

# DESIGNING FOR EQUAL OCCUPANT PROTECTION – LEARNING FROM THE PAST, MOVING FORWARD

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## ABSTRACT

This study presents a real-world based car safety development working process, implemented more than 50 years ago, and provides analyses of five decades of real-world crash data showing its capabilities to develop equal occupant protection. Specifically, it includes a data-driven process of continuous learnings applied to the development of crash safety of Volvo passenger cars.

The Volvo Cars Traffic Accident Database covering crashes with Volvo cars in Sweden since 1970 was filtered for restrained occupants and grouped by five car model year decades from 1970s to 2010s. MAIS2+ injury risks over the years were put in the context of the car safety advancement steps to show and further understand the key areas of this car safety working process, called Circle of Life.

The data shows continuous MAIS2+ injury risk reductions, benefitting both females and males, and occupants in different seat positions and crash types. Examples are the early rear seat countermeasures keeping rear seat passengers on par with front seat occupants, the substantial MAIS2+ injury reductions in car-to-large animal crashes, and the side impact improvements during the 90s, significantly reducing MAIS2+ injury risks for the near-side occupants, but also for the far-side occupants. Over the years, a shift has taken place from frontal and side impacts accounting for the highest relative share of MAIS2+ injuries, to more recently the highest share is seen for multiple crashes.

The foundations of the human-centric and real-world based Circle of Life, targeting understanding of the injury mechanisms, defining protection principles and focusing on the most vulnerable combination together with an understanding of the distributions and exposures, were shown successful. Addressing even further needs of robustness with the future challenges on more unique cases, complex crashes and increased occupant variabilities, the working process can support when moving forward.

**Keywords:** car occupant protection, real-world crashes, safety development process, crash analysis, equal protection

## INTRODUCTION

Passenger car occupant protection has improved substantially over the last half century. Fatality risks have been reduced with newer car model years [1-3] as well as for different injury severity risks [4, 5]. Vehicle improvements have been highlighted as one of several contributing factors for the overall risk reductions [3, 5, 6].

Car occupant protection is about protecting a heterogeneous population of people when possibly exposed to a large variety of crashes, while seated in any of the seats in the car in a variation of postures. Research on differentiation with respect to crash situations, seat positions and occupant characteristics provide e.g. insights on relative differences between female and males over the years. Using FARS data on car model years 1960 to 2020, [2] observed a higher fatality risk for females, although steadily decreasing with newer vehicle models and being influenced by crash type, occupant age, in addition to restraint use and safety technology available. Forman et al. [4] studied restrained occupants in frontal impacts and reported that females were at greater risk of AIS2+ and AIS3+ injury compared to

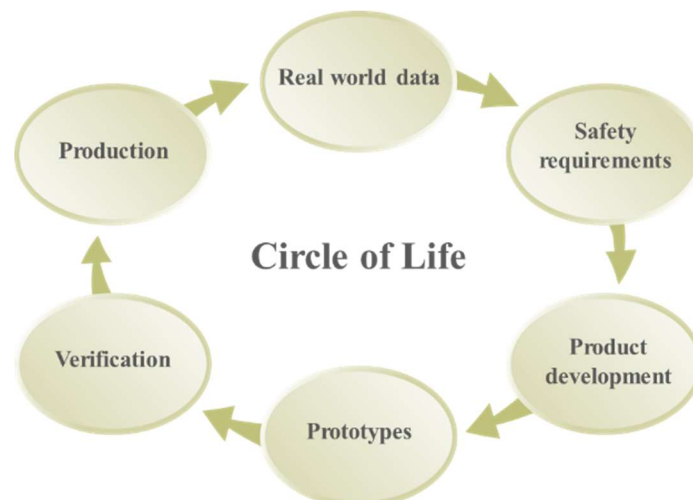
males. Brumbelow and Jermakian [7] controlled for vehicle types and used a refined estimation of the crash severity, leading to the conclusion that the risk difference is smaller than shown by [4]. Brumbelow [8] emphasized the importance of accounting for vehicle type and crash difference between females and males when seeking to compare relative injury risk. When including a broad range of crash types, pre-crash and crash variables and occupant characteristics, [9] concluded that it was not one single answer for increased or decreased odds of injury for females versus males, since it was depended on several factors associated with type of injury and its severity. Adding to this, some factors which might influence real-world occupant protection, such as sitting posture at impact, are not commonly available in large statistical datasets.

