that the vehicle and RVT were not damaged even when the vehicle stepped over at a speed of 60 km/h, and the RVT travel at a maximum speed of 60 km/h equipped with a dummy model.

3D balloon dummy: The VUT does not recognize the RVT as a vehicle. Therefore, a balloon dummy model should be mounted on the RVT. In the case of such a dummy model, The VUT must be able to recognize the dummy as a real vehicle when sensing the vehicle ahead with a radar or a camera. It should also not damage the VUT in the event of a collision.

As shown in the Figure 4 below, a 3D dummy model was created to have the shape of the actual vehicle using a balloon to minimize the impact quantity when colliding. The 3D balloon dummy was verified using a radar system. The radar used in the verification uses radio waves in the 24 GHz band. The verification method was evaluated by comparing the radar reflectance of the actual vehicle with the radar reflectance of the balloon target pile. Also, we confirmed that the target dummy was recognized as a vehicle by using the vehicle equipped with the actual AEBS.

The AEBS vehicle ran at more than 30 km/h with the balloon target pile up and checked whether there was a warning in the vehicle. The test results confirm that the head-up display gives a vehicle crash warning as shown in the Figure 5. This result shows that AEBS is recognized as a vehicle and can be used for testing.



Figure 4. Shape of Balloon dummy car



Figure 5. AEBS warning test of 3D balloon dummy car

ACTUAL VEHICLE TEST

An actual vehicle test was conducted on the scenarios developed using a real vehicle equipped with an AEB. Each of the scenarios was tested three times and the AEB operation and collision were observed. In case of collision, the velocity at the time of collision was observed. In case that a collision did not occur the minimum approach distance was observed. In addition, the deceleration of the vehicle caused by the AEB was also analyzed.

Scenario Test Results

Test Results: The AEB collision test scenarios shown in Figure 3 was repeated twice for each scenario. The results of the actual vehicle tests are summarized in Table 1. Based on the experimental speed of VT and VUT, it is classified into the items according to the scenario. The classified scenarios are Rear-end, Cut-in, 50% Offset Rear-end, and 50% offset cut-n. If there is no collision, 'no collision' is indicated and the minimum distance is indicated at the bottom. In case of collision, 'collision' is indicated and the speed of collision is indicated at the bottom. In case that a collision did not occur in the actual vehicle experiment, the relative distance when the VUT was closest to the VT was measured. When a collision occurs, the relative velocity of the VUT and VT at the moment of collision is measured.

In the 10 tests with five rear-end collision scenarios, AEB was operating normally and did not crash. VT was very close to the VUT, but it was observed to avoid collision with a maximum of 3.11m margin. Therefore, in the simple rear-end collision situation proposed by the Euro NCAP, the present AEB function shows good performance.

In the 50% offset rear-end collision scenario, one collision occurred when the VUT speed was 70 km/h, but in all cases the AEB was operating normally. As the speed increases, the AEB fails to avoid one collision to the increased difficulty level, but still shows good performance. Also, It has been confirmed that if the AEB of the VUT is operating normally, it will defend the collision situation.

As a result of the general cut-in collision test scenario, five collisions occurred in 10 tests. The AEB response was delayed in all five crashes, which is the main reason for not recognizing the vehicle that changed the lane in the next lane. Likewise, it has been confirmed that the detection performance of the vehicle coming in the next lane is considerably deteriorated in the collision situation in which the AEB must respond.

Table 1. Scenario test results of vehicle test

VT	VUT	Rear-end		Cut-in	
		No Collision (Minimum relative distance) Collision occurred (Relative impact speed)			
20km/h	30km/h	No Collision 2.12	No Collision 2.58m	Collision 11.26km/h	Collision 11.29km/h
	40km/h	No Collision 3.11m	No Collision 2.96m	No Collision 6.02m	No Collision 9.95m
	50km/h	No Collision 1.06m	No Collision 0.58m	No Collision 0.06m	No Collision 12.99m
	60km/h	No Collision 1.44m	No Collision 2.06m	Collision 38.52km/h	Collision 39.20km/h
	70km/h	No Collision 0.15m	No Collision 0.06m	No Collision 0.78m	Collision 42.56km/h
VT	VUT	50% offset rear-end		50% offset Cut-in	
20km/h	30km/h	No Collision 3.14m	No Collision 1.31m	Collision 10.8km/h	Collision 7.19km/h
	40km/h	No Collision 1.58m	No Collision 1.45m	No Collision 0.70m	Collision 8.84km/h
	50km/h	No Collision 1.12m	No Collision 1.41m	Collision 2.49km/h	Collision 8.52km/h
	60km/h	No Collision 1.13m	No Collision 1.44m	Collision 18.3km/h	Collision 17.8km/h
	70km/h	Collision 9.83km/h	No Collision 1.14m	Collision 21.1km/h	Collision 19.7km/h

CONCLUSIONS

Experimental results show that level 2 automated vehicles have a lack of ability to avoid a crash in cut-in collision situations. 2018 Euro NCAP's proposed AEB test protocol scenarios did not have good response capabilities in a barrage situation, even for vehicles with good performance.

In some cases, the VUT did not detect the vehicle target so it strikes target without any deceleration. The sensor seems to detect only the same lane of the vehicle not for its side lanes.

In view of the injury analysis results, the current AEB performance alone does not seem to prevent any serious injury to the driver in the event of interruption.

The cut-in and 50% offset cut-in experimental scenarios were constructed from the actual accident. Four types of vehicle tests were conducted and test results were analyzed. In each scenario, relative speed and deceleration were analyzed. The safety performance for an automotive vehicle in cut-in rear collision situations was evaluated. Further studies on safety assessments in various test scenarios are needed in order to validate the safety performance of automated vehicles.

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TOLERABILITY OF UNEXPECTED AUTONOMOUS EMERGENCY BRAKING MANEUVERS ON MOTORCYCLES - A METHODOLOGY FOR EXPERIMENTAL INVESTIGATION

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The authors are solely responsible for the content.

Ethical approval for the test track studies was obtained from the Ethics Commission of Technische Universität Darmstadt (reference EK 32/2018).

ABSTRACT

Motorcycle riders are subject to a high risk of suffering severe or fatal injuries. Previous research has identified autonomous emergency braking for motorcycles (MAEB) as one of the most promising technologies to increase safety for riders (e.g., [2]).

Compared to drivers of two-track vehicles, emergency braking maneuvers are much more challenging for motorcyclists. As there is no restraint system such as a safety belt, riders need to support their upper body movement and they need to control and stabilize their vehicle. This requires attention, situation awareness and body tension. Before applying maximum deceleration, the rider has to achieve this ‘prepared-for-braking’ state. To generate optimal crash mitigation or even crash avoidance, the velocity should be reduced even before this state is achieved. Therefore, it is necessary to determine applicable preparatory braking profiles. As sudden unexpected braking maneuvers are critical for unprepared riders, there is still a great uncertainty on how high these decelerations can be. The identification of the limits would enable to determine the safety benefit of MAEB, when the full deceleration potential before reaching the ‘prepared-for-braking’ state is used.

One of the main challenges in MAEB studies is the rider state. On one hand, to evaluate to what extent autonomous interventions can support riders, participants need to be unprepared to receive unbiased results. On the other hand, due to safety and ethical reasons, it is out of question to determine the limits of controllable decelerations with unprepared riders. For this purpose, the experiments within this project are split up:

In a first study with experts, the deceleration limits are identified. The experts are asked to evaluate if different automatically applied braking interventions are controllable for unprepared average riders. By increasing the decelerations until the experts rate them as intolerable for unprepared riders, maximum tolerable decelerations for different braking profiles in real riding scenarios are defined.

In a following participant study, average riders experience a realistic emergency braking scenario (suddenly braking vehicle ahead). The deceleration profiles defined during the expert study are applied. With these experiments, the reaction of the unprepared participants to unexpected autonomous braking maneuvers are analyzed. The result is an evaluation on how partial braking maneuvers can help to reduce the transition time and on the potential decrease of velocity during the transition period.

In a third study, more critical scenarios (different secondary tasks) and the influence of warnings prior to the autonomous braking intervention are investigated on a dynamic motorcycle simulator.

The studies provide empirically obtained data on maximum deceleration values for different automatic braking interventions that are tolerable for average riders in unexpected emergency braking situations. The results also show the maximum amount of velocity – and thus kinetic energy – that can be reduced during the partial automatic braking phase before the maximum deceleration can be applied. The simulator experiments show the influence of different secondary tasks and the effect of visual-auditory warnings. The described method can be used as a reference for future development and configuration of MAEB.

INTRODUCTION

In previous research projects, it has been shown that autonomous emergency braking systems for motorcycles (MAEB) offer a high safety potential to reduce consequences of accidents or even avoid them (e.g., [3]). In these projects, important aspects of MAEB have already been discussed.

Project PISa investigated the influences of braking interventions on the stability of a motorcycle rider on his vehicle [4]. Other studies have shown that low decelerations up to 3 m/s^2 can be applied automatically without making the rider feel like losing control [5]. Within the MOTORIST project the researchers evaluated usual behavior of riders in different braking situations and showed that riders themselves do mostly not use the full deceleration potential [2]. The described projects are examples for a variety of research that has been performed in terms of MAEB. This research is highly important to develop a base line for the design of automatic brake applications.

The contents of the previous work are important aspects for the development and design of autonomous emergency braking systems for motorcycles. In particular, it has been shown that decelerations up to 3 m/s^2 are controllable for motorcycle riders and do not negatively affect the rider's postural stability. However, to our knowledge there is no study that determines the maximum autonomous deceleration that is controllable for unprepared riders.

The aim of an AEB is to maximize the reduction of kinetic energy prior to a collision to mitigate the consequences of an accident. In case of an emergency scenario, this requires building up a maximum deceleration as fast as possible. The achievable decelerations are subject to certain limits. Besides the physical limits, these include limits that the rider sets to the applicability. As an integral part of the rider-vehicle system, the rider must be able to control the MAEB intervention. This is essential to avoid destabilizing the vehicle or cause a fall.

The approach of the work described in this paper is based on the assumption that the rider must be in a prepared-for-braking state to be able to control an autonomous maximum deceleration. In order to bring him/her into this state and at the same time being already able to achieve a reduction of speed before reaching the braking readiness, preparatory partial braking maneuvers are used. These partial braking interventions are the main content of the investigations within the project.

The discussed research questions are:

- Can partial braking maneuvers be used to prepare the rider for a maximum deceleration, i.e., to motivate him/her to get to the prepared-for-braking state?
- How fast is the transition to the prepared-for-braking-state completed using different braking profiles?
- What is the potential velocity reduction during the transition phase, i.e. what is the maximum deceleration that is controllable for an unprepared rider?

METHOD

One of the main challenges with investigating MAEB is the fact that on one hand emergency braking situations are always critical scenarios but on the other hand riders need to be unprepared in order to provoke realistic reactions in the studies.

For safety reasons, it is not possible to identify the limits with unprepared participants. Due to this fact, the test track experiments were split up into two studies. First, in an expert study, it was analyzed which decelerations and decelerations profiles would be controllable for average riders. This identification of the deceleration limits was performed with riding instructors and trainers as these people are assumed to be particularly suitable to assessing the skills of unexperienced riders.

