Crashworthiness of Euro NCAP compliant vehicles: Risk of occupant injury in different side impact constellations

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Abstract – The incidence of side impacts was investigated from GIDAS data. Both vehicle-fixed object and vehicle-vehicle collisions were analysed as these are enclosed within the consumer testing program. Vehicle-fixed object collisions were stratified according to ESC availability. Results indicated that vehicles equipped with ESC rarely have pure-lateral impacts. An increase in oblique collisions was seen for the vehicles with ESC whereby most vehicle were driving in left curves. The analysis of vehicle-vehicle collisions developed injury risk curves were developed at the AIS3+ injury severity for the vehicle-vehicle side impacts. Results suggested that greatest injury risk occurred when a Pre Euro NCAP vehicle was struck by a Post Euro-NCAP vehicle. The remaining curves did not show different behaviour, indicating that stiffness increased have been equally combatted This was attributable to the few Post Euro-NCAP vehicles that had a deployed curtain airbag available in the sample. The integration of Euro NCAP testing has shown to improve vehicle crashworthiness for pole collisions, as those vehicles with ESC rarely incur lateral impacts.

INTRODUCTION

Side impacts account for 30% of all crashes involving severe or fatal injuries [1]. The orientation of a side impact is unfavourable for the vehicle occupants due to the closeness of the intruding vehicle and the limited structural supported afforded by the side of the vehicle. It has been shown that the frontal structure of a vehicle can withstand five times greater energy than the side structure [2].

With the integration of passive and active safety technologies in vehicles, the collision environment is constantly changing. Consumer testing was introduced in 1997 with the European New Car Assessment Program (E.NCAP) and aimed to encourage vehicle manufacturers to exceed occupant safety legal requirements [3]. Testing protocol for side impacts include a moveable deformable barrier striking the side of a vehicle at 50km/h in a purely lateral orientation. The barrier yields geometry and stiffness characteristics similar to a typical European car [4]. Protocols were updated in 2000 to include the provisions of a lateral pole test.

Crashworthiness refers to the degree to which a vehicle will protect its occupants from the effects of an accident and aggressivity is the degree to which a vehicle will injure the colliding parties. The aim of the research is to review real world side impacts and identify any shifting trends in terms of crashworthiness and aggressivity since the introduction of consumer testing. The study investigated how relevant the consumer tests replicated in E.NCAP are in reference to real-world accidents. Collisions from the German In-Depth Accident Study (GIDAS) were analysed.

MATERIALS AND METHODS

Materials

GIDAS commenced in 1999 and investigates traffic accidents in two German regions. Any form of traffic accident where the inspecting police officer deems an occupant injured is reported to the GIDAS team. Each case is then reconstructed and coded into the database. Annually 2,000 accidents involving various traffic participants (vehicle occupants, pedestrians, cyclists, etc.) are recorded in a statistical random procedure representative of the national accident statistic [5]. Inclusion for the proposed study required the occupants to be: travelling in a passenger car, seated in the front row, have primary damage recorded to the side of the vehicle and be aged 16 years or older [6]. The dataset included collisions from 2000-2015. Occupant injuries were coded with AIS 2005 - 2008 Update [7].

Methods

Vehicle-fixed object collisions

Research indicated that a significant proportion of serious and fatal injuries were sustained during side pole impacts, although these accidents did not occur as often as vehicle-vehicle collisions [8]. Injuries to the head and thoracic were frequently incurred. The primary testing protocols did not assess head impact; therefore, a pole test was integrated into the side impact testing envelope with first results released in 2000 [3]. Impacts with poles are generally more aggressive due to the greater depths of associated intrusions [9]. The advent of the pole test occurred around the period when crash avoidance technologies were becoming more readily available in vehicles.

The primary function of crash avoidance technology is to reduce the likelihood of an accident happening [3]. One of the most notable technologies was Electronic Stability Control (ESC). The technology aims to prevent a possible instability of a vehicle when a car does not follow the steering angle [10]. It has shown to yield significant effectiveness estimations [11]. The issue associated with estimating ESC efficacy values is difficult in that it may prevent the accident from occurring. In 2009 the consumer testing protocols integrated ESC into the rating scheme [3]. The research aimed to investigate if ESC could be identified as causing a shift to the collision environment.

