Predicting crash configurations in passenger car to passenger car crashes to guide the development of future passenger car safety

Martin Östling, Hanna Jeppsson, Nils Lubbe

Abstract Recent years have seen a rapid increase in the number of passenger cars equipped with Advanced Driver Assistance Systems (ADASs), a development that affects the nature of future vehicle crashes. Predicting this change, understanding future crash frequencies and crash configurations and thereby deriving the most relevant load cases for occupant restraint systems, is key to ensuring future occupant protection. This study contributes by assessing how fully implementing today's known ADASs in the future German car fleet will impact crash scenarios and crash configurations for modern passenger cars with occupants sustaining an at least moderate injury, 2 or higher, on the Abbreviated Injury Scale (AIS2+).

Applying today's known ADASs was found to decrease the number of such crashes markedly, but to increase the relative frequency of intersection crashes. These remaining intersection crashes were divided into distinct crash configurations. From this, five distinct and clearly defined load cases were identified to aid the development and evaluation of future occupant restraint systems. It must be noted, however, that these load cases are based on an analysis of a limited number of crashes.

Keywords ADAS, Crash configuration, Future crash scenarios, GIDAS, Load case.

I. INTRODUCTION

Car manufacturers have been equipping new cars with Advanced Driver Assistance Systems (ADASs) for many years, systems that provide the driver with valuable information, perform difficult tasks, and that may soon automate the whole task of driving with the overall goal of providing safe travel for everyone on the road. Anti-Lock Braking Systems (ABS) and Electronic Stability Control (ESC) have, for example, been around for a long time and have proven their value [1-5]. Autonomous Emergency Braking (AEB) for both rear-end and pedestrian crashes are soon to be standard in passenger cars and are also expected to reduce the number of crashes substantially [6-10].

One of the reasons for these new ADASs becoming widespread in modern passenger cars is that the European New Car Assessment Program (Euro NCAP) requires an increasing amount of safety technology in order to assign a vehicle a five-star rating [11], and a high rating is desirable for both car manufacturers and customers. Euro NCAP is currently assessing AEB for rear-end, pedestrian and bicycle crashes, and for Lane Keeping Assist (LKA), Lane Change Assist (LCA), Blind Spot Detection (BSD) and Intelligent Speed Assist (ISA). The Euro NCAP roadmap further suggests including AEB for intersection, Automatic Emergency Steering (AES) and Driver Monitoring (DM) in the rating by 2020 [12], which is likely to increase the implementation rate of these new systems. Indeed, some manufacturers already have many in production, even though they have not yet been included [13-18].

In the future, such systems will affect not only the frequency of car crashes but also how exactly cars collide, i.e. the crash configurations. Predicting this change, understanding future crash frequencies and thereby deriving the most relevant load cases for the occupant restraint system is vital to protect future occupants.

While there are many studies predicting the effect of single ADAS, few have done so for a bundle of many non-independent systems. Flannagan and Flannagan [19] provide a software tool (the Unified Tool for Mapping Opportunities for Safety Technology, UTMOST) to assess the effects of implementing various combinations of safety measures, which can also help to understand the remaining future safety issues. This tool, based on US data, handles several safety features and assesses the safety benefits of implementing them, but it is not able to provide sufficient detail on crash configurations to derive future load cases. Strandroth *et al.* developed [20] and

M. Östling (e-mail: martin.ostling@autoliv.com; tel: +46-322626959), H. Jeppsson and N. Lübbe work at Autoliv Research.

validated [21] a deterministic analysis method to predict future road traffic fatalities when a large bundle of systems is implemented. This method is as follows: first, a set of assumptions about available future technologies is established; secondly, a case-by-case analysis determines whether a certain crash from today is expected to occur in the future; and thirdly, remaining crashes are analysed to identify future safety gaps. These steps provide a logical and stepwise approach to reducing the crash population by taking away crashes that are known or assumed to be avoidable in the future. This method was applied to describe road users and crash scenarios of fatal crashes in Sweden [20]. Recent studies of fatal crashes in the USA [22] and Germany [23] added a description of expected future crash directions and violence but did not derive crash configurations, therefore they did not provide sufficient detail to derive future load cases for occupant protection evaluation. Notably, these studies concluded that crash directions and violence are not expected to change substantially in the future.

Road safety policies, however, do not only target fatalities, but also severe injuries. Research addressing this has predicted which crashes causing such injuries will remain, analysed by road-user type for Sweden [24] and by crash scenario for the USA [25]. In both cases, a future was assumed in which a large bundle of future safety systems is implemented, but only [25] provides sufficient detail to derive future load cases for occupant protection for the USA. As the current and future crash situations in the USA and other countries are not necessarily the same, predicted load cases are needed for other countries as well.

The objective of this study is to derive future load cases for occupant protection in passenger car to passenger car crashes in Germany to aid the design of future occupant restraint systems. We therefore describe how full implementation of today's known ADASs in the future car fleet will change the crash scenarios and crash configurations for modern passenger cars with occupants sustaining an at least moderate injury, 2 or higher, on the Abbreviated Injury Scale (AIS2+).

II. METHODS

First, modern passenger car to passenger car crashes, involving cars with a registration year 2000 or later and in which AIS2+ injuries were sustained, were identified and extracted from the German In-Depth Accident Study (GIDAS) and weighted to national statistics. Secondly, a deterministic ruleset representing 15 ADASs (see section *Applying the ADAS ruleset*) was applied to determine which crashes would remain. Thirdly, a graphical method was developed to give a detailed description and understanding of the remaining crash configurations in terms of their geometrical and dynamic conditions. Finally, occupants sustaining AIS2+ injuries were described by their seating position and injured body regions. The overall goal is to understand and describe the most frequent remaining crashes, grouping them into a few distinct load cases by describing the crash configuration and occupant seating position (see Fig. 1).

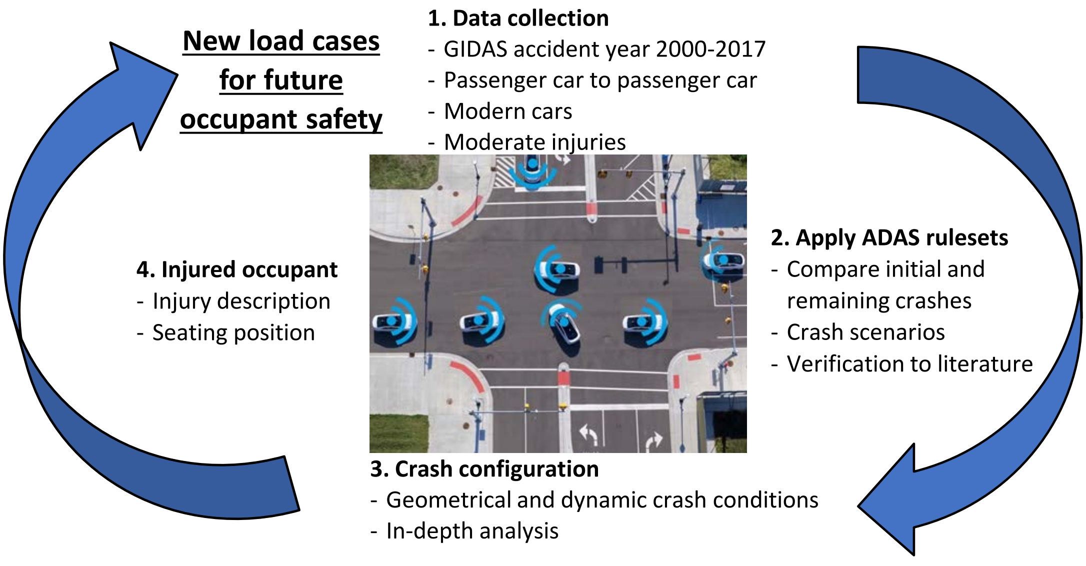


Fig. 1. An overview of the method: starting with data collection to understand real-world traffic car-to-car crashes where occupants have sustained AIS2+ injuries, then creating, applying and verifying ADAS countermeasures, followed by understanding how the countermeasures affect the crash configuration and injured persons, with the target of identifying new possible load cases.