However, while the expert study is appropriate for determining the limits of controllable decelerations, it cannot be used to assess the rider reaction because the experts were informed that there will be an automatic deceleration. As mentioned above, riders need to be unprepared to analyze how the partial braking interventions influence the transition to the prepared-for-braking state. Thus, the expert study was followed by a participant study. In this study, average riders were confronted with unexpected emergency braking situations which were followed by autonomous braking interventions according to the deceleration profiles identified in the expert study. The focus was to analyze the riders' reactions, particularly how different deceleration profiles affect their transition to the prepared-for-braking state. Moreover their subjective evaluation of the interventions was examined.

In the real life experiments, especially those with unprepared motorcycle riders, automatic braking interventions are only applied while going straight (roll angle close to zero) and with the riders' full attention to the riding situation.

In addition to these two studies, a simulator study was conducted. This simulator study aimed for analyzing the influence of visual-manual distraction on the riders' ability to control the motorcycle. This offered the opportunity

to analyze potentially critical situations in a controlled environment without exposing the participants to the risk of getting injured.

Figure 1 gives an overview of the performed studies.

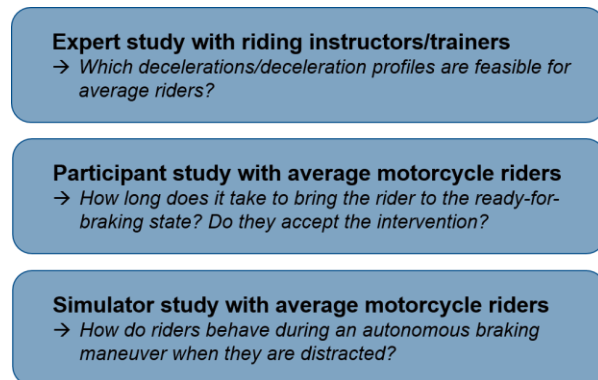


Figure 1. Overview of the performed studies

Test tools

The experiments on the test track were performed with a test motorcycle equipped with a variety of sensors to evaluate the state of the vehicle. These include, e.g., an inertial measurement unit to record translational and rotational accelerations, pressure sensors to monitor the brake pressures and a GPS antenna to track the vehicle. In order to decelerate the vehicle without an intervention of the rider, the vehicle is equipped with an actuator that operates the foot brake. The test vehicle has a combined brake system. This means that by operating the foot brake, brake pressure is not only built up at the rear wheel, but also at the front. With this setup, automatic decelerations up to 7 m/s^2 can be applied. Figure 2 shows the three implemented braking profiles. The brake actuator is activated via remote control. To ensure that the engine is not stalled and that the rider is not able to accelerate unintentionally during an automatic braking intervention, the clutch is also actuated automatically by an external actuator.

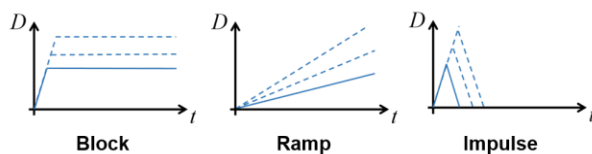


Figure 2. Implemented braking profiles

To evaluate the rider state, additional measurement technology is installed. During the experiment, the rider is equipped with a 3-axis acceleration sensor to analyze the upper body movement. The sensor is mounted on the back at the level of the shoulder blades. To monitor the rider inputs, forces on the handlebar as well as brake actuation, clutch actuation and throttle are also recorded.

Although, the emergency braking shall be unexpected, it should not get the character of a false positive braking intervention. Therefore, it is necessary to create a situation that presents a realistic true positive emergency braking scenario, like a suddenly decelerating target vehicle, to the rider. In order to avoid the risk of collisions between the motorcycle and the target vehicle, the dummy target EVITA (Experimental Vehicle for Unexpected Target Approach) was used. This test tool was developed to allow collision free investigation of anti-collision systems [6]. The dummy target consists of a towing vehicle and a trailer with a vehicle rear. The trailer can be decelerated independently from the front vehicle to simulate a rear-end collision situation. If the time-to-collision (TTC) between the following vehicle and the dummy target gets too short, the trailer is pulled forward to avoid a collision. The system is shown in Figure 3.



Figure 3. Dummy target EVITA

The simulator experiments were carried out at the Würzburg Institute for Traffic Sciences (WIVW). The dynamic motorcycle riding simulator DESMORI is based on a 6-degrees-of-freedom motion base. A real motorcycle body is mounted on the platform so that the rider can operate the virtual motorcycle with authentic control elements (clutch, throttle, brake levers etc.). The simulator allows the rider not only to steer the motorcycle by applying steering torque to the handlebar, but also with shifting his/her body relatively to the motorcycle. The visual representation of the environment is realized by a cylindrical screen (4.5 m diameter, 2.8 m height, 220° horizontal field of view) while sound is displayed via in-helmet speakers. Velocity and acceleration dependent haptic cues are delivered via a G-vest simulating forces to the rider torso [7]. The simulation is implemented in WIVW's simulation software SILAB, the virtual motorcycle is simulated in VI-BikeRealTime (VI-grade).



Figure 4. DESMORI Dynamic Motorcycle Riding Simulator at WIVW

RESULTS

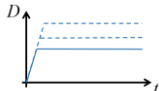
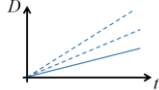
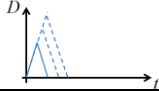
Expert Study

As explained before, the expert study was supposed to identify the limits of deceleration that are controllable for average riders who do not expect an automatic braking intervention. There were three braking profiles (shown in Figure 2) to be investigated:

- block braking (deceleration is built up quickly and then is kept at the required level)
- deceleration ramp (deceleration is built up slowly to a maximum of 7 m/s^2)
- braking impulse (deceleration is only is short to 'wake up' the rider)

For each of the profiles, limits of decelerations or deceleration gradients that can be used in the participant study, needed to be identified. The experts were decelerated by remote control while driving straight ahead and then they were asked to give a rating as to whether the respective braking intervention is reasonable for an average unprepared rider without affecting the controllability of the situation. If the assessment was positive, the deceleration or the deceleration gradient was increased for the next braking maneuver until the braking intervention was classified as no longer acceptable. The varied parameters and the identified limits are summarized in Table 1. A detailed description of the evaluation of the expert study was introduced in [8].

Table 1. Varied parameters

Braking profiles	Varied parameters		Determined maximum
Block braking	Level of deceleration		5 m/s ²
Deceleration ramp	Gradient		9.1 m/s ³
Braking impulse	Level of deceleration		4.7 m/s ²

With these results from the expert study, limits for unexpected autonomous decelerations are identified.

Participant Study

With the knowledge of which decelerations are acceptable for average riders, the participant study was carried out. This study examined to what extent the different types of interventions (braking profiles) are suitable to assist the rider in an emergency braking situation and which increase in safety this offers compared to the rider himself/herself carrying out an emergency braking maneuver.

During the experiments, the test persons followed the dummy target EVITA on the test motorcycle at a pre-determined distance (time headway 1.5 s, see Figure 5). The initial velocity for the experiments was 70 km/h. At an appropriate point (correct distance between the vehicles, correct velocity, enough straight track left), the dummy target was decelerated and the remote-controlled braking intervention was triggered synchronously. EVITA served merely to make the automatic braking intervention plausible as true positive for the rider.

The study was carried out with 18 participants. Apart from the braking profiles (block, ramp and impulse), reference experiments without automatic braking interventions were performed in order to create a baseline to evaluate how the autonomous interventions can help to decrease the velocity.

With the aim of receiving unbiased assessments and to avoid habituation effects, only two braking maneuvers are performed per participant. After elimination of the invalid runs, 19 braking maneuvers can be evaluated (5x block, 5x ramp, 5x impulse, 4x reference).



Figure 5. Participant study with EVITA

The following paragraphs summarize the evaluation and the results of the participant study. Figure 6 explains how the measured data is presented for the different braking profiles. The upper diagram always shows the vehicle state. It contains the velocity v and acceleration a_{Vx} as well as the brake pressure at the foot brake $p_{MBC,foot}$ that is automatically built up by the braking actuator. In Figure 6 the vehicle state diagram also shows the target deceleration $a_{Vx,tg}$.

The lower diagram mainly presents the rider state and rider inputs. It shows the acceleration measured at the upper body of the rider a_R , the force on the handlebar F_{hand} and the brake pressure at the front brake $p_{MBC,hand}$ applied by the rider. For comparison purposes for the rider body acceleration, the vehicle acceleration is also shown in this diagram. Diagrams for the impulse profile and for reference scenarios also contain the clutch signal.

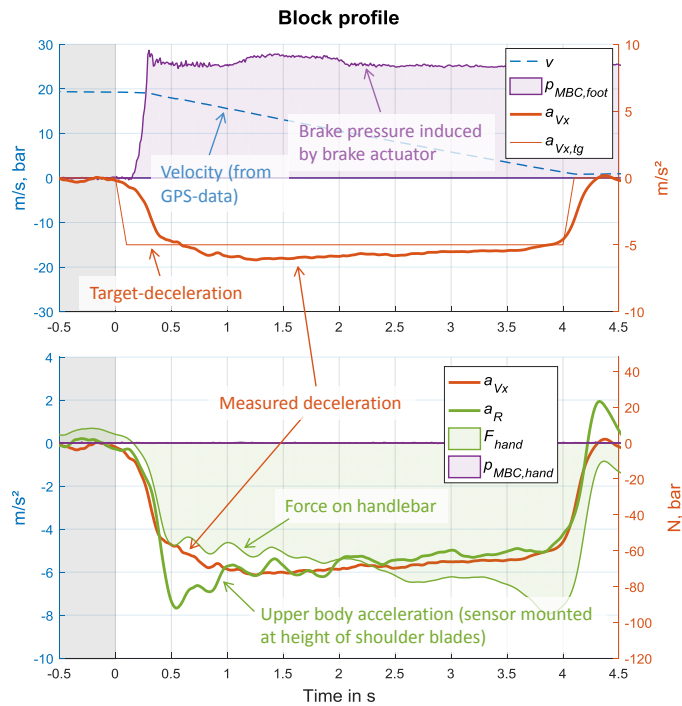


Figure 6. Scheme of measurement data representation

Figure 7 shows the data for a braking maneuver with the block profile. The brake pressure is built up within less than 0.3 s. All block braking maneuvers are analyzed concerning their transition time. The diagram in Figure 7 shows that first, the vehicle deceleration is built up. The deceleration of the rider's upper body then follows with a small time lag. This can be explained by the fact that the upper body is at the first moment moved forward relatively to the vehicle due to the unexpected deceleration. By supporting the resulting force with the arms on the handlebar and straightening the upper body, the upper body deceleration is then adapted to the vehicle deceleration. The transition is considered as completed, as soon as the force on the handlebar or the upper body deceleration does not increase anymore. The earlier of these two points is defined as the end of the transition period.