The benefit of ESC would only become apparent in specific environments. The collisions in GIDAS are categorised according to the accident type. Accidents are classified as driving accidents, accident caused by turning off the road, accident caused by turning into a road or crossing the road, accidents caused by crossing the road or accidents involving stationary vehicles [12]. *Driving accidents* are those that were caused by the driver losing control of his vehicle without any other road users contributing to this. Only these collisions were considered. This excluded any collisions where the driver fell asleep.

Initial research claimed that the ESC would be most influential at higher speeds where the vehicle dynamic performance plays a greater part in the crash [13]. This hypothesis was supported by research ten years later, which found that ESC was twice as effective in preventing crashes in high speed zones as in low speed zones [11]. Therefore, the study was further stratified by only including collisions that occurred in rural areas. The majority of these roads are separated by painted lines and have a speed limit of 100km/h. The purpose was not to investigate the injury risk for occupants, but investigate the collisions of ESC equipped vehicles.

Vehicle-vehicle collisions

Under the guidance of the European Experimental Vehicle Committee (EEVC), side impact specifications were first implemented under the 96/27/EC regulations in October 1998 [3]. Testing protocol would aim to simulate a typical collision, however a retrospective study of English data showed that only 1% of all occupants were involved in an accident that is broadly comparable to the consumer test standard [14]. As mentioned earlier regulations were upgraded in 2000 to include the pole test.

Vehicle manufacturers had already began to introduce passive technologies into their vehicles prior to the mandatory testing of the pole collision. In 1998 BMW introduced their Inflatable Tubular Structure [15] that was later developed by other OEMs and suppliers into the inflatable head curtain systems. The head protecting airbag was often coupled with the already introduced thorax airbag. The thorax airbag aimed to provide a protective cushion between the occupant and the intruding door structure and first appeared in Volvo cars in 1995 [16]. Instead the study shifts away from injury risk solely being described by the struck vehicle’s crashworthiness, but considers the striking vehicle’s aggressivity. Compatibility research showed that the velocity of the intruding door structure is influenced by stiffness ratio of the two vehicles [20].

In side collisions, the intruding door structure is frequently the cause of injury [21]. The longitudinal and lateral stiffness of the vehicle fleet was shown to linearly increase over the last two decades [22-23]. This is attributable to the integration of high strength steels and aluminium alloys into vehicle frames. The presented study investigates the changes to the collision environment since the vehicle stiffness increased. It investigates any difference in injury risk when being laterally struck by a newer or older vehicle. Vehicles are grouped according to E.NCAP compliance (1997). Injury risk for the nearside occupant, at the AIS3+ severity, was compared by developing a series of injury risk curves. Side swipe collisions were excluded. The following assumption was applied:

- Vehicles manufactured to E.NCAP regulations have stiffer frontal longitudinal members and side B-pillar members than those designed prior.

Research investigating the American fleet had indicated that elderly occupants were three times as likely as younger occupants to be seriously injured in similar side impacts [24]. This is attributable to the accelerated frailty of the senior population. Risk curves were developed for the senior and non-senior populations to provide an overview of the German collision environment. The senior population was defined as those aged over 60 years.

Injury Risk Curves

Risk curves are statistically derived estimates of the probability of injury for a given population associated at various levels of stimuli. The stimuli may be forces, moments, deflections, velocities, accelerations or combinations of these measures [25]. Estimates for efficacy values of advanced driver assistance systems can be determined when curves are developed from accident databases. The change of velocity of the struck vehicle, Δv was considered the stimulus for injury.

The GIDAS collisions were considered quasi-experiments and analysed using parametric survival analysis in R, version 3.2.4. The method accounts for the so-called data censoring phenomenon in which the exact stimulus to cause injury is unknown. A parametric Weibull distribution was chosen to describe the probability of sustaining a MAIS3+ injury. The Weibull distribution was selected due to its capability of modelling both symmetrical and skewed distributions [26]. Horizontal (95%) confident intervals (CI) were developed according to the data censoring assumption [27].