Data collection

GIDAS data from 2000 to 2017 was extracted and weighted according to national data for all crashes of all traffic participants using Destatis [26]. To keep the number of crashes equal for weighted and unweighted data, the weighted data was normalised. The data were filtered in three steps (Table I). First, the data were filtered for first collision event being a passenger car to passenger car crash. A passenger car is defined as a vehicle with no more than eight seats in addition to driver's seat. Then, the data were filtered for both involved vehicles being modern passenger cars, defined here as those with registration year (RY) 2000 or later, since improvements in vehicle structure and occupant restraint systems in modern cars have reduced the likelihood of injuries compared to older cars [27], and therefore older cars were judged as not representative. Lastly, the data were filtered for crashes in which at least moderate (AIS2+) injuries were sustained for belted occupants.

TABLE I
DATA EXTRACTION

Filtering	Number of GIDAS crashes 2000-2017 (weighted and normalised)	Percentage
Passenger car–Passenger car crashes	8293.5	100%
Passenger car RY 2000 and later	2170.6	26%
Crashes with AIS2+ injured belted occupants	180.6	2%

Applying the ADAS ruleset

The ability of an ADAS to prevent accidents was expressed through simplified deterministic rules, including specific speed ranges for which each ADAS is active, as in the procedure used in [25] but adapted to fit the GIDAS dataset and variables (see Appendix A). A case-by case analysis was then made for each crash in the dataset and if the conditions in the ruleset were met, the crash was removed from the dataset. The effectiveness of these rules in avoiding crashes was verified against the literature using reference values based on EU data (Appendix B). Where reference values could be found, they generally correspond well, lying within a few percentage points of the estimate. However, one exception to this was AEB rear-end where the estimate is 31%, rather high compared to reference values in the range of 14–20%. ADAS verification is further discussed in Appendix B.

The rules were then applied to the data to predict future passenger car to passenger car crash occurrences after ADAS implementation, assuming 100% implementation of 15 known ADASs; the rules do not account for manual overriding or other system malfunctions. The ADASs modelled were Lane Keeping Assist (LKA), Lane Change Assist (LCA), Blind Spot Detection (BSD), Advanced Front Lighting System (AFLS), Electronic Stability Control (ESC), AEB rear-end, AEB reversing, AEB intersection, Emergency Steering (ES), Driver-initiated Evasive Steering Assist (ESA), Driver Monitoring System (DMS), Intelligent Speed Adaptation (ISA), Traffic Jam Assist (TJA), Highway Assist (HA) and Alcohol Interlock.

Crash scenarios and impact type

The initial crashes, i.e. those crashes existing before the ADAS rules are applied, and the remaining crashes, i.e. those crashes predicted still to occur after the ADAS rules are applied, were grouped into crash scenarios using GIDAS variable UTYP [23]. In addition, each crash was coded for impact type, as follows:

- Front–Front, both vehicles had frontal damage;
- Front–Rear, one of the vehicles had frontal damage and the other rear damage;
- Front–Side, one of the vehicles had frontal damage and the other damage to the side, left or right;
- Other, the crash did not fit in any of the above groups and could be a Side–Side or Rear–Side impact or have missing data.

Crash scenario and impact type were then combined to describe the crashes.

Crash configuration

In addition, to describe the configurations – geometrical and dynamic conditions – of the remaining crashes, a graphical method was used, in principle redrawing the crash reconstruction from the data coded in GIDAS [28]. The graphical method uses the variables STOSSPX and STOSSPY, which describe the point of maximum deformation in the longitudinal direction x and the lateral direction y, in centimetres, from the centre of the foremost point of the vehicle, and Principle Direction of Force (PDOF), coded in the variable VDI1. The vehicle's width (BREITE) and length (LAENGE) were used to draw a model of the car with a dot showing the point of maximum impact deformation and an arrow showing the PDOF of the impact (Fig. 2a). To visualise the crash, models were made for both cars involved and were then moved and rotated so the impact points overlap each other, and the directions of momentum are orthogonal (Fig. 2b). For each case, crash scene photos and sketches were queried to verify the constructed geometrical conditions. In addition to the geometrical conditions, the dynamic conditions were established using delta velocity (the absolute of the vector difference between impact velocity and separation velocity [29]). Detailed information about the passenger cars involved, such as car dimension and weight, and crash configuration can be found in Appendix C.

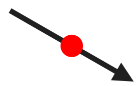


Fig. 2a. Modelled car with the point of maximum deformation (red dot) and PDOF (black arrow).

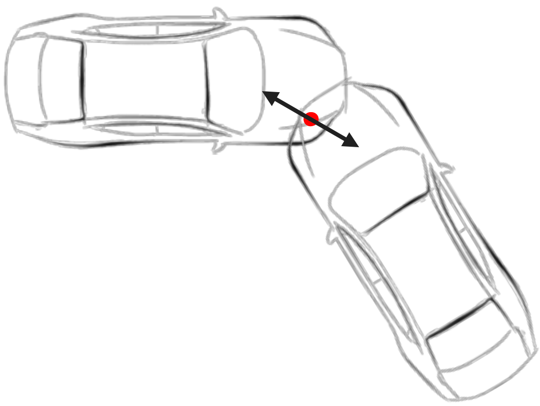


Fig. 2b. Final position of cars involved where the points of maximum deformation overlap and the PDOF work against each other.

Injured occupants

Cars containing an injured occupant were identified; should both cars in one crash contain an injured occupant(s), the crash is presented in two lines in Tables II–VII. The seating position of the injured person was identified, and data regarding all AIS2+ injured body regions were extracted according to AIS 2008. Detailed information about the injured occupants, such as age and gender can be found in Appendix C.

III. RESULTS

Crash scenarios and impact types (colour coded) for the two datasets, "Initial" and "Remaining", were plotted using data weighted to national statistics (Figs 3 and 4). In the initial dataset, five crash scenarios represent 70% of all crashes: Straight Crossing Path (18%); Straight on Path – Same Direction (17%); Left (right) Turn Across Path – Opposite Direction (15%); Lane Departure Opposite Direction (11%); and Left (right) Turn Across Path – Lateral Direction (9%).