The mean transition time for the block profile braking maneuvers is at 0.57 s. Within the transition, a mean of 1.48 m/s of velocity reduction can be achieved.

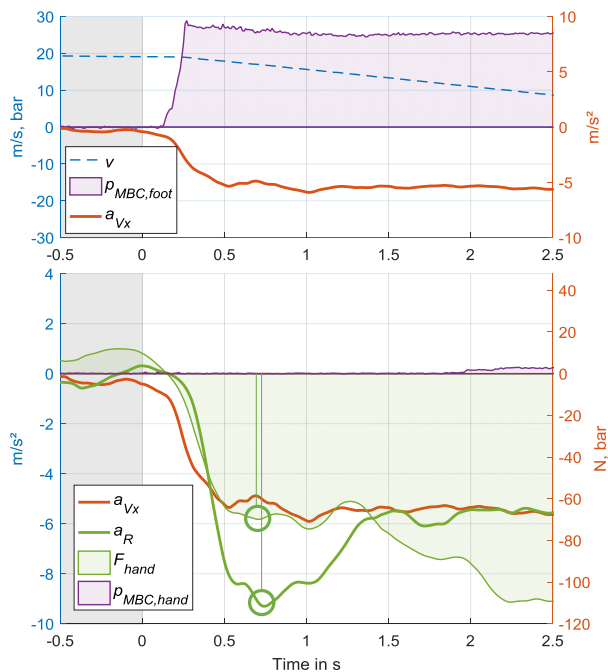


Figure 7. Block profile

Unlike in the block profile, the brake pressure is built up more slowly in the ramp profile braking maneuvers. The built up of the pressure starts at about 0.3 s with a low gradient and then increases progressively, until the target deceleration level of 5 m/s^2 is achieved. The target deceleration gradient (9.1 m/s^3 , system-related scattering) starts at about 0.5 s.

The evaluation of the transition period follows the same scheme as for the block profile (see Figure 8). With a mean time of 1.04 s, the transition takes significantly longer than for the block profile. This shows that the block profile appears more effective in terms of motivating the rider to get to the prepared-for-braking state. Due to the slow brake pressure built up, the decrease of velocity is only slightly higher. The mean velocity reduction is 1.69 m/s.

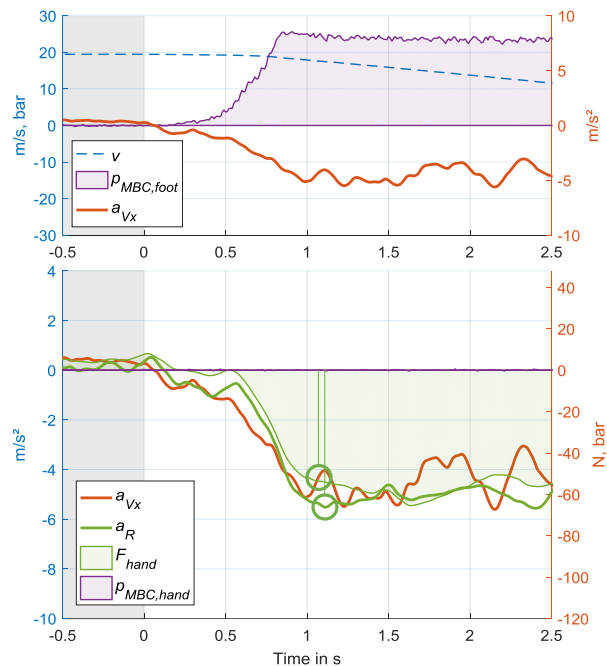


Figure 8. Ramp profile

Unlike the block or ramp profile, the impulse profile only offers a short automatic deceleration without actuating the clutch. Due to the fast increase and decrease of the vehicle deceleration and the resulting pitch movement, the rider is forced to a phase-shifted upper body movement (see Figure 9). Due to the immediate decrease of the deceleration, the upper body swings back. This even results in a pulling force on the handlebar (sign change in the force signal), as the rider needs to retain this movement. Consequently, the force on the handlebar or the no longer increasing upper body deceleration cannot be used as an indicator for the completed transition for the impulse profile.

For the impulse – which is supposed to ‘wake up’ the rider – the transition is defined as completed, as soon as the rider reacts to the automatic intervention in terms of rider inputs, such as applying the brakes (more than 0.5 bars on the hand- or foot brake) or actuating the clutch (increase of the clutch parameter, see blue marking in Figure 9). The earliest of the inputs represents the end of the transition period for the impulse profile.

The impulse causes a mean transition time of 1.37 s. It is thus longer than the time for the block or ramp profile. Due to the fact that the clutch is not actuated and the deceleration is very short, the velocity is only slightly reduced. The mean velocity reduction is 0.77 m/s.

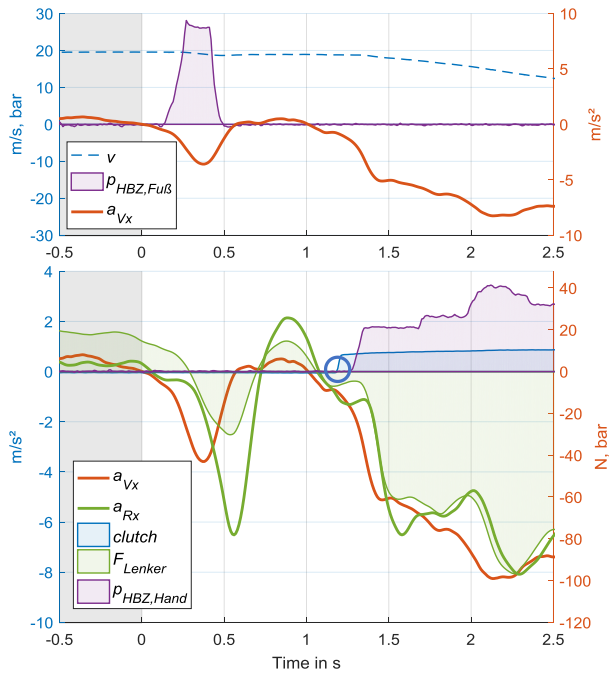


Figure 9. Impulse profile

The reference maneuvers (see Figure 10) were supposed to show how much time the rider needs to initiate a braking maneuver himself/herself after an incident occurs. The incident is represented by the release of EVITA at $t = 0$. The characteristics for the completed transition comply with those for the impulse profile, i.e., the transition is completed as soon as the rider actuates the clutch or the brakes.

In average, it took the participants 1.65 s to react to the deceleration of the dummy target. Within this time, a mean velocity reduction of 0.57 m/s can be observed. This small reduction results from the fact that until the rider reacts, no brake pressure is built up automatically. The deceleration only is only achieved by throttling back.

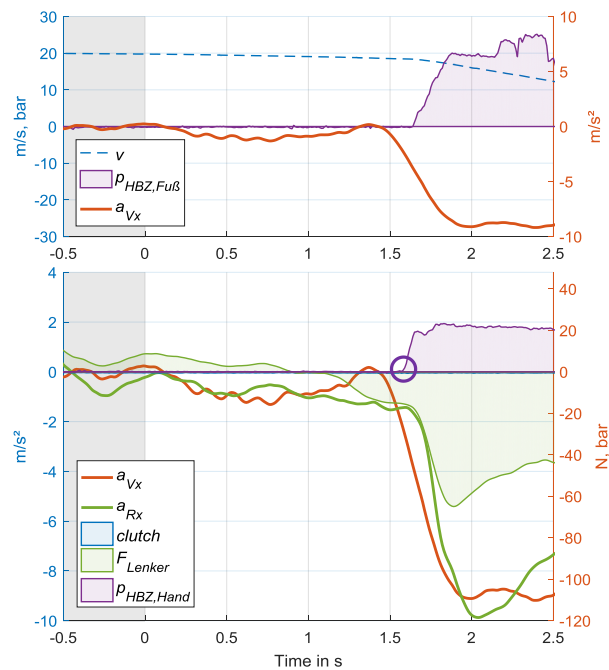


Figure 10. Reference braking maneuver

The test track experiments with participants show that the block profile is the most promising profile in terms of motivating the rider to get ready for full deceleration. The block profile leads to the shortest transition time and at the same time, it leads to the highest velocity reduction within the reference time of 1.65 s. For the ramp and

impulse profile, the transition periods become longer, while the velocity reduction within the reference time decreases.

The velocity reduction within the reference time is calculated based on the assumption that as soon as the transition is completed, the deceleration can be raised to a maximum level. This maximum is not represented by the physical limits of the braking maneuver, but it is set to 7 m/s^2 . This deceleration still allows some friction potential in case the rider decides to perform an evading maneuver during the automatic braking.

To determine the potential velocity reduction Δv_{Red} within the reference time T_{Ref} for each braking profile, it is assumed that after the transition period T_{Trans} , the rest of the reference time span is used to decelerate at $D_{max} = 7 \text{ m/s}^2$. The calculation is exemplarily shown for the block profile in (Equation 1). Within the transition time of 0.57 s, the velocity is reduced by 1.48 m/s (mean reduction determined during experiments). The rest of 1.08 s within the reference phase are used to decelerate at 7 m/s^2 . This results in a total velocity reduction of 9.04 m/s.

$$\begin{aligned} \Delta v_{Red,Block} &= \Delta v_{Trans,Block} + (T_{Ref} - T_{Trans,Block}) \cdot D_{max} && \text{(Equation 1)} \\ &= 1.48 \frac{\text{m}}{\text{s}} + (1.65 \text{ s} - 0.57 \text{ s}) \cdot 7 \frac{\text{m}}{\text{s}^2} \\ &= 9.04 \frac{\text{m}}{\text{s}} \end{aligned}$$

Within the transition time of 0.57 s, the velocity is reduced by 1.48 m/s (mean reduction determined during experiments). The rest of 1.08 s within the reference phase are used to decelerate at 7 m/s^2 . This results in a total velocity reduction of 9.04 m/s.

The starting velocity of 70 km/h equals 19.4 m/s. A velocity reduction of 9.04 m/s thus means a decrease of 47 %.

A summary of all test track results including the determined potential velocity reductions is given in Table 2.

Table 2. Summary of test track experiments

Profile	Mean transition time T_{Trans} in s	Mean velocity reduction within transition period Δv_{Trans} in m/s	Potential velocity reduction within 1.65 s Δv_{Red} in m/s
Block	0.57	1.48	9.04
Ramp	1.04	1.69	5.96
Impulse	1.37	0.77	2.73
Reference	1.65	0.57	0.57

Not only the objective assessment of the measured data is important for identifying the potential of MAEB. A safety system can only be successfully engaged, if it is accepted by the users.

For this purpose, the participants were asked to subjectively assess the controllability of the single braking interventions. The rating follows the scale from Neukum et al. [9]. Within this scale, the participant can first classify the intervention on a rough ordinal scale (not noticeable, noticeable, disturbing, dangerous, not controllable) and afterwards refine the assessment within these categories (0 to 10, see Figure 11).