To eliminate the threat of any bias from slightly-injured, financially motivated occupants, a minimum injury standard was set. Only collisions where the occupant suffered an ISS ≥ 2 were considered. Reporting of minor injuries is often assumed to be motivated by monetary compensation.

RESULTS

Vehicle-fixed object collisions

The frequency of collisions with fixed objects was plotted against Principle Direction of Force (PDOF). Each PDOF interval ranges 30 degrees and refers to specific o'clock orientations. As per the SAE definition, the 12 o'clock orientation represent a frontal collision, the 1-5 o'clock orientations refer to the passenger's side impacts and 7-11 refer to the driver's side impacts. The figure below shows the frequencies of fixed objects collisions for the different ESC availabilities. Note the different y-axis.

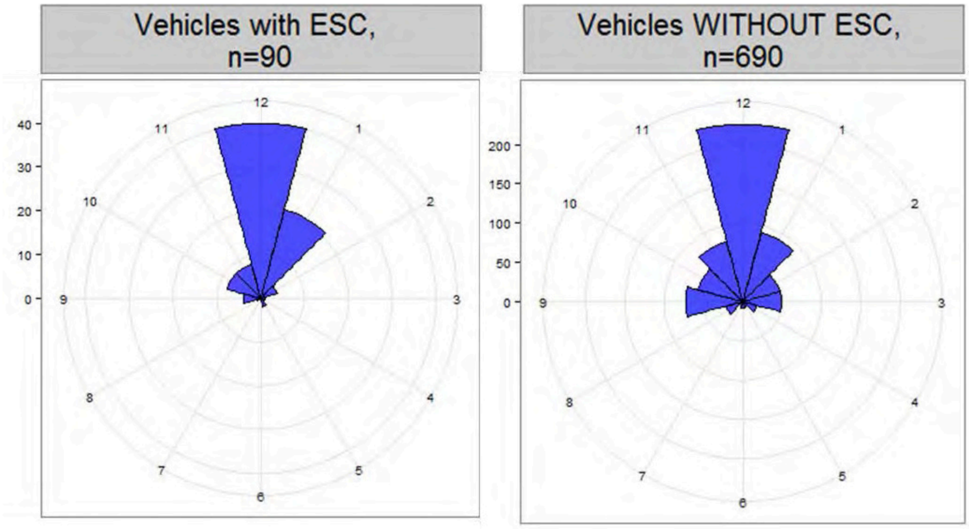


Figure 1 The frequency of fixed objects collisions per PDOF and ESC availability. Note the different scale in the lower graphs.

It becomes apparent that the sample size is significantly smaller for the ESC fitted vehicles. Results indicate that regardless of technology, collisions at the 12 o'clock orientation occur most frequent. Very few collisions occur between the 2–4 and 7–9 o'clock orientations for the ESC fitted vehicles. For the vehicles without ESC, an equal distribution of collisions occurs at the 11 and 1 o'clock orientations, however three times as many collisions occur at the 1 o'clock orientation as the 11 o'clock counterpart for the vehicles with ESC. This was further investigated by plotting the frequency of collisions with respect to PDOF and direction of travel.