Applying the ADAS ruleset markedly reduces the number of crashes from 180.6 to 26.7 weighted and normalised cases, but increases the relative frequency of intersection crashes from 42% (75.6 out of 180.6 cases) to 57% (15.3 out of 26.7 weighted and normalised cases). Intersection crashes consist of three distinct scenarios: Straight Crossing Path; Left Turn Across Path – Lateral Direction; and Left Turn Across Path – Opposite Direction. In the remaining dataset, the Straight Crossing Path (38%) scenario has increased in terms of relative frequency, and, as the two figures also show, the proportion of Front to Front crashes (blue) is reduced while Front to Side crashes (red) dominate those remaining.

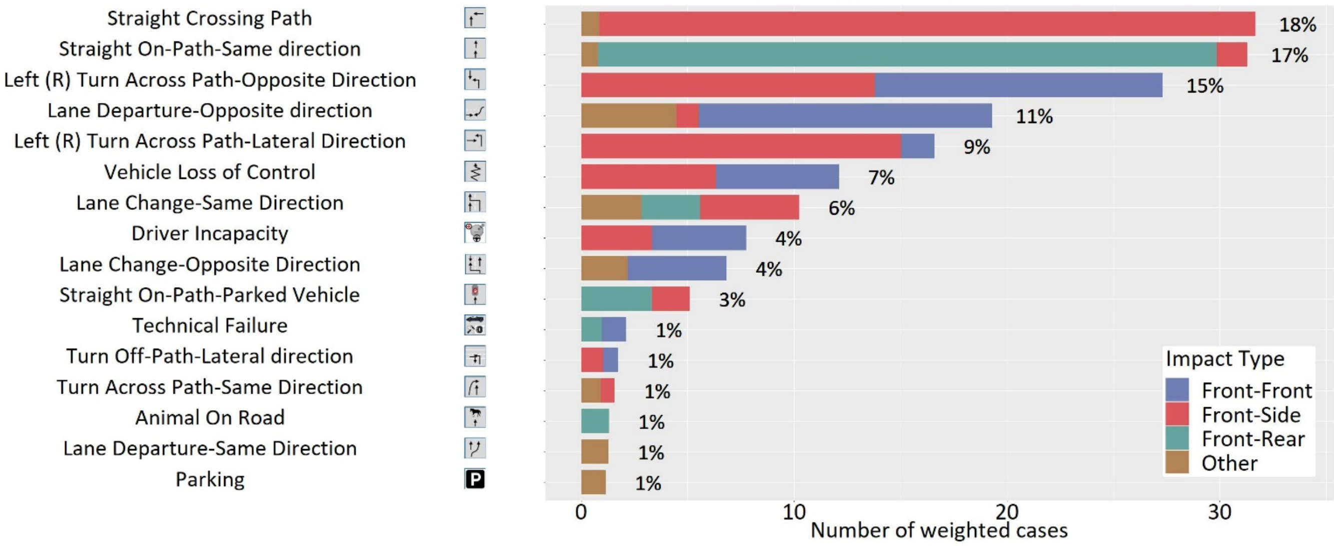


Fig. 3. Initial car-to-car crashes resulting in at least one AIS2+ injury and with both car registration years 2000 or later, in total N=180.6 weighted cases. Crash scenarios on y-axis, impact type colour coded, and number of weighted cases on x-axis.

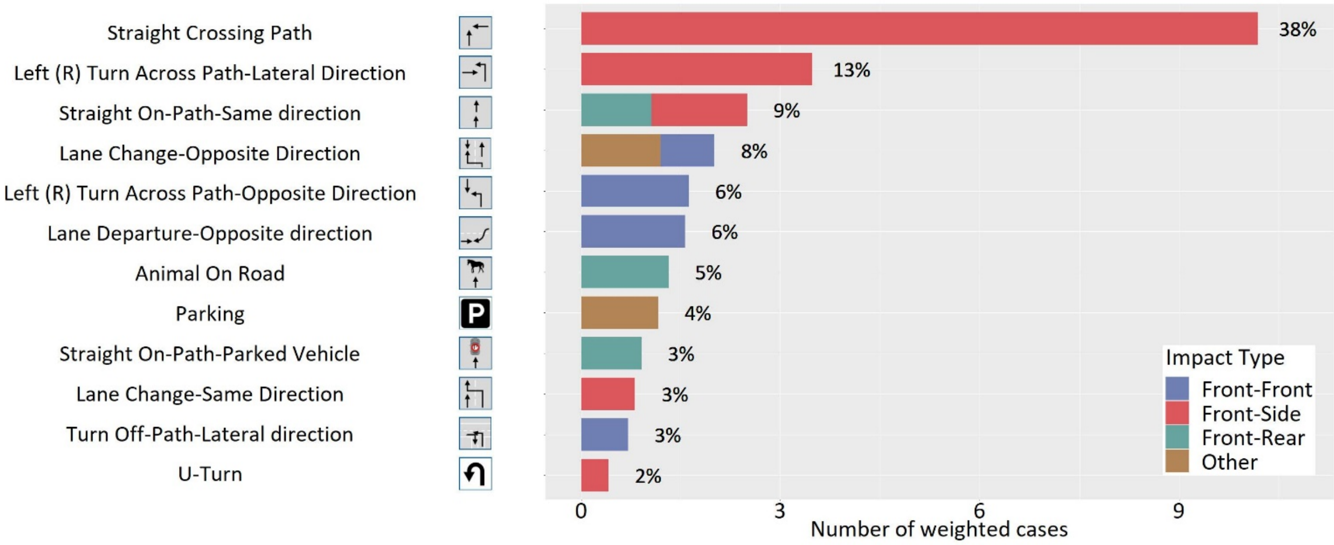


Fig. 4. Remaining car-to-car crashes resulting in at least one AIS2+ injury and with both car registration years 2000 or later, in total N=26.7 weighted cases. Crash scenarios on y-axis, impact type colour coded, and number of weighted cases on x-axis.

The intersection crashes have similar characteristics, involving two cars with crossing trajectories, and as a group increase in relative frequency; these were therefore selected for further analysis in terms of their geometrical and dynamic conditions, i.e. crash configuration. The remaining 15.3 intersection crashes correspond to 18 unweighted intersection crashes, which comprise 11 Straight Crossing Path, two Left Turn Across Path – Lateral Direction, three Left Turn Across Path – Opposite Direction crashes, and two crashes that were removed from the dataset. In the first crash removed the injured person was not inside a car, and in the second crash the initial impact did not result in a direct AIS2+ injury but in one car running off the road which then caused the AIS2+ injury. These unweighted crashes were analysed regarding geometrical and dynamic crash conditions using the graphical method and grouped with respect to crash configuration and position of the injured occupants. Cars that contain one or more AIS2+ injured occupants are coded in red in the graphical image (rightmost column in Tables II–VII). The relative size of the red and blue car images reflects the vehicle geometries (see Appendix C for details). The following groups were identified:

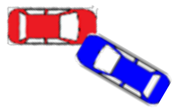
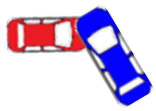
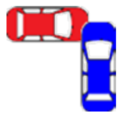
- Frontal Oblique Far-Side, with the driver injured, i.e. left-side impact, Table II;

- Frontal Oblique Near-Side, with the driver injured, i.e. left-side impact, Table III;
- Side Near-Side, impact forward of the compartment, on the left or right-side, Table IV;
- Side Far-Side, impact forward of the compartment, on the right-side, Table V;
- Side Near-Side, impact of compartment, on the left or right-side, Table VI;
- Others, Table VII.