As expected, the participants rated the reference experiments less critical. In these braking maneuvers the brakes were actuated by the riders themselves and thus did not surprise them. The maneuvers were mostly rated at the lower end of the scale within the ‘noticeable’ category. The block profile was also mostly classified in this category. The mean rating for the block (2.8) is only slightly higher than for the reference maneuvers (2.67).

The other two braking profiles (ramp and impulse) were rated more critical. According to the mean rating, the ramp profile still falls into the same category (‘noticeable’) as the block profile and the reference maneuvers. However, there is a greater spread of the ratings and the mean (3.4) is close to the upper border of the category. The ratings for the impulse profile were more critical. The mean rating (4) falls into the ‘disturbing’ category. Although this is the most critical rating, the subjectively experienced criticality is still far away from ‘dangerous’.

The subjective assessment shows that the block profile is not only most promising in terms of transition time and velocity reduction (objective criteria), but also in terms of subjective perception of the criticality of the intervention.

Subjective Assessment of Braking Intervention

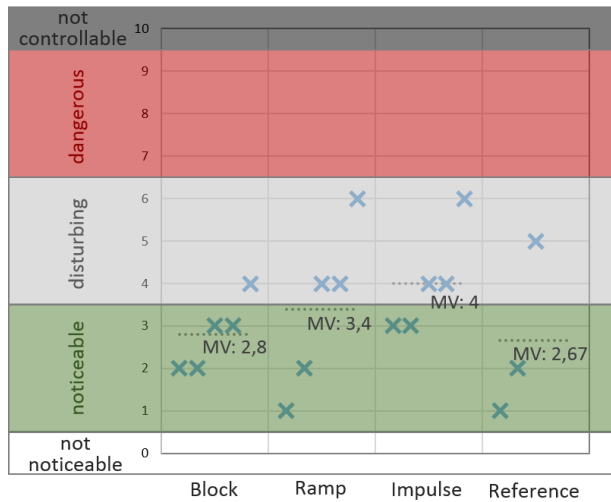


Figure 11. Subjective assessment

Simulator Study

Due to safety reasons, autonomous emergency braking scenarios have usually been tested on the test track while riding straight with full concentration on the riding task. However, MAEB is expected to support the rider especially in situations where the rider is not fully concentrated on the riding task. Thus, the rider might not be in an ideal state (e.g., being visually distracted or not having both hands on the handlebar) to cope with the intervention of an MAEB. Therefore, it is important to investigate the influence of these non-ideal rider states on the controllability of MAEB interventions. For this purpose, a simulator study was conducted. The two main aims of the simulator study were

- to investigate how both-, one- and free-handed riding in combination with visual distraction (eyes not focused on the lead vehicle) affect the riders' behavior and system acceptance in case of an MAEB intervention and
- to assess the potential of a visual-acoustic warning to improve acceptance and controllability of a MAEB intervention.

The test scenario was similar to the test track participant study regarding the primary riding-task. The participants had to follow a lead vehicle in the simulated scenario (with a velocity of 100 km/h) which triggered the autonomous braking maneuver (maximum deceleration of 6 m/s²). To manipulate hand position and visual distraction the riders were instructed to fulfill different secondary tasks which are summarized in the following table:

Table 3. Different secondary tasks used in the simulator study to manipulate hand position and visual attention.

Task	Hand position	Distraction	Implementation
surrogate reference task according to [10]	both handed	visual + manual	controlled via two buttons at the handlebar
operation of a navigation device	one-handed	visual + manual	navigation device mounted at the handlebar
free-handed lateral control	free-handed	manual	simulation of adaptive cruise control for longitudinal guidance

In order to assess the potential of a visual-acoustic warning the riders experienced each condition either with or without a visual-acoustic warning prior to the MAEB intervention in permuted order.

Rider behavior was analyzed by means of brake and clutch operation (i.e., frequency of additional brake reactions and brake reaction time) and steering behavior. Both can be used as indicators for a rider take-over or the rider being back in the control loop. Subjective ratings of controllability based on the scale of [9] were obtained after

each intervention like in the test track studies. In addition, the riders received a questionnaire at the end of the study to assess the acceptance of interventions with/without warnings.

The frequency of additional brake reactions for the front brake lever does not indicate differences between MAEB with or without warnings. In all conditions more than 50% of the riders showed additional brake reactions on the front brake lever (with warning: 57%-61%; without warning: 52%-65%). However, riders in all conditions (both-handed, one-handed and free-handed) respond slightly faster to the autonomous emergency braking of the motorcycle if a warning is presented prior to the onset of the intervention (cf. Figure 12). In addition, the reaction times seem to be more homogenous if a warning has been presented (please note that this interpretation is only based on descriptive data).

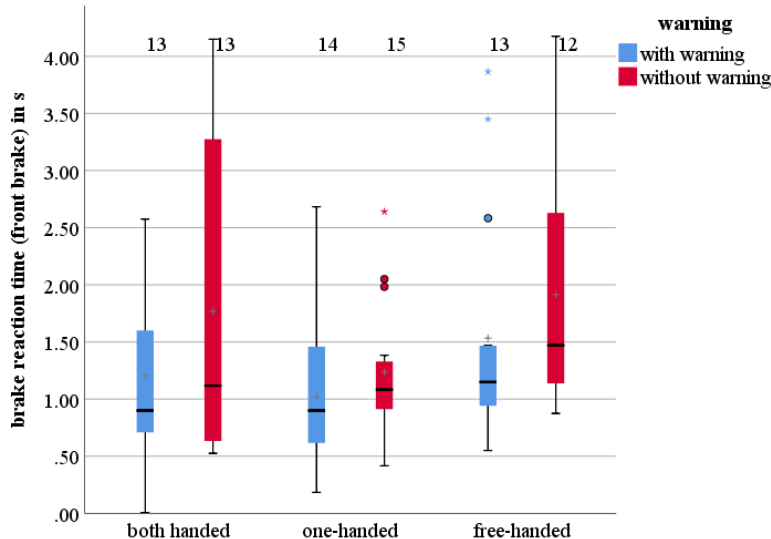


Figure 12. Reaction time depending on warning availability and type of secondary task

The subjective controllability ratings obtained after each intervention show that riders rated autonomous braking interventions with a prior warning as more controllable than interventions without a prior warning ($F(1,120) = 8.99, p = .003$). This is especially reflected in the distribution of the ratings according to the rating categories (cf. Figure 13).

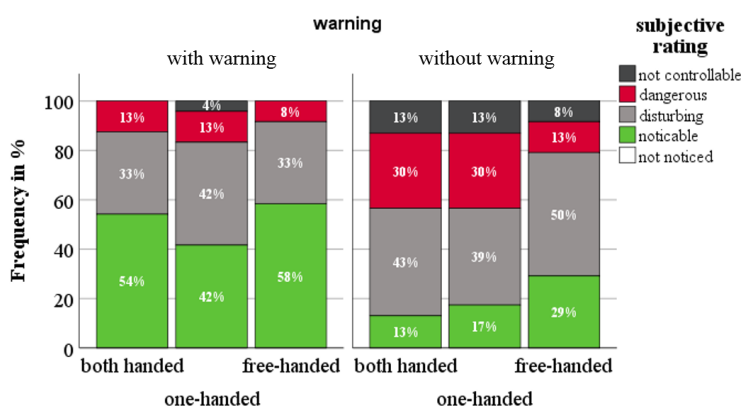


Figure 13. Subjective assessment of intervention controllability depending on warning availability and type of secondary task

The overall rating of acceptance at the end of the study revealed that riders rated autonomous braking interventions with a warning to be *more helpful, more relieving* and *safer* compared to interventions with no warning. In addition, the riders showed high consent with the statement that “*the warning made the intervention more controllable*”.

Consequently, the results of the simulator study indicate that warnings can not only support the rider in his/her reaction, they also have a positive influence on the acceptance of the interventions. However, it has still to be verified whether the results regarding the effects of warnings can be replicated on a real motorcycle. Furthermore, studies should test how the warning should be designed (visual, auditory, haptic or kinesthetic) to ensure that riders are able to perceive the warning and it’s meaning in time to react adequately.

CONCLUSION

With the work described in this paper, a method for the evaluation of controllability and acceptance of autonomous emergency braking for motorcycles has been developed and validated. Furthermore, it has been shown how the prepared-for-braking state of the rider can be detected. The proposed methods prove that automatic braking maneuvers can be applied to and controlled by unprepared riders in participant studies. Thereby, this work provides an important foundation for the future design of MAEB and the assessment and evaluation of its safety potential. The results indicate that the block profile offers the greatest potential to decrease velocity while being well accepted by the riders. This design leads to a high potential of future MAEB solutions. In the tested scenarios with autonomous interventions, the velocity can be reduced by up to 47 % compared to reference scenarios without interventions (due to the delay in the braking response by the rider). In addition, the simulator experiments show that visual-acoustic warnings prior to autonomous braking interventions have the potential to reduce reaction times and further increase the acceptance of the system.

Limitations

So far, the participant study has only been performed at one specific initial velocity (70 km/h) on a specific vehicle. Therefore, it should be considered that the achieved results are only applicable for the setup used in our studies. In addition, we expect that the vehicle geometry has a significant influence on the controllability and acceptance of autonomous braking interventions. Future studies should focus on the influence of the vehicle type, the influence of the initial velocity and the influence of the test scenario (e.g. braking while driving in a straight line vs. braking while cornering).

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TYPICAL PRE-CRASH SCENARIOS RECONSTRUCTION FOR TWO-WHEELERS AND PASSENGER VEHICLES AND ITS APPLICATION IN PARAMETER OPTIMIZATION OF AEB SYSTEM BASED ON NAIS DATABASE

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ABSTRACT

The crash between two-wheelers and passenger vehicle causes a higher fatality rate and many casualties for the two-wheelers riders. Both two-wheelers and pedestrians are considered as VRU. Compared to pedestrians, two-wheelers are featured with fast moving speed and uncertain driving route, which poses a challenge to the optimal control for the autonomous emergency braking (AEB) system. This paper firstly screened 216 cases of frontal collision accidents between passenger vehicles and two-wheelers from the database of National Automobile Accident In-depth Investigation System (NAIS) in China, extracted the static and dynamic variables related to the pre-crash scenarios reconstruction in each case. This paper extracted four typical pre-crash scenarios between two-wheelers and passenger vehicles from 216 accident scenarios through clustering analysis and chi-square test, reconstructed and simulated typical pre-crash scenarios by using PreScan software and completed matching, optimization and analysis on the field of view (FoV), braking trigger width (w), time to collision (TTC) of AEB system to obtain the boundary parameter conditions of the AEB system to avoid crash or greatly reduce the collision speed, providing a reference for the development of AEB systems applicable to China's road traffic scenarios. The research method used in this paper is applicable to the reconstruction and simulation analysis of pre-crash scenarios for passenger vehicles and pedestrians as well as the parameter optimization of other ADAS. In addition, the research method used in this paper also provide a technical solution for the design, test and evaluation of the automatic driving function based on typical scenarios.