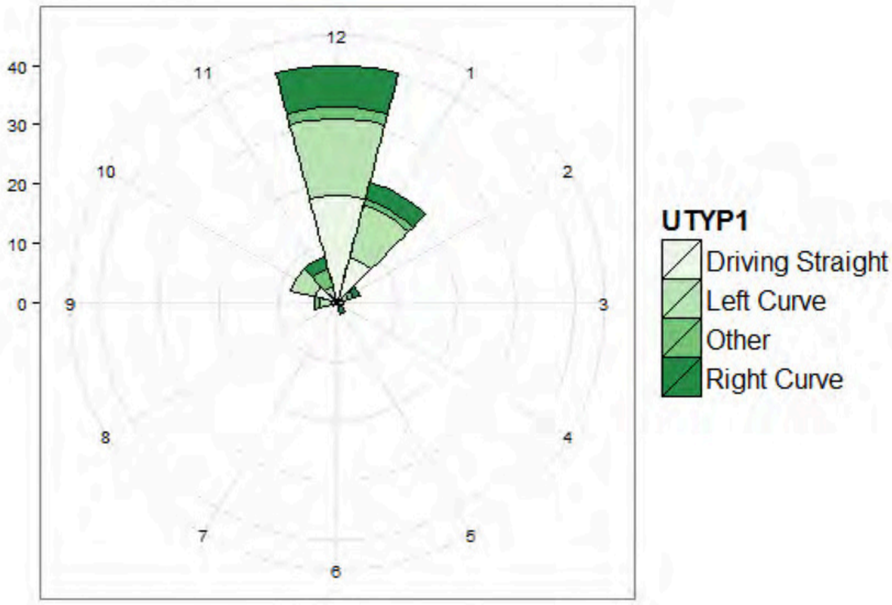


Figure 2 The frequency of fixed objects collisions per PDOF and direction of travel for vehicles with ESC

Figure 2 indicates that the majority of collisions at the 1 o'clock PDOF occurred in left curves or straight segments of road. A table was generated for both ESC equipped and not vehicles, regardless of PDOF, to compare the distributions for direction of travel.

Table 1 Summary table for the vehicles direction of travel for both ESC groups.

	Straight Segment		Left Curve		Right Curve		Other	
Vehicles ….	n	*%*	n	%	n	%	n	%
with ESC	34	*38*	32	36	15	16	9	10
without ESC	225	*33*	215	31	198	29	52	7

The most noticeable difference occurred with right curve collisions with 13% difference between the ESC groups. The relative percentages for the other directions of travel did not vastly differ between ESC availability. Given very few collisions occurred at lateral impacts, yet more were seen in left curves at the 1 o'clock orientation for the ESC equipped vehicles, it was hypothesised that:

- Lateral impacts do not occur at lower speeds as ESC is able to prevent the collision from sliding out of control, and
- At higher speeds, the ESC prevents the vehicle from sliding out of control, however the accident cannot be avoided and occurs at an oblique orientation (1 o'clock).

The first hypothesis cannot be tested as no collision occurs, however a difference in means test can assess the latter. A one-sided test was selected, where the alternative hypothesis assessed a greater average speed in the second group. Thus the following hypotheses were formulated, where μ represents the average:

- $H_0: \mu_{Collision\ Velocity} i = \mu_{Collision\ Velocity} j$
- $H_1: \mu_{Collision\ Velocity} i > \mu_{Collision\ Velocity} j$

When only considering the collisions at the 1 o'clock orientation, *i* represent the vehicles with ESC and *j* is the vehicles without ESC. The outcome of interest is the mean collision velocities of the two groups. A non-parametric, Mann–Whitney U test was applied to test for a difference in means. The test statistic returned a p–value < 0.1. One was able to reject H_0 and accept H_1.

Vehicle-vehicle Collisions

Injury risk curves were developed for the two age populations in Figure 3. Age was separated at 60 years to account for the differences in frailty. The red curve for the senior populations exhibits a much steeper slope, indicating greater susceptibility to injury. Results were significantly different as indicated by the separation of the confidence bands.