Frontal Oblique Far-Side

For the group Frontal Oblique Far-Side, cars with an injured occupant (red), all of whom were in the driver's seat, were impacted at the front right corner with impact angle of between 30 and 90 degrees, and mean and max delta velocity of 20 km/h and 26 km/h, respectively. Situated in the middle of the impact angle range and having the highest delta velocity, Case 2 is selected as the representative load case. The injured occupants in the Frontal Oblique Far-Side group, which contains three crashes, sustained AIS2+ head and thorax injuries.

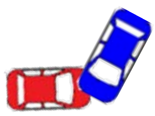
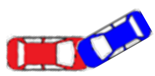
TABLE II
FRONTAL OBLIQUE FAR-SIDE (N=3)

#	Vehicle	Delta V [km/h]	AIS2+	Position	Injured body region	Graphic
1	Red	17	Yes	Driver	Head	
	Blue	16	No	-	-	
2	Red	26	Yes	Driver	Thorax	
	Blue	17	No	-	-	
3	Red	16	Yes	Driver	Thorax	
	Blue	12	No	-	-	

Frontal Oblique Near-Side

For the group Frontal Oblique Near-Side, cars with an injured occupant (red), all of whom were in the driver's seat, were impacted at the front left corner with impact angle of between -30 and -60 degrees, and mean and max delta velocity of 37 km/h and 44 km/h, respectively. As this group only contains two crashes, Case 2, the one with the higher delta velocity, is selected as the representative load case. The only AIS2+ injuries reported in the two crashes were to the upper extremities.

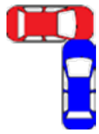
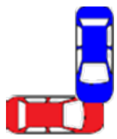
TABLE III
FRONTAL OBLIQUE NEAR-SIDE (N=2)

#	Vehicle	Delta V [km/h]	AIS2+	Position	Injured body region	Graphic
1	Red	29	Yes	Driver	Upper extremity	
	Blue	25	No	-	-	
2	Red	44	Yes	Driver	Upper extremity	
	Blue	54	No	-	-	

Side Near-Side, impact forward of compartment

For the group Side Near-Side with impact forward of the compartment, cars with an injured occupant (red), who were either in the driver's or passenger seats, were impacted at the front right or left corner with impact angles of between -90 and -120 degrees for the left-side impact and 90 degrees for the right-side impact. Mean and max delta velocity were 16 km/h and 22 km/h, respectively. Case 3 is selected as the representative load case as two out of three crashes had a 90-degree impact and Case 3 represents the highest delta velocity. The injured occupants sustained AIS2+ injuries to either the thorax or the upper extremities.

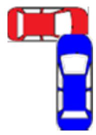
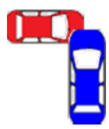
TABLE IV
SIDE NEAR-SIDE, IMPACT FORWARD OF COMPARTMENT (N=3)

#	Vehicle	Delta V [km/h]	AIS2+	Position	Injured body region	Graphic
1	Red	18	Yes	Driver	Thorax	
	Blue	12	No	-	-	
2	Red	8	Yes	Passenger	Upper extremity	
	Blue	8	No	-	-	
3	Red	22	Yes	Driver	Thorax	
	Blue	19	No	-	-	

Side Far-Side, impact forward of compartment

For the group Side Far-Side with impact forward of the compartment, cars with an injured occupant (red), all of whom were in the driver's seat, were impacted at the front right corner with impact angle of 90 degrees, and mean and max delta velocity of 34 km/h and 44 km/h, respectively. As this group only contains two crashes and both having a 90 degrees impact, Case 2, the one with the higher delta velocity, is selected as the representative load case. The AIS2+ injuries reported in the two crashes were to the head and the lower extremities.

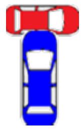
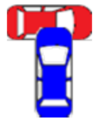
TABLE V
SIDE FAR-SIDE, IMPACT FORWARD OF COMPARTMENT (N=2)

#	Vehicle	Delta V [km/h]	AIS2+	Position	Injured body region	Graphic
1	Red	23	Yes	Driver	Head	
	Blue	15	No	-	-	
2	Red	44	Yes	Driver	Lower extremities	
	Blue	35	No	-	-	

Side Near-Side, impact of compartment

For the group Side Near-Side with impact to the compartment, cars with an injured occupant (red), who were either in the driver's or passenger seats, were impacted at the right or left side with impact angles of between 60 and 90 degrees for the right-side impact and 60 degrees for the left-side impact. Mean and max delta velocity were 27 km/h and 37 km/h, respectively. Case 4 is selected as the representative load case as two out of four crashes had an oblique impact both having delta velocity 29 km/h. The injured occupants sustained AIS2+ injuries to thorax, abdomen and pelvis.

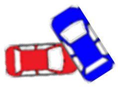
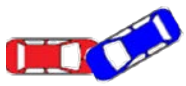
TABLE VI
SIDE NEAR-SIDE, IMPACT OF COMPARTMENT (N=4)

#	Vehicle	Delta V [km/h]	AIS2+	Position	Injured body region	Graphic
1	Red	12	Yes	Passenger	Thorax	
	Blue	7	No	-	-	
2	Red	37	Yes	Passenger	Thorax and abdomen	
	Blue	31	No	-	-	
3	Red	29	Yes	Driver	Pelvis	
	Blue	25	No	-	-	
4	Red	29	Yes	Passenger	Thorax	
	Blue	21	No	-	-	

Others

Two crashes were found that did not fit into the earlier described groups, one which impacted another car in the side head-on and another that had injured occupants in the rear seat.

TABLE VII
OTHERS (N=2)

#	Vehicle	Delta V [km/h]	AIS2+	Position	Injured body region	Graphic
1	Red	46	Yes	Driver	Thorax	
	Blue	29	No	-	-	
2	Red	55	Yes	Rear seat left	Thorax	
				Rear seat right	Thorax	
	Blue	53	No	-	-	

IV. DISCUSSION

Intersection crashes predominate, both in the initial dataset and in those accidents remaining after the safety benefits of ADASs have been applied. In the initial crashes, intersection crash scenarios rank first, third and fifth (Fig. 3), together representing 42% of all crashes. For the remaining crashes, intersection crash scenarios rank first, second and fifth (Fig. 4), representing 57% of all remaining crashes. Intersection crashes are not only significant in Germany but also in the USA: [25] found that intersection crashes with modern cars represent 57% of all initial passenger car to passenger car AIS2+ crashes and 81% of all remaining passenger car to passenger car AIS2+ crashes.

Proposed future load cases

The remaining intersection crashes were grouped by crash configuration and position of the injured occupants into five distinct groups. From each of the groups, one representative crash was selected based on injured occupant position, impact angle and delta velocity. We propose these five load cases to be used as a basis in the future assessment of occupant safety and possible variations to each load case.