Key Words: two-wheelers; pre-crash scenario; accident in-depth investigation; clustering analysis; autonomous emergency braking system; advanced driving assistance system

INTRODUCTION

The vision for development of autonomous vehicle is to achieve “zero casualty, zero accident”. Advanced driving assistance systems (ADAS) have been put into the market as an important part of autonomous vehicles. However, in complex and diverse traffic scenarios, ADAS is still facing major challenges in the accuracy of scenario recognition and rationality of decision algorithms. At present, the test and evaluation on ADAS is mainly based on limited field operational test (FOT). But in real traffic scenarios, ADAS faces more complex and special traffic scenario elements, especially in different countries and regions with the particularity of traffic scenarios. Therefore, the evaluation method based on the limited field operational test has certain limitations and the test methods based on natural driving scenarios and dangerous scenarios gradually attracting great attention in the industry [1].

Both two-wheelers and pedestrians are vulnerable road users (VRU) in traffic scenarios. Two-wheelers riders and pedestrians are often vulnerable groups in road traffic accidents. Compared with pedestrians, two-wheelers are featured with fast moving speed and uncertain driving route, so the two-wheelers are more likely to cause casualties. According to the 2015 statistical report of the World Health Organization (WHO), cyclists and motorcyclists of powered two or three wheelers accounting for 27% of fatality rate in road traffic [2]. The number of two-wheelers is huge in China, in recent years, especially after the promotion of green travel and shared bicycle travel in large and medium-sized cities in China, the number of riders and passengers of two-wheelers has increased significantly. At the same time, the number of fatality and injury of riders and passengers of two-wheelers in traffic accidents are also increasing. According to statistics, from 2004 to 2010 the number of fatality in road traffic accidents decreased from 107,077 to 65,225, but the number of fatality from powered two-wheelers (PTW) in road traffic accidents increased from 589 to 4,029 in China [3] [4]. In the Advanced Driving Assistance System (ADAS), the AEB system is the most popular type and has a great effect on improving the safety of vehicle in collisions. According to the research data providing by the Insurance Institute for Highway Safety (IIHS), AEB can reduce 27 % of traffic accidents [5]. The Federal Highway Research Institute (BAST) study shows that 70% of serious traffic accidents can be avoided by ADAS [6]. However, AEB still needs further research and evaluation on the accurate identification and reasonable decision-making of VRU, especially two-wheelers. With the gradual increase in the fatality rate of two-wheelers in recent years, global attention has been paid to the two-wheelers collision accidents. Some institutions have added or are ready for adding the collision avoidance assessment indicators for the two-wheelers in the relevant collision evaluation procedures. At present, Europe New Car Assessment Program (Euro-NCAP) [7] has added the AEB safety test for the protection of users of two-wheelers in the protection of VRU in 2018 and will add the AEB safety test for PTW in 2020. But now China New Car Assessment Program [8] (C-NCAP 2018 version) have not included the safety requirements for the AEB system aiming at two-wheelers.

At present, the AEB system as a key ADAS, has been installed and used in some vehicles and has been gradually launched in the market. However, the AEB system has caused a defective car recall case due to its false identification and mis-operation in complex road traffic scenarios. Therefore, the accuracy of the AEB system for scenario identification still requires in-depth research and test, especially the accuracy of identifying VRU. But currently, there are limited research literature about the safety tests of the AEB for VRU and the research literature mainly focuses on the safety tests of the AEB for pedestrians, so there are fewer literature about the safety tests of the AEB for two-wheelers. Based on the typical pedestrian dangerous condition on the roads in Shanghai, Liu Ying et al. [9] obtained five typical hazard scenarios by using clustering analysis and simulation analysis of AEB-pedestrian, but this study did not analyze the matching and optimization of AEB parameters. Su Jiangping et al. [10] made the analysis based on the pedestrian dangerous condition stored in the natural driving data of five cities in China and obtained four typical pedestrian traffic conflict scenarios. Chen Qiang et al. [11] analyzed three typical pedestrian use scenarios based on accident data and obtained the result that AEB system can reduce by 20% of pedestrian collision accidents, but this study also did not analyze the matching between pedestrian dangerous scenarios and AEB parameters. James Lenard et al. [12] conducted an analysis on pedestrian risk scenarios based on the UK OTS and STATS19 accident databases and constructed an AEB test scenario based on parameter deduction. Huang and Yang et al. [13] analyzed the typical pedestrian use scenarios based on the STRADA database and expertise, established a mathematical model and analyzed the field of view (FoV) parameter selected of the AEB sensor, but this study did not involve other parameters of the AEB system. Erik Rosen et al. [14] analyzed the correlation between the selection of FoV parameters of the AEB system and reduction of pedestrian collision

accidents based on German GIDAS data. David Good et al. [15] analyzed the collision speed distribution between pedestrians and vehicles based on the US GES and FARS accident data and designed the pre-crash system test scenario.

The extraction of pedestrian risk scenarios and the analysis on the parameters of AEB system based on natural driving data and accident data provide reference for the extraction of two-wheelers risk scenarios with optimization and design of corresponding parameter of AEB system. Liers [16] analyzed the accident pattern of PTW and the typical accident scenarios based on the German GIDAS data, concluded that the proportion of collisions of PTW crossing the road and intersection is high and analyzed the main cause of PTW accident, but this study did not consider the design of the AEB two-wheelers test scenario. Based on the typical risk use cases of two-wheelers on the roads in Shanghai, Li Lin et al. [17] obtained seven typical risk scenarios by using clustering analysis and chi-square test and conducted simulation analysis by using simulation software, but the matching and optimization of the AEB parameters were not studied here. Sui and Zhou et al. [18] analyzed the basic situation of crush accident between two-wheelers and automobiles based on Chinese road traffic accident data and concluded that the main scenarios of crush between two-wheelers and automobiles is that the car going straight at the speed of 60km/h or above has a vertical collision with the PTW going straight at an intersection in the day and recommended as a typical scenario for the AEB two-wheelers test, but this study did not perform scenario reconstruction and simulation analysis. Based on traffic accident data, Hu Lin et al. [19] extracted 11 typical car and two-wheelers collision accident scenarios by using clustering analysis and respectively obtained the AEB test scenarios of cars-electric powered two wheelers, cars-motorcycles and cars-bikes collision, but this study did not perform scene reconstruction and parameter optimization analysis. Compared with pedestrians, two-wheelers, especially PTW, have the characteristics of fast driving speed and uncertain driving route. They pose great challenge to sensor selection, parameter optimization and performance evaluation of AEB system and they need to be solved urgently.

In view of two-wheelers safety test by the AEB system, this paper firstly screened the frontal collision accident between passenger cars and two-wheelers based on the NAIS accident in-depth survey data, extracted the static and dynamic variables of the accident cases, extracted the typical pre-crash scenarios of two-wheelers and passenger cars by clustering analysis and chi-square test and performed reconstruction and simulation of typical pre-crash scenarios by using PreScan software. Then, the main control parameters of the AEB system were matched and optimized to obtain the boundary parameter conditions for the AEB system to avoid collision or greatly reduce the collision speed.

DATA SOURCES

The basic data studied in this paper is derived from the vehicle accident in-depth data collected by the National Automobile Accident In-depth Investigation System (NAIS). NAIS mainly collects the data about serious road traffic accidents in China. In such accident case, one or more fatality exists or accident participant injury value is $AIS \geq 3$. Each accident case includes about 2,200 parameters, including people, vehicles, roads and environmental information. NAIS was established by the State Administration for Market Regulation Defective Product Administrative Center together with universities and research institutions, as shown in Figure 1. The purpose of establishing NAIS is to collect in-depth data with the characteristics of road traffic accidents in China and establish a basic database for active and passive safety research of vehicles. The accident areas include plain areas, mountainous areas, plateau areas and coastal areas etc. In addition, the data about urban road accidents, highway accidents and rural road accidents are also collected. The accident data is representative. The NAIS database includes coded data, accident photos, police data, accident scene videos (if available), PC-Crash accident reconstruction files, CAD accident scene maps and accident analysis reports.



Figure 1. Map of NAIS sites

This paper selected and analyzed 2,203 motor vehicle collision accident cases (by the end of 2017) from the NAIS accident database. There were 406 accidents involving motor vehicles and two/three-wheelers, accounting for 18% of all accidents, as shown in Figure 2. According to the number of accidents, it can be seen that the proportion of collisions between motor vehicles and two/three-wheelers is high in China and the proportion of such accident will continue to increase with the increasing number of Chinese two-wheelers, especially bicycles. At present, two-wheelers are widely used in China, they are popular in large and medium cities and rural areas. And there are many violations of traffic regulations by two-wheelers riders. Meanwhile, the routes and rules of two-wheelers in the traffic scene are more complicated. Therefore, it is more difficult for ADAS especially the AEB system to identify. And it is necessary to carry out in-depth research and analysis.

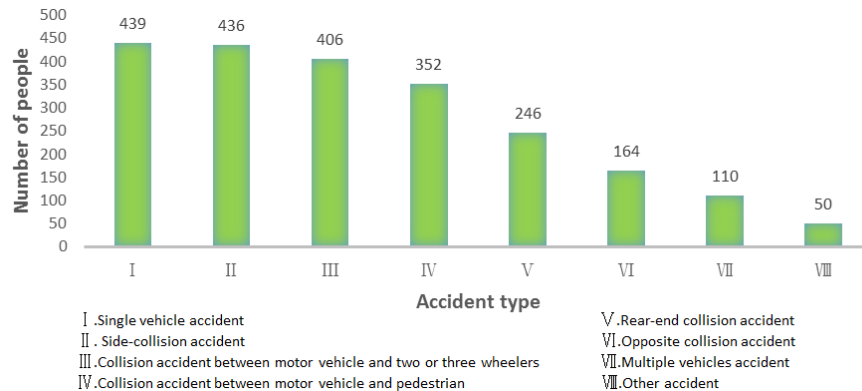


Figure 2. Classification of NAIS accident data (by accident pattern)

In the analysis of NAIS data about 2203 accidents, it is found that the number of fatality in the collision accident between motor vehicles and two or three wheelers is 362 people, where the most fatality occurred. Meanwhile, it is also found that its accident fatality rate is second only to the collision accident between motor vehicle and pedestrian, up to 33%, as shown in Figure 3. Therefore, both the riders of two or three wheelers and pedestrians are VRU, which should be given more attention to study during the development of ADAS and automated driving functions. Because the AEB system is mainly used to reduce vehicle frontal collision accidents and it is considered that three-wheelers are seldom used in other parts of the world, this paper selected 216 frontal collision accidents between passenger car and two-wheelers to explore and extract the static and dynamic information about pre-crash scenarios.