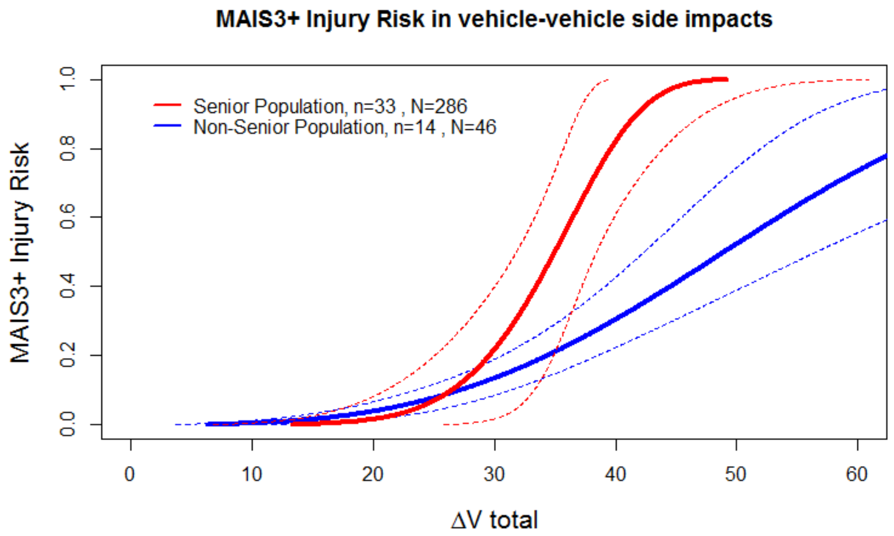
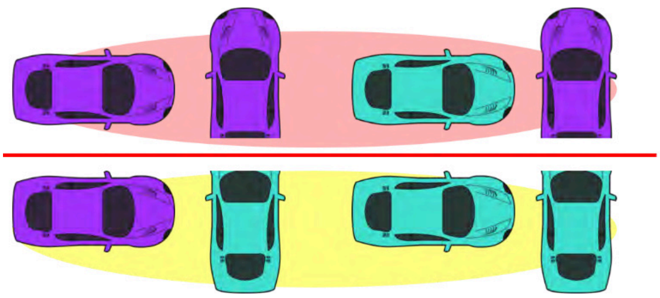


Figure 3 The MAIS3+ injury risk curves for the senior and non-senior populations. The dashed lines represent the 95% confidence bands. n is those injured MAIS3+ and N is the sample size.

Only the non-senior population was sufficiently large to assess the injury risk as a function of vehicle structure. Secondary MAIS3+ injury risk curves were developed stratified on E.NCAP compliancy. Following the assumption related to vehicle stiffness changes, Figure 4 summarises how the population groups were formed. The purple vehicle represents vehicles designed to E.NCAP regulations and the green are the vehicle designed prior.



	Striking Post	Striking Pre
Struck Post	55	35
Struck Pre	56	107

Figure 4 The purple vehicle represents vehicles designed to E.NCAP regulations and the green represents the older (Pre E.NCAP) vehicles. Two populations were created that assumed a similar lateral stiffness (shown with the red and yellow shading). They were further stratified in respect to stiffness of the striking vehicle. The table shows the absolute numbers of collisions obtained from GIDAS.

The resultant MAIS3+ injury risk curves are shown in Figure 5. The curves for the group highlighted in yellow (Pre E.NCAP) (refer to Figure 4) are shown with dashed lines. When considering the Pre-E.NCAP struck vehicles, the curves remain relatively similar until a severity of 35 km/h, then the slope for the newer striking vehicles (dashed blue curve) exhibits a steeper slope than the older striking vehicles (dashed red curve). This result incurs that predicted injury risk occurs at lower Δv severities when the striking vehicle was designed E.NCAP specifications.