- Frontal Oblique Far-Side, impact angle of 60 degrees and delta velocity 26 km/h, with the occupant in the driver's seat. Variations could include impact angles of between 30 and 90 degrees and delta velocities between 16 and 26 km/h.
- Frontal Oblique Near-Side, impact angle of -30 degrees and delta velocity 44 km/h, with the occupant in the driver's seat. Variations could include impact angles of between -30 and -60 degrees and delta velocities between 29 and 44 km/h.
- Side Near-Side, impact forward of compartment, impact angle of 90 degrees and delta velocity 22 km/h, with the occupant in the driver's seat. Variations could include impact to either left (driver) or right (passenger) side, impact angles of between -90 and -120 degrees and delta velocities between 8 and 22 km/h.
- Side Far-Side, impact forward of compartment, right side impact with an impact angle of 90 degrees and delta velocity 44 km/h, with the occupant in the driver's seat. Variations could include delta velocities between 23 and 44 km/h.
- Side Near-Side, impact of compartment, impact angle of 60 degrees and delta velocity 29 km/h, with the occupant in the passenger seat. Variations could include impact to either left (driver) or right (passenger) side, impact angles of between 60 and 90 degree and delta velocities between 12 and 37 km/h.

Implications – How to implement and test the new load cases

In current legal and consumer rating testing, intersection crashes are only represented by a near-side impact to the occupant compartment. The five load cases identified could therefore serve as complement to current load cases. Adding new load cases does not necessarily mean more full-scale car testing: four out of the five load cases do not include compartment deformation due to the relatively low delta velocity and the impact not being directly to the occupant compartment. Similarly, [25] proposed new load cases of the frontal oblique type, both near and far side, and side impacts forward of the occupant compartment, all at speeds well below current legal and consumer ratings tests. Such impact conditions could be evaluated either by sled testing or by a virtual assessment method.

In such complex load case conditions, where the loading is in more than one direction, current physical crash test dummies, technically known as anthropomorphic test devices (ATDs), cannot be used reliably as validation of those against such loading conditions is missing. Instead we propose the use of Human Body Models (HBMs), which are more suitable for complex load cases. HBMs have been in use for some time, but mostly for kinematic investigations and chest injuries [30]. The HBM must be further developed regarding injury criteria with corresponding injury risk curves and validation to oblique load cases. This, in turn, indicates the need for a defined and validated virtual assessment method [31].

The HBM can also be morphed to represent the population more closely than current ATDs, which only exist in three sizes: the 5th percentile female, the 50th percentile male, and the 95th percentile male. Morphing is useful if the exact conditions from a specific crash need to be reconstructed or when performing a population study in which there is a large variation in anthropometry (gender, age and length). Population studies can identify unique individuals or groups that are "most challenging" for the restraint systems. However, the HBM needs to be validated for this use in terms of both kinematics and injury prediction.

Road infrastructure contribution to reduce injuries in intersection crashes

An alternative to using ADASs to prevent intersection crashes is to improve road infrastructure. Moderate changes, such as reducing speed limits or implementing traffic lights with dedicated phases for each traffic flow, coupled with enforcement, can be effective. More drastic changes, in particular replacing intersections with roundabouts have been proposed: roundabouts inherently and without further enforcement not only simplify the traffic flow, as in comparison to conventional intersections they have fewer possible conflict points, but also reduce the speed and thereby the severity of the potential crashes [32-33]. Roundabouts complemented with tailored driver assistance are likely to reduce traffic injuries substantially. However, not all traffic flows are suitable for roundabouts [33-34]; in addition, roundabout access and exits are prone to crashes with cyclists [35], and improvements to the infrastructure are a large investment. There is no expectation, therefore, that all intersections will be replaced by roundabouts in the near future.

Limitations

The method used has proved useful in that five load cases have been identified. However, these representative load cases are based on a small number of crashes and their selection has therefore not been made using statistical methods such as clustering. To increase case numbers and thereby the robustness of the new proposed load cases, the dataset could be extended to include AIS1 injury crashes. The increased number of crashes would include less severely injured occupants, but the presence of an only slightly injured occupant indicates that there is a risk of being more severely injured. An AIS1-type injury for one occupant, for example, could be more severe for a more vulnerable occupant, such as an elderly person.

The crash configurations are not described by their initial geometrical contact condition but by their deformation crash condition, using PDOF and point of maximum deformation. This method has been used with the purpose of visualising the loading direction to the occupants. If the purpose instead is to reconstruct the whole crash event using full-scale simulation models or physical crash tests, then an initial geometrical description is a better descriptor. In this case, the point of first contact and impact angle of each car should be used instead of the points of maximum deformation and PDOF; these values are listed in Appendix C to enable such analysis.

When using data with injured occupants, the car's crashworthiness is important: restricting the dataset to newer cars with today's state-of-the-art crash structures and occupant restraints is preferable but will reduce the number of cases drastically. This is a balance between having relevant cases and still having a large enough dataset. We included cars with RY 2000 or later to increase the size of the dataset, meaning that some did not have modern occupant restraint systems. The mean RY in the remaining crashes with injured occupants was 2006.

Further limitations to the method used have been described in [25]; they are therefore listed but briefly here, as follows: the dataset used has insufficient detail for some analyses; crashes can only be avoided or not avoided, not mitigated, nor can new possible crash scenarios or modified crash configurations be analysed; finally, the driver does not interact with the ADAS and cannot override it, as would be possible in reality.

Our results are based on German data, hence on the road infrastructure in Germany. As intersection crashes will depend on specific road infrastructure, our findings should only be generalized to countries where this is similar.

Future work

Future work should include a larger dataset of crashes and the use of mathematical methods, such as clustering, to derive load cases, instead of the graphical representation and visual inspection used in this study. In the meantime, the proposed future load cases can be used for more detailed reconstruction using numerical simulation models to better understand the injuries and injury mechanisms in future vehicle interiors.

V. CONCLUSIONS

When Advanced Driver Assistance Systems (ADASs) are implemented fleet-wide, future passenger car to passenger car accidents are predicted to be dominated by intersection crashes. This study identifies five distinct and clearly defined load cases for the development and evaluation of future occupant restraint systems.

VI. ACKNOWLEDGEMENTS

The work was partly carried out at SAFER, the Vehicle and Traffic Safety Centre, at Chalmers, Sweden. We thank Vinnova, the Swedish Energy Agency, the Swedish Transport Administration and the Swedish vehicle industry for funding parts of this work through the strategic vehicle research and innovation (FFI) program for the project 2017-01945 Assessment of Passenger Safety in Future Cars. We also thank Dr Helen East for her help with language revisions.

VII. REFERENCES

[1] Kahane, C. J. and Dang, J. N. (2009) The Long-Term Effect of ABS in Passenger Cars and LTVs. NHTSA Technical Report DOT HS 811 182. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811182.

[2] Evans, L. (1999) Antilock brake systems and risk of different types of crashes in traffic. *Journal of Crash Prevention and Injury Control*, **1**(1): pp. 5–23.

[3] Farmer, C. M. (2004) Effect of electronic stability control on automobile crash risk. *Traffic Injury Prevention*, **5**(4): pp. 317–25. doi:10.1080/15389580490896951.

[4] Dang, J. N. (2007) Statistical Analysis of the Effectiveness of Electronic Stability Control (ESC) Systems. Evaluation Division; National Center for Statistics and Analysis National Highway Traffic Safety Administration Washington, D.C. 20590. DOT HS 810 794.