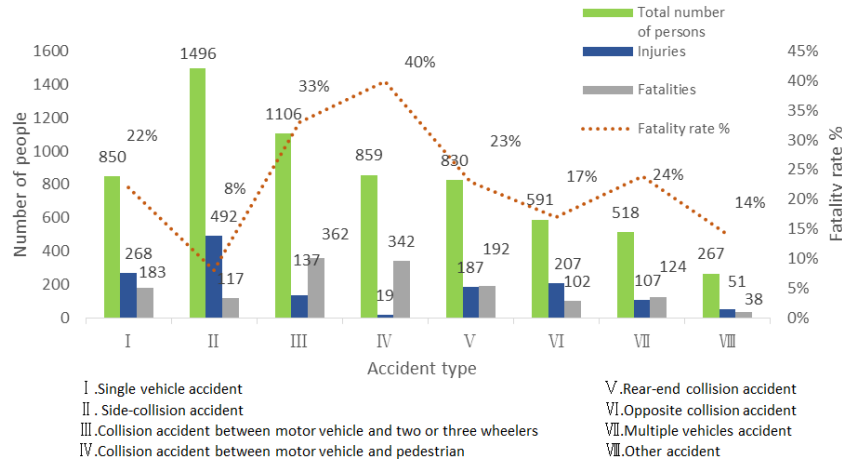


Figure 3. Classification of NAIS accident data (by casualty)

EXTRACTION OF TYPICAL SCENARIOS BASED ON CLUSTERING ANALYSIS AND CHI-SQUARE TEST

Variables Selection and Definition

The main purpose of this paper is to extract the typical scenarios from the in-depth accident data to conduct simulation analysis on the parameters of the AEB system. It is necessary to select the parameter variables that are highly compatible with the AEB system function and sensor environment and are easy to reproduce in the field operational test for clustering analysis. The parameter variables include environment variables, road variables, traffic participants variables and dynamic variables. The in-depth accident data involves more than 2,200 parameter variables. After analysis and screening, seven parameter variables are selected and defined as follows:

- (1)Section: It refers to the type of road and it is divided into straight road and intersection;
- (2)Light: It means whether the light is good when the accident occurs. It is divided into daytime, light at night and no light at night.
- (3)Motion of passenger vehicle: It refers to the motion pattern of passenger vehicle. It is divided into “go straight, turn left and turn right”, as shown in Figure 4.
- (4)Motion of two-wheelers: It refers to the motion pattern of two-wheelers. It is divided into “go straight, turn left and turn right”, as shown in Figure 4.
- (5)Relative motion zones: It is determined by the angle α formed by the speed direction of passenger vehicle v_p and two-wheelers v_t . If both passenger vehicle and two-wheelers have a turn, the speed direction before the turn is taken as the direction, the direction v_p is 0° and the counterclockwise direction is positive. Based on the different range of α value, it is divided into Zone 1, Zone 2, Zone 3 and Zone 4, as shown in Figure 5. The relative motion relationship between passenger vehicle and two-wheelers can be uniquely determined by the relative motion zones and the motion pattern of both passenger vehicle and two-wheelers.
- (6)Type of two-wheelers: It includes bicycles, electric two-wheelers and motorcycles. Because electric two-wheelers and motorcycles are faster than bicycles, they are deemed as PTW in this paper. That is to say, two-wheelers are divided into bicycles and PTW.
- (7)Speed of passenger vehicle: It refers to the vehicle speed during collision, which can be accessed through accident site trace calculation, accident reconstruction simulation analysis and accident calculation by video.

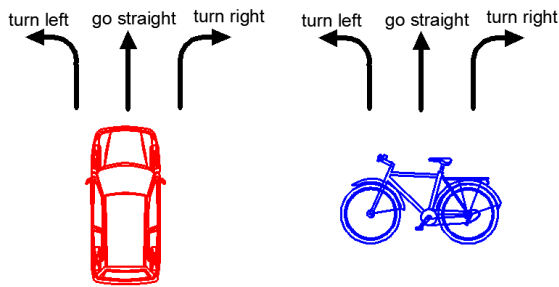


Figure 4. Motion of passenger vehicle and two-wheelers

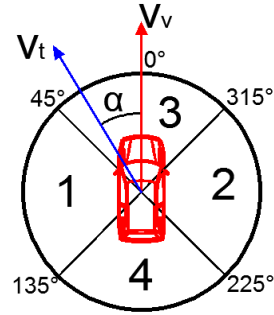


Figure 5. Relative motion zones

The selected variables are shown in Table 1.

Table 1.
Type and Value of Variables

Name	Type	Value	Numeric Representation
Section	Nominal	Intersection	1
		Straight road	2
Light	Nominal	Daytime	1
		Light at night	2
		No light at night	3
Motion of passenger vehicle	Nominal	Go straight	1
		Turn left	2
		Turn right	3
Motion of two-wheelers	Nominal	Go straight	1
		Turn left	2
		Turn right	3
Relative motion zones	Nominal	Zone 1	1
		Zone 2	2
		Zone 3	3
		Zone 4	4
Type of two-wheelers	Nominal	Bicycle	1
		PTW	2
Speed of passenger vehicle (km/h)	Scale	2 (Minimum speed)	0
		102 (Maximum speed)	1

Clustering analysis and chi-square test

The clustering analysis is used to collect the data with similar features. Then the chi-square test is used to extract the parameters with significant features, so as to obtain typical pre-crash scenarios. This method can reduce the influence on subjective scenario classification by human factors and is repeatable [17, 19].

The variables should be pre-processed before clustering. Variables are divided into interval scale variables (such as speed of passenger vehicle) and nominal scale variables (such as light, type of two-wheelers etc.). For interval scale variables, the distance between variables takes the absolute value of the difference between the values of the variable, which should be subject to normalization. For example, for the variable "speed of passenger vehicle" after normalization, the maximum value of the distance is 1 and the minimum value of the distance is 0. The calculation formula is $v' = \frac{v_v - v_{\min}}{v_{\max} - v_{\min}}$, where: v' is the speed value after normalization, v_v is the speed value of the sample, v_{\max} and v_{\min} are the maximum and minimum values of the sample. For nominal scale variables, the distance is 0 when the values of the variable are same, while the distance is 1 when the values of the variable are different. However, when the nominal scale variable is greater than or equal to 3, such as the variable "motion of passenger vehicle" includes "go straight", "turn left" and "turn right", the distance between any two of the three variable values is 1. However, based on the values of the variables showed in Table 1, "go straight" and "turn left" are represented

by "1" and "3" and the absolute value of the difference is 2, which is logically inconsistent with the distance 1 between the two variables. Therefore, in order to ensure that the distance between the two variables is 1, the variable value is represented by three values, as shown in Table 2. Similarly, when the variable value is represented by four values, it can also be processed by this method.

Table 2.
Conversion of Variable Parameter Values

Motion of passenger vehicle	Before conversion	After conversion		
		0	0.5	0.5
Go straight	1	0	0.5	0.5
Turn left	2	0.5	0	0.5
Turn right	3	0.5	0.5	0

Take 216 accident cases as 216 samples, calculate the distance between different samples, merge the two nearest samples into a new group, then calculate the distance between the new group and other groups, continue to merge two groups in the nearest distance. In this way, cut a group each time, until the number of groups ultimately required is obtained. The distance between samples are calculated by using the City Block, while the distance between groups are calculated by using the Average Linkage Method. After clustering analysis, multiple samples with higher similarity are clustered into one group.

Obtain significant results by using chi-square test, identify the typical eigenvalues of each type of scenario and construct a typical scenario. The degree of confidence is 90% and the chi-square value χ^2 obtained by comparison with the standard. If the chi-square value χ^2 is greater than the standard value, it indicates that the variable value is significant and it can be used as a parameter of the typical scenario.

Analysis and extraction of typical scenario

Firstly, the "inconsistent" formula in MATLAB is used to calculate the inconsistency coefficient. Found the inconsistency coefficient is greatly improved after 208 clusters and the first four groups account for 88.4% of the total samples. Therefore, all samples are clustered into nine groups [12].

Secondly, the nominal variables in nine groups of scenarios and their sample size, variable value ratio and calculated chi-square value are listed in Table 3. The first four groups with most sample size are taken as the research object. For the variables with significance, the typical values are selected by the proportional value of the variable values; for the variables without significance, the value of variable with the largest number of absolute values is selected as the typical value. Therefore, a typical scenario in the four classes of clustered samples is extracted. During the analysis, it is found that the variable "motion of two-wheelers" in the fourth group of sample is significant, but the scenario composed of the value "turn right" and the remaining variable values does not belong to the logical category of the motion pattern of the accident sample. So, the variable value selected based on the absolute number. In addition, the interval scale variable (speed of passenger vehicle) is represented by a box diagram, as shown in Figure 6.

Table 3.
Results of Clustering

Variable			group					Total
			1	2	3	4	5-9	
Section	Number (proportion)	Intersection	78 (55.7%)	1 (0.7%)	27 (19.3%)	16 (11.4%)	18 (12.9%)	140
		Straight road	1 (1.3%)	43 (56.6%)	15 (19.7%)	10 (13.2%)	7 (9.2%)	76
	Chi-square value		39.86	75.47	0.01	0.12		
Light	Number (proportion)	Daytime	48 (40.7%)	18 (15.3%)	30 (25.4%)	10 (8.5%)	12 (10.2%)	118
		Light at night	23 (34.3%)	23 (34.3%)	6 (9%)	12 (17.9%)	3 (4.5%)	67
		No light at night	8 (25.8%)	3 (9.7%)	6 (19.4%)	4 (12.9%)	10 (32.3%)	31

	Chi-square value		1.62	9.66	5.96	3.18		
Motion of passenger vehicle	Number (proportion)	Go straight	78 (43.1%)	44 (24.3%)	42 (23.2%)	0 (0%)	17 (9.4%)	181
		Turn left	0 (0%)	0 (0%)	0 (0%)	25 (100%)	0 (0%)	25
		Turn right	1 (10%)	0 (0%)	0 (0%)	1 (10%)	8 (80%)	10
	Chi-square value		13.18	8.51	8.12	182.52		
Motion of two-wheelers	Number (proportion)	Go straight	78 (52%)	40 (26.7%)	0 (0%)	22 (14.7%)	10 (6.7%)	150
		Turn left	0 (0%)	3 (5.8%)	41 (78.8%)	0 (0%)	8 (15.4%)	52
		Turn right	1 (7.1%)	1 (7.1%)	1 (7.1%)	4 (28.6%)	7 (50%)	14
	Chi-square value		32.09	9.56	124.62	10.30		
Relative motion zones	Number (proportion)	Zone 1	51 (72.9%)	8 (11.4%)	5 (7.1%)	4 (5.7%)	2 (2.9%)	70
		Zone 2	27 (67.5%)	7 (17.5%)	3 (7.5%)	0 (0%)	3 (7.5%)	40
		Zone 3	1 (1.7%)	21 (35%)	17 (28.3%)	5 (8.3%)	16 (26.7%)	60
		Zone 4	0 (0%)	8 (17.4%)	17 (37%)	17 (37%)	4 (8.7%)	46
	Chi-square value		72.47	9.41	18.08	31.55		
Type of two-wheelers	Number (proportion)	Bicycle	17 (45.9%)	8 (21.6%)	3 (8.1%)	1 (2.7%)	8 (21.6%)	37
		PTW	62 (34.6%)	36 (20.1%)	39 (21.8%)	25 (14%)	17 (9.5%)	179
		Chi-square value		1.07	0.03	2.95	3.23	
Total	Number (proportion)		79 (36.6%)	44 (20.4%)	42 (19.4%)	26 (12%)	25 (11.6%)	216