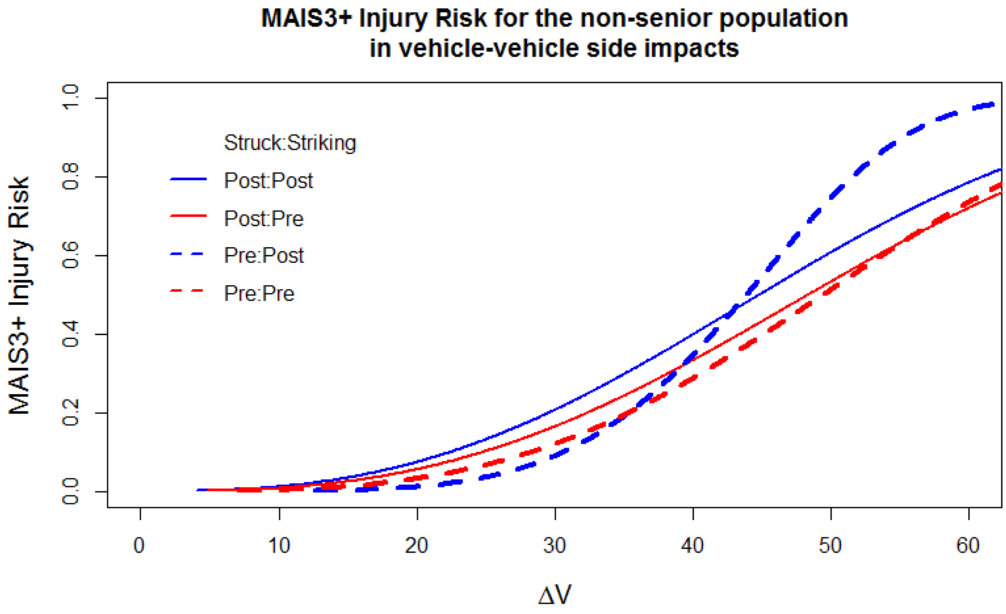


Figure 5 MAIS3+ injury risk curves for the non-senior population. Groups were formed with assumed equivalent lateral stiffness. The dashed curves show the predict injury risk for Pre NCAP designed vehicles and the solid lines are the Post NCAP vehicles.

The solid lines represent the E.NCAP compliant vehicles. Both curves are similar to the Pre E.NCAP-Pre E.NCAP curve (dashed red line). One must note that for this study the Euro NCAP compliancy was defined by the 1997 design year. Very few vehicles had curtain airbags until the pole test was integrated in 2000. The curtain airbag has shown strong injury and fatality mitigation in the field [17, 18]. Within the sample, the E.NCAP compliant vehicles with a deployed curtain airbag did not consist of any occupant suffering a MAIS3+ injury. Therefore as more E.NCAP vehicle become available in GIDAS, it is expected the curves for the E.NCAP complaint vehicles be shifted to the right.

At severities greater than Δv 45 km/h the occupants of older vehicles struck by E.NCAP compliant vehicles (dashed blue) yielded greatest injury risk. The curve exhibits a steep slope where injury risk changes from 0.15-0.8 within the range of 15 km/h. All injury risk curves with 95% confidence intervals are shown in the Appendix.

DISCUSSION

Vehicle Pole Collisions

Results indicate that for the specific GIDAS subset, very few vehicles fitted with ESC had side impacts with fixed objects. Furthermore, results suggested a positive collision mitigation of the ESC equipped vehicles. Very few lateral collisions occurred within the 2-4 and 8-10 o'clock PDOF.

The results for both the ESC and non-ESC population indicated collisions at a 12 o'clock principle direction of force (PDOF) were the most frequent. These collisions occur when the driver strikes the fixed object in a full frontal manner. ESC has no collision avoidance capacity when a vehicle has a head-on impact. Interesting to note was that the collisions without ESC yield a symmetrical distribution across both 1 and 11 o'clock PDOFs. However, this was not apparent for vehicles fitted with ESC. Vehicles with this technology collided against poles at the 1 o'clock orientation three times more frequently than at the 11 o'clock PDOF. Additionally, very few collisions occurred in right curves for the ESC equipped vehicles. One reason may be that the vehicle has additional time to manoeuvre the right curve as it may veer into the lane designated for oncoming traffic. It would be interesting to know if countries with opposite driving regulations to Germany yielded an increase in right curve collisions for ESC fitted vehicles.

It was proposed that ESC has shifted the orientation of high speed impacts from traditional lateral impacts towards an oblique orientation. This train of thought resulted from the increased number of left curve impacts with the 1 o'clock PDOF. The hypothesis test indicated that the mean collision speed for the ESC vehicles at the 1 o'clock orientation was greater than those without ESC, however not at the typical $p < 0.05$ level. It is likely that the small sample size did not allow for such.

Vehicle-vehicle Collisions

Senior and non-senior population

The risk curves indicate that the senior population are injured more readily at significantly lower speeds than the non-senior population. This is attributable to the increased frailty, namely due to the structural and material changes that occur in the ageing bony thorax. Kent et al. found that the thorax underwent a series of changes associated with time that can be categorized as material, composition or geometric changes. It was shown that the changes to the material properties of the rib were the most influential contributor to rib fracture. The most common material change is the decrease in elastic modulus of the cortical and cancellous bone tissue [28].

Whilst results indicate the greater susceptibility of injury for the senior population, one must consider that the non-senior population was more than two times larger.