[5] Lie, A., Tingvall, C., Krafft, M. and Kullgren, A. (2006) The effectiveness of electronic stability control (ESC) in reducing real life crashes and injuries. *Traffic Injury Prevention*, **7**(1): pp. 38–43.

[6] Jermakian, J. (2011) Crash avoidance potential of four passenger vehicle technologies. *Accident Analysis and Prevention*, **43**: pp. 732–40.

[7] Cicchino, J. B. (2017) Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. *Accident Analysis and Prevention*, **99**: pp. 142–52.

[8] Kusano, K. and Gabler, H. C. (2015) Comparison of Expected Crash and Injury Reduction from Production Forward Collision and Lane Departure Warning Systems. *Traffic Injury Prevention*, **16**: pp. S109–S114.

[9] Edwards, M., Nathanson, A. and Wisch, M. (2014) Estimate of potential benefit for Europe of fitting Autonomous Emergency Braking (AEB) systems for pedestrian protection to passenger cars. *Traffic Injury Prevention*, **15**: pp. S173–82.

[10] Rosén, E. (2013) Autonomous Emergency Braking for Vulnerable Road Users. In *Proceedings of IRCOBI conference*, 2013, Gothenburg, Sweden, pp. 618–27.

[11] European New Car Assessment Program (Euro NCAP) (2018) Assessment programme – Safety Assist Version 8.0.4 November 2018.

[12] Euro NCAP 2025 (2017) Euro NCAP 2025 Roadmap in pursuit of vision zero.

[13] Mercedes-Benz USA (2016) S-Class Operator's Manual. Stuttgart, Germany: Daimler AG, 2016.

[14] Volvo Car Corporation (2017) Volvo XC60 Owner's Manual. Gothenburg, Sweden, 2017.

[15] Audi (2016) Audi Q7 Owner's Manual. Germany, 2016.

[16] http://www.lexus.com/models/LS/safety.

[17] https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/propilot.html.

[18] https://www.audi-technology-portal.de/en/electrics-electronics/driver-assistant-systems/audi-q7-turn-assist.

[19] Flannagan, C. A. and Flannagan, M. J. (2007) UTMOST: A tool for comprehensive assessment of safety benefits. Report No. UMTRI-2007-22 June 2007.

[20] Strandroth, J., *et al*. (2012) A new method to evaluate future impact of vehicle safety technology in Sweden. *Stapp Car Crash Journal*, **56** (October): pp. 497–509.

[21] Strandroth, J. (2015) Validation of a method to evaluate future impact of road safety interventions, a comparison between fatal passenger car crashes in Sweden 2000 and 2010. *Accident Analysis and Prevention*, **76**: pp. 133–40.

[22] Puthan, P., Östling, M., Jeppsson, H. and Lubbe, N. (2018) Passive Safety Needs for Future Cars: Predicted Car Occupant Fatalities in the USA. *Proceedings of FISITA World Automotive Congress*, 2018, Chennai, India.

[23] Lubbe, N., *et al*. (2018) Predicted road traffic fatalities in Germany: The potential and limitations of vehicle safety technologies from passive safety to highly automated driving. In *Proceedings of IRCOBI conference*, 2018, Athens, Greece.

[24] Strandroth, J., Nilsson, P., Sternlund, S., Rizzi, M. and Krafft, M. (2016) Characteristics of future crashes in Sweden – identifying road safety challenges in 2020 and 2030. *Proceedings of IRCOBI Conference*, 2016, Malaga, Spain.

[25] Östling, M., Lubbe, N., Jeppsson, H. and Puthan, P. (2019) Passenger car safety beyond ADAS: Defining remaining accident configuration as future priorities. *Proceedings of 26th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2019, Eindhoven, The Netherlands.

[26] Statistisches Bundesamt (2018) Verkehr Verkehrsunfälle, Fachserie 8 Reihe 7, 2017,

https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Verkehrsunfaelle/Publikationen/Downloads-Verkehrsunfaelle/verkehrsunfaelle-jahr-2080700177004.pdf?__blob=publicationFile&v=4.

[27] Kullgren, A., Axelsson, A., Stigson, H. and Ydenius, A. (2019) Developments in car crash safety and comparison between results from Euro NCAP tests and real-world crashes. *Proceedings of 26th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2019, Eindhoven, The Netherlands.

[28] Codebook GIDAS 2018.

[29] ISO 12353-1, 2002. Road Vehicles – Traffic Accident Analysis – Part 1: Vocabulary.

[30] Pipkorn, B., *et al*. (2018) Occupant Protection in Far-Side Impacts. In *Proceedings of IRCOBI conference*, 2018, Athens, Greece.

[31] http://osccarproject.eu/.

[32] Massachusetts Highway Department. (2006) Design Guide Project Development & Design Guidebook, 2006th Edition, Mass Highway

[33] Robinson, B.W. *et al*. (2000) Roundabouts: An Informational Guide. National cooperative highway research program. https://www.fhwa.dot.gov/publications/research/safety/00067/000675.pdf

[34] Valdez, M. (2010) Effects of unbalanced approach volumes on roundabout operations. University of Texas at El Paso

[35] Gesamtverband der Deutschen Versicherungswirtschaft e. V. (2012) Unfallforschung kompakt Verkehrssicherheit innerörtlicher Kreisverkehre. https://udv.de/download/file/fid/1587

[36] Hummel, T., Kühn, M., Bende, J. and Lang, A. (2011) Advanced Driver Assistance Systems: An investigation of their potential safety benefits based on an analysis of insurance claims in Germany. German Insurance Association, Research report FS 03. Available at:
https://udv.de/sites/default/files/tx_udvpublications/RR_12__fas.pdf.

[37] Sternlund, S., Strandroth, J., Rizzi, M., Lie, A. and Tingvall, C. (2017) The effectiveness of lane departure warning systems: A reduction in real-world passenger car injury crashes. *Traffic Injury Prevention*, **18**(2): pp. 225–9.

[38] Wilkie, S. M. and Tate, F. N. (2003) Implication of travel patterns for ISA.
http://www.its.leeds.ac.uk/projects/isa/deliverables/Deliverable%201.pdf.

[39] Lai, F., Carsten, O. and Tate, F. (2012) How much benefit does Intelligent Speed Adaptation deliver: An analysis of its potential contribution to safety and environment. *Accident Analysis & Prevention*, 48(September 2012, Pages 63-72

VIII. APPENDICES

APPENDIX A: ADAS CRASH PREVENTION RULESETS

APPENDIX B: VERIFICATION OF ADAS EFFECTIVINESS

APPENDIX C: DESCRIPTION OF CARS AND CRASH CONFIGURATION

APPENDIX A:
ADAS CRASH PREVENTION RULESETS

The ADAS rules were created in the same way as in [23] but with slight differences, as follows. First, only ADASs that affect passenger car to passenger car crashes were included; in-crash protection features, like seat belt reminders and airbags, were not included, nor were systems that address other types of crash, such as those involving cyclists and pedestrians. Secondly, the following ADASs were added: Blind Spot Detection (BSD), Advanced Front Lighting System (AFLS), Emergency Steering (ES), driver-initiated Evasive Steering Assist (ESA), Driver Monitoring System (DMS), Traffic Jam Assist (TJA), Highway Assist (HA) and Alcohol Interlock. Thirdly, the conceptual rules 'safety-minded driving' and 'cautious driving' that were assumed to reflect a higher level of automated driving in [23] were not used. Finally, it is worth noting that where [23] and [25] used two sets of ADAS rules, a conservative and an optimistic set, this investigation used only the optimistic ruleset, i.e. did not include any limitations of the ADASs.