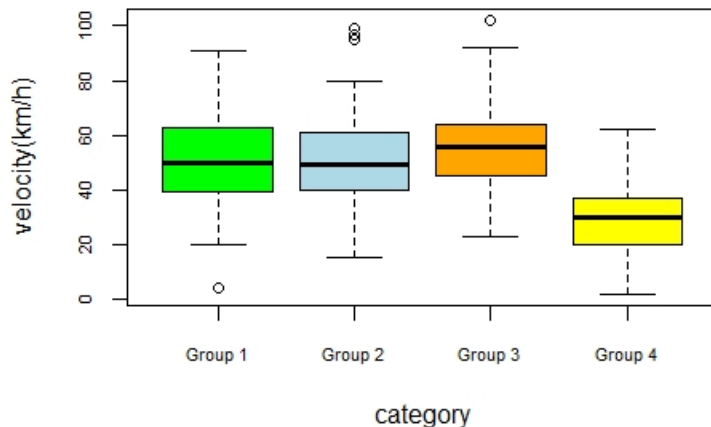
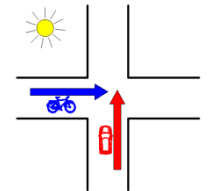
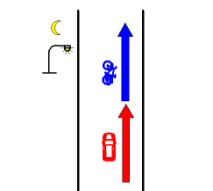
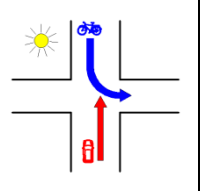
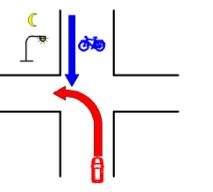


Figure 6. Box diagram of different groups in speed

Finally, the variable values with outstanding features in the four groups of scenarios are extracted and integrated. The speed of passenger vehicle uses the 25th to 75th percentile of each group as the upper and lower bounds. PTW is extracted from the variable “type of two-wheelers” as a typical value, indicating the typicality of PTW among two-wheelers under Chinese road traffic conditions - PTW speed is generally higher than the bicycle. The typical pre-crash scenarios for four types of collision between two-wheelers and passenger vehicle are formed, as shown in Table 4. Typical scenarios 1 and 2 are similar with the test scenarios of E-NCAP, but they do not involve relatively complex conditions such as turning; typical scenarios 3 and 4 involve turning, which accounts a high proportion in real accidents, so these scenarios are the focus of the analysis. The extraction of typical risk scenarios can provide a reference for the design of simulation test scenarios and field test scenarios.

Table 4.
Typical Pre-crash Scenarios

Variable	Typical Pre-crash Scenarios			
	1	2	3	4
Section	Intersection	Straight road	Intersection	Intersection
Light	Daytime	Light at night	Daytime	light at night
Motion of passenger vehicle	Go straight	Go straight	Go straight	Turn left
Motion of two-wheelers	Go straight	Go straight	Turn left	Go straight
Relative motion zones	Zone 1	Zone 3	Zone 4	Zone 4
Type of two-wheelers	PTW	PTW	PTW	PTW
Speed of passenger vehicle (km/h)	39.5-63	40-60.58	45.75-63.75	20-36.75
Diagram				

PARAMETER MATCHING AND OPTIMIZATION OF THE AEB SYSTEM BASED ON RECONSTRUCTED SCENARIOS

Reconstruction and simulation analysis of typical scenarios

Based on the above four typical pre-crash scenarios, the simulation test scenarios for collision between two-wheelers and passenger vehicle are constructed through the given key parameters such as road environment, participants and sensors. The road selected is two-way four-lane road, where bicycle lanes are set on both sides and street lamps are installed to adjust the lighting conditions. The velocity of passenger vehicle is set with reference to the upper and lower limits of the velocity in each type of scenario, rounding to the times of 10. The velocity gradient is 10km/h. The PTW velocity is set to 10km/h, 20km/h and 30km/h. When AEB is not triggered, the collision point is the front center point of passenger vehicle and the front/rear wheel center points of PTW. PreScan and MATLAB/Simulink software are used for simulation analysis. The selected sensor in the simulation is medium and short range millimeter-wave radar and the AEB control strategy used is full brake. The trigger distance w refers to the maximum lateral distance between two-wheelers and the side of the passenger vehicle when the two-wheelers is recognized as a dangerous obstacle and the AEB system is triggered. TTC_{max} refers to the maximum predicted time to collision, for an unbraked passenger vehicle, when the brake decision is triggered. Referring to the research [20,21], the main parameters used in the construction of simulation test scenarios are shown in Table 5.

Table 5.
Main parameters used in the construction of the simulation test scenarios

Category	Parameter	Value
Environment	Number of driveways (pcs)	4
	Width of driveway (m)	3.5
	Width of bicycle lane (m)	2
Participant	Velocity of passenger vehicle (km/h)	40/50/60 (Scenario 1 & Scenario 2) 50/60 (Scenario 3) 20/30/40 (Scenario 4)
	PTW velocity (km/h)	10/20/30
	Maximum braking deceleration (g)	0.9
Sensor	FoV (°)	60
	Trigger width w (m)	0.75
	Detection range (m)	40
	TTC _{max} (s)	0.9

The simulation test results of four typical pre-crash scenarios are shown in Figure 7. Specifically, collision occurred in the first and third classes of scenarios, while collision was avoided by using the AEB system in the second and fourth classes of scenarios. The velocity of passenger vehicle during the collision in the first and third classes of scenarios are shown in Table 6. It can be found that the higher the velocity of passenger vehicle or two-wheelers is, the higher the velocity is at the time of collision. When the velocity of two-wheelers is same in these two classes of scenarios, it is more dangerous in the first class of scenario than the third class of scenario. In the first and third scenarios, even if the vehicle is equipped with an AEB system, collision cannot be avoided under certain conditions. Therefore, it is necessary to optimize the parameter matching of the AEB system in the first and third classes of scenarios.

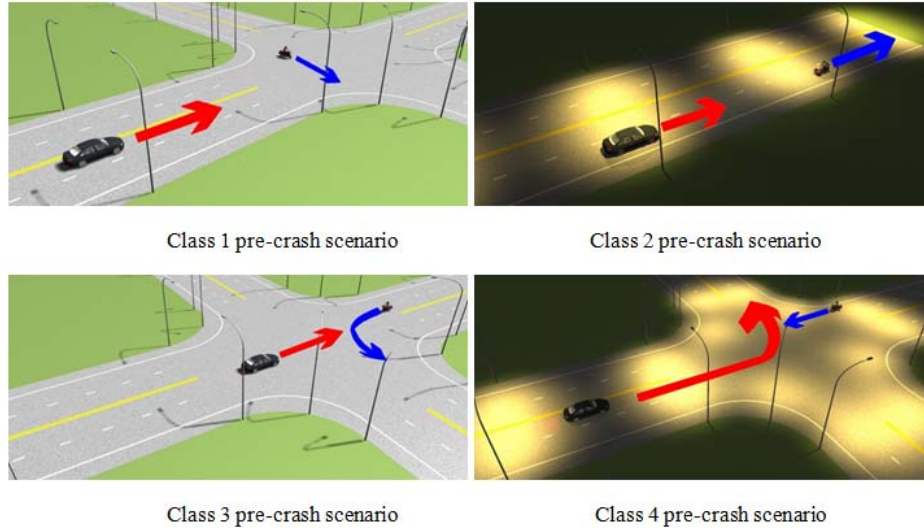


Figure 7. Simulation tests

Table 6.
Simulation results of Scenario 1 and Scenario 3

Scenario Number	Velocity of passenger vehicle (km/h)	PTW velocity (km/h)		
		10	20	30

		Velocity of passenger vehicle during collision (km/h)			
1	40	18	30	40	
	50	31	40	50	
	60	44	49	54	
3	50	10	38	44	
	60	25	47	54	

Parameter matching and optimization of the AEB system

Take the front sensor of the passenger vehicle as the origin, build a coordinate system, mark the target position points of the object sensed by the sensor at different times before collision on the coordinate system, connect all position points in a line and obtain the approximate motion trail of the two-wheelers on the coordinate system. As time goes on, the two-wheelers continues to approach the passenger vehicle along the motion trail. When there is no AEB function and the velocity of the passenger vehicle is set as 50km/h, the motion trail of the two-wheelers at three different speeds in the motion coordinate system is shown in Figure 8. $a = \frac{v_v}{v_t}$ where: v_v and v_t respectively represent the velocity of passenger vehicle and the two-wheelers.

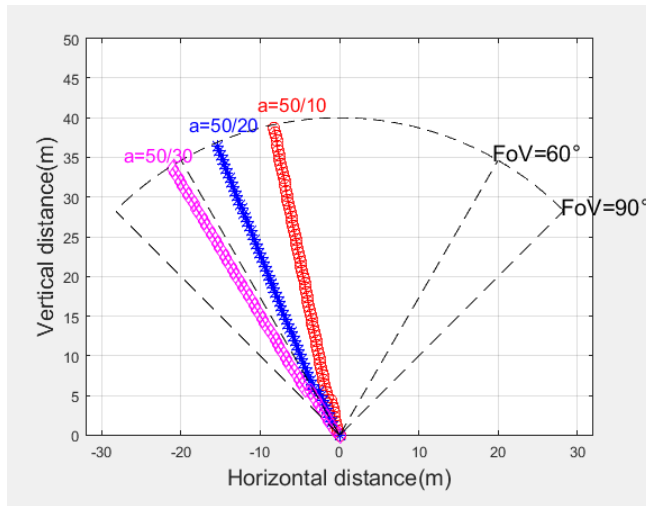


Figure 8. Motion trail of two-wheelers on the motion coordinate system

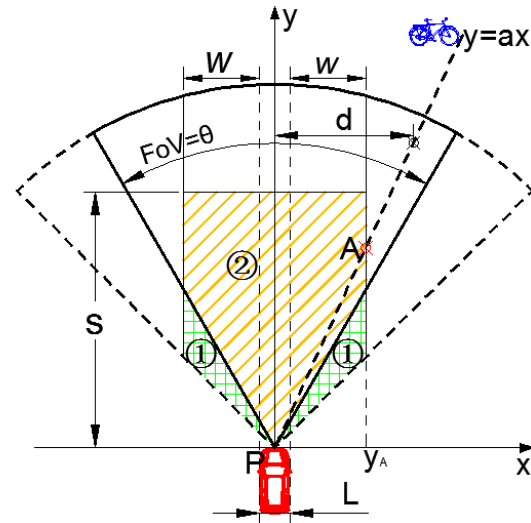


Figure 9. AEB-based collision avoidance mode on the motion coordinate system

It is found from the above figure that the motion trail of the two-wheelers on the coordinate system is almost straight. If the two-wheelers is regarded as a mass point, its motion can be regarded as being continuously approached to the passenger vehicle along a straight line $y = ax$, as shown in Figure 9. Two conditions are required for the two-wheelers to trigger the AEB system: one is the lateral distance $d \leq (w + \frac{L}{2})$, where L is the width of the vehicle (its value is 2m in the simulation model); another one is $TTC \leq TTC_{max}$. To trigger AEB, the longitudinal distance between vehicle and two-wheelers must below the maximum longitudinal distance s . And $s = v_v \times TTC_{max}$. Therefore, when the motion trail of the two-wheelers is in the Zone ②, the AEB system is triggered to take full-force braking. The AEB system trigger area can be extended to Zone ① by increasing the FoV.