Vehicle Performance in lateral vehicle-vehicle collisions

Struck vehicles were grouped according to lateral stiffness classes. Injury risk curves for the non-senior population were then developed according to E.NCAP compliancy (1997) of the striking vehicle. That way, the injury risk for older vehicles was compared when struck by a newer and older vehicle. The same was repeated for the newer struck vehicles. The group most at risk was the Pre E.NCAP (struck) – Post E.NCAP (striking). At greater impacts severities, the difference in predicted injury risk was most noticeable.

Frontal consumer testing within E.NCAP incorporates an offset collision that only engages one longitudinal structural member. The test aims to encourage engineers to develop stiff passenger compartment with less stiff front ends that absorb energy. E.NCAP resulted in greatly improved front-end crumple zones and occupant compartments [29]. Until a collision severity of 35km/h, all curves do not differ. At greater severities, when the striking vehicle was designed to E.NCAP standards and the struck vehicle was older, the slope of the curve accelerates. It is assumed this corresponds to the limit of maximum compartment strength, and once exceeded, occupant injury risk increases sharply.

The other three curves did not show different behaviour. This indicates that while frontal and lateral stiffness values have increased, injury risk has not changed. It becomes apparent by reviewing the similar Post:Post and Pre:Pre curves. These curves remain the same because the risk of occupant contact with the B-pillar or window has not changed. Fortunately very few collisions have occurred where a curtain airbag deployed. The Post E.NCAP vehicles are expected to have lower injury risks given their integration of passive safety systems as more collisions become available with a deployed curtain airbag.

Despite the sharp rise of the Pre:Post curves, there remains very low risk of this collision happen. A study in 2011 showed that of the 42.3 million cars registered in Germany, 60% were ≤ 10 years old and 80% were ≤ 15 years old [30]. Therefore, considering today vehicle fleet, we expect few pre NCAP vehicles on the road.

Limitations

Given the small sample size of the ESC equipped vehicles, it is difficult to gauge how representative the results are towards wider populations. Additionally, research has shown that vehicle drivers knowingly drive faster when their vehicles are fitted with certain safety systems [31]. It is not certain if this applies to ESC fitted vehicles.

Despite the first results of Euro NCAP were released in 1997, only 55 collisions were found in the database whereby a Post Euro NCAP vehicle laterally struck another Post Euro NCAP vehicle. This not only makes it difficult to develop conclusive results on the associated injury risk for the current vehicle fleet, but also makes estimating efficacy values of passive safety systems difficult.

CONCLUSIONS

The crashworthiness of the vehicle fleet was investigated in terms of side collisions. Both vehicle-vehicle and vehicle-fixed objects impacts were considered. In the fixed-object collisions, the influence of ESC was analysed. Despite a small sample size, results indicated that very few pure-lateral collisions occur. An increasing trend in the number of collisions at the 1 o'clock orientation was seen. It was hypothesized that this resulted from vehicles entering left curves with high speeds. As such the pure lateral collisions that once occurred with older vehicles have shifted to an oblique orientation. Nonetheless, the implementation of the Euro NCAP pole test has shown a positive influence of real-world accidents. The aggressivity of the striking vehicle in a collision was also investigated. Results trended towards a detrimental effect when a Pre E.NCAP vehicle was struck by stiffer, Post E.NCAP vehicle. Curves for newer struck vehicles did not differ compared to the older vehicle, which indicates that lateral and longitudinal stiffness increases have been combatted. As more curtain airbags become available, it is expected these (solid) curves will shift to the right.