TABLE AI
ADAS CRASH-PREVENTION RULESETS

Technology	Ruleset using GIDAS variables	Ruleset in text
LKA, Lane Keeping Assist Typical crash scenarios that can be avoided are run off road, drift into oncoming vehicle and side swipes.	KLASSECE = 1 SPVERLA [1,3,4,8] v0 >= 60	Passenger vehicle Initial critical pre-crash event Speed > 60 km/h
LCA, Lane Change Assist Typical crash scenarios that can be avoided are side-swipes and rear-end crashes when changing lane.	KLASSECE = 1 UTYP_LCA = [652, 651, 649, 646, 645, 644, 642, 641, 639, 635, 634, 632, 631, 552, 551, 315, 233] v0 >= 60	Passenger vehicle Pre-event movement equal to changing lane Speed > 60 km/h
BSD, Blind Spot Detection Typical crash scenarios that can be avoided are side-swipes and rear-end crashes when changing lanes or merging.	KLASSECE = 1 UTYP_BSD = [643, 633, 314, 305, 652, 651, 649, 646, 645, 644, 642, 641, 639, 635, 634, 632, 631, 552, 551, 315, 233] v0 >= 10	Passenger vehicle Pre-event movement equal to changing lane or merging Speed > 10 km/h
AFLS, Advanced Front Lighting System Typical crash scenarios that can be avoided are running off roads in dark conditions.	KLASSECE = 1 KONBETEI = 0 LICHT1 = 2 RICHTUE = (4,5) ORTSL = 4	Passenger vehicles Run off road Light condition equal to dark Curve to right or left Rural road
ESC, Electronic Stability Control Typical crash scenarios that can be avoided are skidding crashes.	KLASSECE = 1 SCHLEU [1,99] ESP [2,9]	Passenger vehicles Skidding prior to crash Vehicle without ESC

AEB rear-end, Autonomous Emergency Braking rear-end Typical crash scenarios that can be avoided are impacts to rear end of vehicle in same lane.	KLASSECE = 1 UTYP = [201, 231, 541, 542, 549, 583, 584, 601, 602, 603, 604, 609, 611, 612, 613, 614, 619, 621, 622, 623, 624, 629, 501, 502, 509, 741, 742, 749, 591, 592, 593, 594]; (v0 -v0_opp <= 100) | isnan(v0) |v0 > 800)	Passenger vehicles Rear-end crash scenario Relative speed < 100 km/h
AEB reversing, Autonomous Emergency Braking reversing Typical crash scenarios that can be avoided are impacts to another vehicle when reversing.	KLASSECE = 1 UTYP_REV = [571, 572, 711, 712, 714, 715] v0 <= 30	Passenger vehicles Reversing crashes Speed < 30 km/h
AEB intersection, Autonomous Emergency Braking intersection Typical crash scenarios that can be avoided are crossing and turning in intersections.	KLASSECE = 1 UTYP_intersection = [202, 232, 251, 252, 259, 211, 212, 281, 351, 354, 271, 301, 311, 321, 322, 331, 353, 355, 561, 562, 215, 261, 302, 312, 322, 332, 352, 303, 304, 213, 214, 262, 286, 306, 323, 324, 326, 333, 334, 313, 314]; v0 <= 60 SICHTBV ! = [1,4]	Passenger vehicles Intersection crash scenario Speed < 60 km/h No sight obstruction
Emergency Steering assistance upon risk of head-on crash Typical crash scenarios that can be avoided are head-on scenarios where the driver is not performing any manoeuvre.	KLASSECE = 1 UTYP = [225, 245, 325, 334, 335, 363, 364, 521, 543, 554, 581, 582, 661, 664, 681, 682, 683, 721, 722, 723, 724, 731, 732] REAKTLE = 2 v0 <= 140 & v0 >= 40	Passenger vehicles Head-on crash scenario Driver is not initiating a manoeuvre 40 km/h < Speed < 140 km/h
Driver-initiated Evasive steering assist Typical crash scenarios that can be avoided are head-on scenarios where the driver was not steering enough to avoid the crash.	KLASSECE = 1 UTYP = [225, 245, 325, 334, 335, 363, 364, 521, 543, 554, 581, 582, 661, 664, 681, 682, 683, 721, 722, 723, 724, 731, 732] REAKTLE != 2 v0 <= 100 & v0 >= 20	Passenger vehicles Head-on crash scenario Driver is initiating a manoeuvre 20 km/h < Speed < 100 km/h
DMS, Driver Monitoring System All types of crashes where driver is distracted can be addressed.	KLASSECE = 1 UTYP = [761, 762, 763]	Passenger vehicles Driver distraction
ISA, Intelligent Speed Adaptation Addresses crashes where	KLASSECE = 1 HURSU = [12,13]	Passenger vehicles Speeding

the cause is speeding.		
TJA, Traffic Jam Assist Typical crash scenarios that can be avoided are low-speed side-swipes and rear-end impacts.	KLASSECE = 1 STRART = (3,4,5) MARK = (6,7) VSTUFE = 5 VDI2 = (1,2,4) v0 <= 65	Passenger vehicles Highway Divided road, with and without barrier High traffic density Damage to vehicle equal to front and side Speed < 65 km/h
HA, Highway Assist Typical crash scenarios that can be avoided are high-speed side-swipes and rear-end impacts on highways.	KLASSECE = 1 STRART = (3) VDI2 = (1,2,4) v0 >= 80	Passenger vehicles Federal motorway Damage to vehicle equal to front and side Speed > 80 km/h
Alcohol Interlock Prevents the driver from driving when affected by alcohol.	KLASSECE = 1 ALKO = 1	Passenger vehicles Police reported alcohol presence

APPENDIX B

VERIFICATION OF ADAS EFFECTIVENESS

When calculating ADAS effectiveness, all passenger car to passenger car crashes and all single passenger car crashes having status four (completed cases) in the GIDAS database from 1999 to 2017 were included, in total 11,317 crashes weighted to 12,047 crashes. This was done – in contrast to the rest of the paper, where only modern passenger car to passenger crashes with AIS2+ injuries were used – to increase the number of crashes and to create similar datasets to those found when searching the literature for reference values. Verification of the 15 ADAS rules was undertaken through comparison to reference values based on EU data only, to keep conditions as similar as possible to those in the dataset and thereby minimise the effects of noise factors such as vehicle fleet and traffic environment. For LCA, AFLS, AEB intersection, ESA, DMS, ISA, TJA, HA and Alco Interlock no reference values were found in the literature that match the dataset used in this paper, i.e. passenger car to passenger car and single passenger car crashes.