As shown in Figure 9, the critical point of the two-wheelers triggering the AEB system is the boundary point between the straight line $y = ax$ and Zone ②. Assumed that the intersection of the straight line $y = ax$ and the straight line $x = (w + \frac{L}{2})$ is A, the longitudinal distance between Point A and the passenger vehicle is $y_A = a \times (\frac{L}{2} + w)$. If $s > y_A$, i.e. $TTC_{max} > (\frac{L}{2v_t} + \frac{w}{v_t})$, the triggering boundary is on a straight line $x = (w + \frac{L}{2})$. It means that TTC_{max} is large enough now and there is no influence on improving collision avoidance of the AEB system by increasing TTC_{max} . In this case, it is required to continue to adjust w value to improve collision avoidance.

Similarly, in case of $w > \frac{2v_tTTC_{max}-L}{2}$, the increase in w value has no effect on improving collision avoidance. As shown in Figure 6, when the velocity of passenger vehicle is 50km/h, it is closest to the 50th percentile of the velocity in the first scenario. Therefore, 50km/h is used as the object for analysis in the subsequent simulation analysis.

(1) Optimization of FoV

Assumed that the FoV value is α , if $\alpha < \cot\frac{\theta}{2}$, it indicates that the target two-wheelers is beyond the sensor detection range. The AEB system is useful only under the premise that the target object is within the detectable range. When FoV is 60° , $\cot\frac{\theta}{2}=1.73$, if α is less than 1.73, the sensor will fail to detect and the simulation showed that the collision velocity was equal to the initial velocity. In most cases, v_v is greater than v_t , thus the FoV of the sensor increases to 90° from 60° . The optimized results are shown in Figure 10. Increase in FoV value may improve collision avoidance when the PTW velocity is high, while it has no significant effect when the PTW velocity is low.

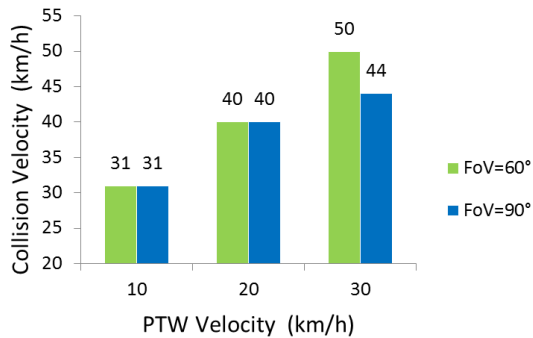


Figure10. Result of FoV parameter matching and optimization

(2) Optimization of TTC

The sensor FoV is fixed at 90° . TTC_{max} is optimized on this basis. The simulation results under different values are shown in Figure 11. With the increase in TTC_{max} , in the same v_t , the collision velocity is gradually reduced until it is stable. Combined with the above analysis, when w is 0.75m and v_t is 10km/h, 20km/h and 30km/h, the critical value TTC_{max} respectively is 0.45s, 0.225s and 0.15s. TTC_{max} corresponding to the inflection point of the collision velocity obtained by simulation is close to the critical value of TTC_{max} calculated theoretically, which proves that the theoretical reasoning is reasonable. Therefore, during the parameter optimization process, it is not better when TTC_{max} is larger. When other parameters are unchanged, if TTC_{max} exceeds its threshold value, there is no improvement in collision avoidance.

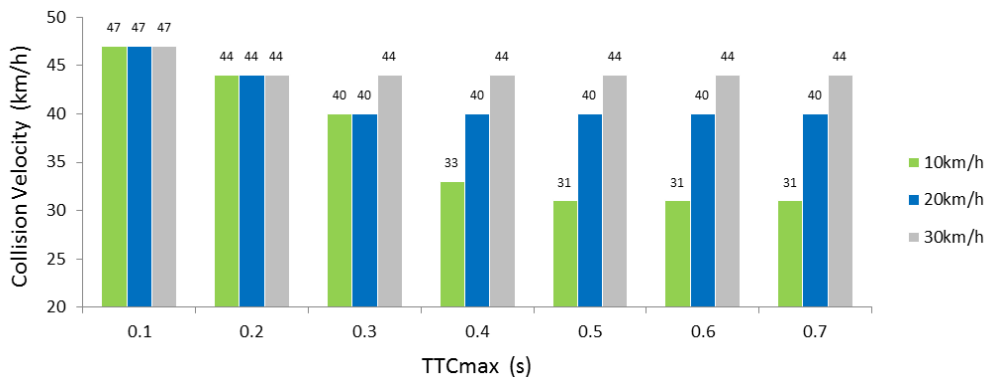


Figure 11. TTC optimization result

(3) Optimization of w

The sensor FoV is fixed at 90° , TTC_{max} is fixed at 0.5s and v_t is set as 10km/h, 20km/h and 30km/h. The simulation results under different w values are shown in Figure 12. Where v_t is 10km/h and 20km/h, it can be seen that the collision velocity firstly decreases and then stabilizes with the increase of w . When v_t is 30 km/h, the collision velocity is gradually reduced. Theoretically, the critical point of the w value respectively is 0.89m, 2.28m and 3.67m, when $TTC_{max} = 0.5s$ and v_t is 10 km/h, 20 km/h and 30 km/h. When v_t is 10km/h and 20km/h, the w value corresponding to the inflection point of the collision velocity obtained by simulation is close to the critical value of w value calculated theoretically, which proves that the theoretical reasoning is reasonable. Similarly, it can be inferred that the collision velocity tends to a stable value with the increase in the w value when v_t is 30 km/h.

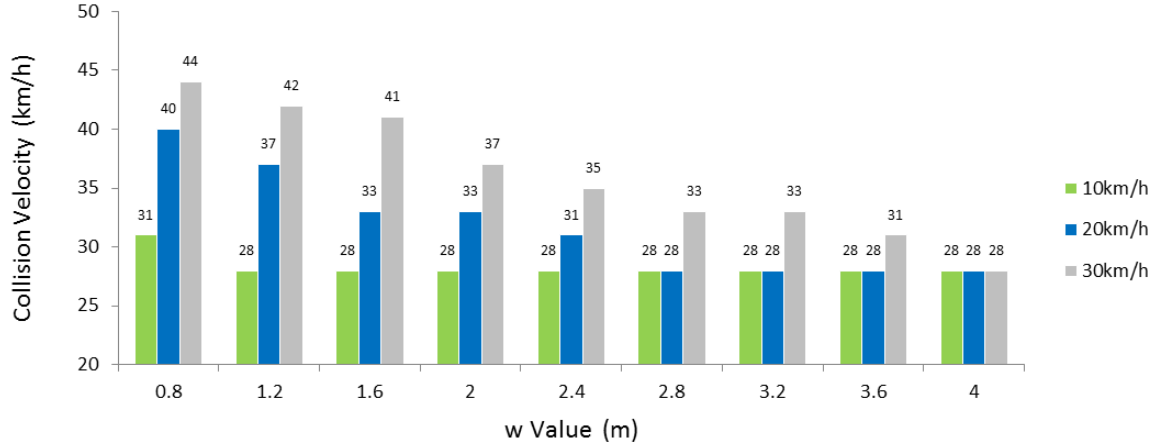


Figure 12. w value optimization result

In summary, in the pre-crash scenario 1, when $TTC_{max} > (\frac{L}{2v_t} + \frac{w}{v_t})$, the increase in TTC_{max} value is not helpful to improve collision avoidance performance; when $w > \frac{2v_tTTC_{max}-L}{2}$, the increase in the w value is also not helpful to improve collision avoidance performance. Therefore, the AEB parameter optimization needs to consider the mutual constraint relationship among the parameters. Only when the optimal parameters are achieved at the same time, it can guarantee the safety to the greatest extent. v_t is a key variable used in the theoretical derivation formula. The larger value range of this variable has a greater impact on the AEB parameter setting and it is also a challenge that has to be faced in the identification by sensors in the scenarios involving two-wheelers.

DISCUSSION AND CONCLUSIONS

“How safe is safe enough” has become an unavoidable scientific and engineering challenge for the test validation of automated driving functions and advanced driving assistant system (ADAS). This paper proposes an autonomous emergency braking (AEB) system parameter optimizing method based on typical risk scenarios, which can speed up the development and verification of the AEB system and lay the foundation for field operational test and actual road test. This paper analyzed the data of collision accidents between passenger car and two-wheelers stored in the NAIS database, extracted the typical scenarios by using clustering analysis and chi-square test and then reconstructed and simulated typical pre-crash scenarios and analyzed the matching of AEB system parameters applying PreScan software. The main conclusions are as follows:

1. Under normal circumstances, it is difficult to obtain more urgent emergencies in natural driving scenarios and the acquired scenario data has little effect on the development of the AEB system. However, it is a more effective engineering method for the development, verification and evaluation of AEB system by extracting representative typical pre-crash scenarios based on the accident-related big data and applying them in system parameter matching design and function test.

2. This paper extracted four typical pre-crash scenarios between passenger car and two-wheelers, which cover 88.4% of the sample and are representative. Especially, the first and second scenarios in the four typical scenarios are similar to the AEB test scenarios of cyclist crossing and cyclist along the roadside introduced by Euro-NCAP 2018, but the first and second scenarios in this paper are more complicated. In addition, the third and fourth scenarios extracted in this paper occur at the intersection, indicating that the AEB system needs to focus on the identification and collision avoidance of the two-wheelers at the intersection in the process of development, test and evaluation.

3. Since the speed of two-wheelers is higher than that of pedestrian and the route is more complicated, the AEB system is facing great challenges to detecting two-wheelers riders in both hardware and software. The simulation analysis reveals the larger the sensor FoV is, the larger the identification field of two-wheelers is and the better the performance of the AEB system in avoiding collision or mitigating collision speed. This shows that the AEB system should select a sensor with a larger detection angle to effectively identify the fast-moving two-wheelers and make correct decision.

4. During the simulation, it is found that the collision avoidance problem cannot be completely solved by merely increasing the angle of FoV. It is necessary to comprehensively adjust the braking trigger width, brake trigger time to avoid vehicle collision. In the simulation analysis of the first scenarios, the AEB can avoid the occurrence of collision accidents or greatly mitigate the speed of the collision by comprehensively adjusting the above key parameters.

The research of this paper still has certain limitations. At present, the number of collision accidents used for scenario clustering analysis is limited and the pre-crash scenarios that may be extracted cannot completely represent the typical collision scenarios between passenger car and two-wheelers in China. But, the method studied in this paper is a good reference for the development of the AEB system. And AEB system can be improved with more accident data of NAIS in the future. In addition, the simulation specified in this paper does not consider the specific shape parameters and the variability in the movement of two-wheelers. In the subsequent research, it is considered to establish a unified bicycle and PTW model for the simulation, test and evaluation of the AEB system.

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