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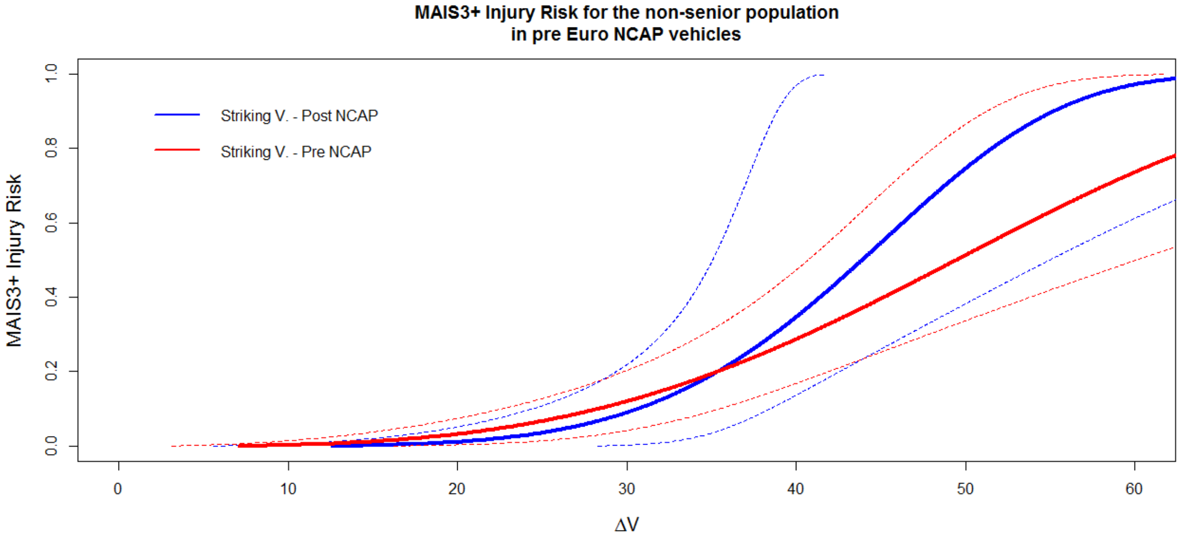
APPENDIX



MAIS3+ Injury Risk for the non-senior population
in pre Euro NCAP vehicles
Striking V. - Post NCAP
Striking V. - Pre NCAP
MAIS3+ Injury Risk
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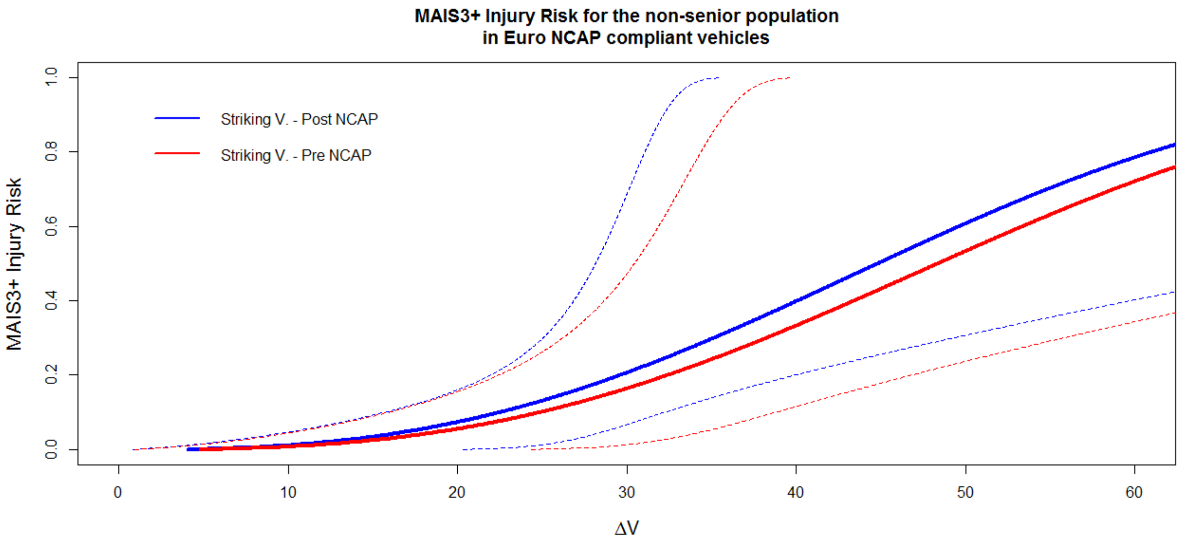

MAIS3+ Injury Risk for the non-senior population
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Striking V. - Post NCAP
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MAIS3+ Injury Risk
0.0
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ΔV