TABLE BI
VERIFICATION OF ADAS EFFECTIVENESS

Technology	Literature finding	Our estimate
Lane Keeping Assist (LKA)	2–8% [36-37]	12%
Lane Change Assist (LCA)	-	2%
Blind Spot Detection (BSD)	1–2% [36]	3%
Advanced Front Lighting System (AFLS)	-	3%
Electronic Stability Control (ESC)	17% [5]	21%
AEB rear-end	14–20% [36]	31%
AEB reversing	2% [36]	2%
AEB intersection	-	32%
Emergency Steering (ES)	1% [36]	1%
Driver-initiated Evasive Steering Assist (ESA)	-	2%
Driver Monitoring System (DMS)	-	1%
Intelligent Speed Adaptation (ISA)	8–30% [38-39]	9%
Traffic Jam Assist (TJA)	-	0%
Highway Assist (HA)	-	8%
Alcohol Interlock	-	2%

The ADASs found to be most effective in preventing passenger car to passenger car crashes and single passenger car crashes are AEB Intersection, AEB Rear-end, ESC and LKA. These four were also found to be the most effective in [25] and to a similar degree: AEB Intersection 29%, AEB Rear-end 24%, ESC 27% and LKA 15%. This similarity implies that there is a robustness and validity to the method used.

Although most of the ADAS rules correspond well to the reference values found in the literature, there are exceptions, and the design of the rules is rather simple. To better align these values to the those found in the literature, a refinement of the rules might be needed. In [25] it was found that the optimistic rules for AEB Intersection and LKA overpredicted effectiveness when compared to values found in the literature. However, in [25] two rulesets were used, one optimistic, which corresponds to the one used in this study, and one conservative, which included limitations on the ability of an ADAS to prevent a crash. Example of such limitations are lower functionality in harsh weather, missing lane markings, speeding or skidding, and poor road conditions, such as snow or ice being on the road. Results from the conservative ruleset in [25] were more in line with the literature findings for AEB Intersection and LKA, reducing their effectiveness to 8% and 7%, respectively.

APPENDIX C

DESCRIPTION OF CARS AND CRASH CONFIGURATION

The remaining crashes that were further analysed consist of 16 unweighted intersection crashes. Each car is described by registration year, dimensions and curb weight in Table CI. Further to this, the crash configuration is described by initial velocity, collision velocity, delta velocity and PDOF of each car. The impact conditions are described by point of maximum intrusion in x and y, collision angle and first contact point in x and y. The occupants that sustained AIS2+ injuries are described by age, gender, height and weight. All data are taken from GIDAS. Table CI is grouped and sorted in the same order as Tables II–VII.

TABLE CI

DESCRIPTION OF CARS, CRASH CONFIGURATION AND INJURED OCCUPANTS

Case #	T 2-7 Car	TDEZJ Registration Year	LAENGE Length (cm)	BREITE Width (cm)	LGEW Curb weight (kg)	V0 Initial Velocity (km/h)	VK Collision Velocity (km/h)	DV Delta v (km/h)	VDI1 PDOF	STOSSPX Point of maximum deformation *x* (cm)	STOSSPY Point of maximum deformation *y* (cm)	KWINK Collision angle (°)	BRPX First contact point *x* (cm)	BRPY First contact point *y* (cm)	ALTER1 Age (year)	GESCHL Male or female	GROESP Height (cm)	GEWP Weight (kg)
Frontal Oblique Far-Side																		
1	Red	2000	414.9	173.5	1337	Not known	12	17	1	40	74	126	0	86	18	Female	163	70
	Blue	2002	454.1	172.8	1535	Not known	22	16	12	15	22	-126	0	0	-	-	-	-
2	Red	2001	377.3	163.9	975	32	30	26	1	36	14	131	0	5	90	Male	170	70
	Blue	2000	472.9	176.1	1496	10	14	17	11	56	-67	-131	64	-80	-	-	-	-
3	Red	2016	379.5	166.5	920	30	26	16	1	23	52	94	2	42	62	Female	167	65
	Blue	2002	422.2	164.6	1205	0	10	12	10	65	-71	-94	68	-81	-	-	-	-
Frontal Oblique Near-Side																		
1	Red	2007	388.4	193.9	1030	15	20	29	11	19	-20	-113	3	-30	51	Female	Not known	Not known
	Blue	2006	433.6	204.5	Not known	50	47	25	1	46	60	113	87	91	-	-	-	-
2	Red	2003	396	164.6	1220	76	76	44	11	35	-30	-152	0	-15	22	Female	158	46
	Blue	2008	349.5	149.5	930	70	40	54	12	38	39	152	0	44	-	-	-	-
Side Near-Side impact forward of compartment																		
1	Red	2008	360.2	165.5	1110	50	50	18	12	25	-39	118	5	-50	50	Female	168	56
	Blue	2005	404.2	169.4	1375	42	42	12	10	357	-56	-118	310	-85	-	-	-	-
2	Red	2015	426.3	181.6	1370	45	45	8	2	74	79	110	80	87	51	Female	171	55
	Blue	2006	441	171	1405	18	18	8	11	5	-3	-110	0	10	-	-	-	-
3	Red	2002	459.6	179.8	1435	10	10	22	10	57	-73	-92	53	-89	45	Male	188	83
	Blue	2011	452.5	182	1569	68	68	19	1	22	11	92	0	14	-	-	-	-
Side Far-Side impact forward of the compartment																		
1	Red	2002	381.7	164.6	1010	25	25	23	2	62	60	106	117	80	51	Female	Not known	Not known
	Blue	2004	454.1	172.8	1535	45	29	15	11	20	-7	-106	0	-26	-	-	-	-
2	Red	2012	359.5	159.5	1060	67	67	44	1	63	65	99	5	63	25	Male	173	92
	Blue	2001	447.1	173.9	1395	35	35	35	10	56	-71	-99	0	-78	-	-	-	-
Side Near-Side impact of the compartment																		
1	Red	2000	341	147.5	795	64	64	12	10	210	-65	-94	200	-74	29	Female	Not known	Not known
	Blue	2002	443.9	174.2	1266	Not known	17	7	1	20	-30	94	0	-30	-	-	-	-
2	Red	2011	398.6	171.9	1055	14	27	37	3	210	55	92	213	86	70	Female	158	62
	Blue	2011	425.5	176.5	1265	74	74	31	12	37	35	-92	0	0	-	-	-	-
3	Red	2005	382.2	165.4	985	0	17	29	10	195	-62	-122	220	-82	84	Male	166	68
	Blue	2000	416.4	169.8	1220	60	60	25	12	30	-25	122	0	40	-	-	-	-
4	Red	2009	424.9	175.3	1230	50	50	29	1	107	61	109	66	86	57	Female	160	70

	Blue	2012	489.7	183.2	1695	41	28	21	11	32	23	-109	0	0	-	-	-	-
Other																		
1	Red	2005	341	147.5	800	63	63	46	12	25	-35	108	1	-50	38	Male	Not known	Not known
	Blue	2000	353.6	163.9	950	44	44	29	10	176	-55	-108	140	-74	-	-	-	-
2	Red	2001	443.9	174.2	1387	80	80	55	12	31	-18	-145	3	-15	43	Female	160	62
	Blue	2001	457.6	177.2	1425	30	30	53	1	33	32	145	5	60	-	-	-	-