Addressing the wide scope of car occupant protection is challenging. Bohlin et al. [10] framed it as “*Being a group, each occupant nevertheless must be considered an individual with his specific qualifications. The task of the packaging designer is thus - within one concept – to offer not only the whole occupant population, but also each individual occupant an optimally safe and comfortable transportation environment*”. Such a human-centric approach emphasizes that human injury tolerances are the foundation in occupant protection. Jakobsson et al. [11] further elaborated that it addresses the needs of the occupants based on who they are, how they are sitting and what forces they are exerted to. Equal occupant protection means that people of different sizes, ages and sex in different seat positions, sitting postures and exposed to a variety of crash situations are considered. Real-world crashes inherently incorporate such a variety of crashes and individual differences, which then naturally can function as a knowledge wealth and driving force for equal occupant protection.

With the purpose of exploring an existing working process using learnings from the past, understanding its suitability moving forward, the objective of the study was to present and discuss how this human-centric and real-world based car safety development working process can generate equal occupant protection. This was done by investigating the effect of occupant protection over the years in relation to car safety advancements, using a sample of car models for which the safety design advancements are well known, and for which the crash data has been collected in a consistent way for 50 years.

## METHODS

In 1970, a structured data collection of Volvo cars involved in crashes in Sweden was established [12]. At the same time Volvo established a car safety development working process, called Circle of Life, characterized by a holistic view focusing on knowledge from real-world crashes [13]. The Circle of Life forms a continuous loop of knowledge from real-world crashes, defined into safety requirements and test methods, feeding into vehicle development through prototyping, verification and production, continuing into real-world data, Figure 1. The data collection and working process have been ongoing since then.



**Figure 1. The Circle of Life, a car safety development working process characterized by a holistic view focusing on knowledge from real-world crashes.**

An important area of the Circle of Life is the identification of injury mechanisms and establishment of protection principles based on the learning from the real-world crash data. This forms the foundation for the car safety advancement steps. Another area is the ability to correlate real-world crash data with laboratory data using exposure-based methodologies [14,15]. These methodologies provide a holistic perspective and guide prioritization towards highest injury reduction potential. Isaksson Hellman and Norin [16] showed some of the effects of the working process summarizing data from the first thirty years. The data showed a decrease of MAIS2+ for restrained drivers by two-thirds during that time period.

Using Volvo car model years from 1970 to 2019, for which the design advancements are known, and real-world crash data has been collected in a consistent way, the current study investigates the effect of occupant protection over five decades in relation to car design safety advancements.

### **Car Design Advancement Steps**

Following the Circle of Life, car design advancement steps were taken by analyzing the injury mechanisms and understanding the combinations of the most vulnerable combination of occupant and crash characteristics. The analyses were supported by exposure-based methodologies on addressing and assessing varieties in crash severity and occupant characteristics. Such methodology helps predict real-world performance of different systems and settings in an early stage of the development process, enabling forecast of real-world outcome as well as inclusion of the heterogeneous population. It helps when setting restraints or padding characteristics to ensure that the designs were tuned after the situations mostly exposed, thereby having most real-world benefit. The advancement steps focused on in this study are examples of structural improvements and restraint developments.

**Rear seat passenger protection** Real-world knowledge has driven rear seat occupant protection for a long time in Volvo cars. The three-point seatbelt was introduced as standard on the outboard seat positions 1972, and for the mid seat position 1986-1992. Seat designs including anti-submarining ridges were available from 1982. The side impact protection systems (SIPS) introduced 1991, followed by the Inflatable Curtain (IC) in 1998, both contributed to enhance protection of rear seat occupants in side impacts. The rear seat seatbelts have improved over the years, pretensioners were introduced as standard in 1998, followed 10 years later by a two-stage load limiter, adapted based on occupant weight and crash severity. None of these advancements were driven by legal or other third-party test incentives. They were all driven by real-world needs.

**Large animal crashes** The main injury mechanisms in car-to-large animal crashes, such as when impacting a moose, are identified as head, neck and upper extremity injuries caused through contact with the deformed roof structures or the large animal. Also, minor head, face and upper extremity laceration injuries often occur mainly due to glass splinter [17]. The occupants in the front seat are the most exposed. During the 80s, a test method was developed, comprising of a large animal impactor [18]. Using this test method, typical car-to-large animal crashes could be simulated. The occupant injury mechanisms can be investigated by assessing structural performance, such as maximum dynamic intrusion together with crash test dummy kinematics and responses. Over the following decades the structural performance of the header and A-pillars were further improved, and the effect was demonstrated in [17], comparing two vehicle generations.

**Frontal impacts** Frontal impact advancements include front structure design, enhanced seatbelt technologies, introduction and refinement of airbags, collapsible steering column designs and improved seat structures. Frontal airbags were introduced in the late 80s and by 1994 almost every car model was equipped with driver airbags [16]. Collapsible steering columns were introduced 1973, followed by a refined multi-stage version the year after. The seatbelt was continuously improved, introducing a first generation pretensioner in 1987 and further refined over the years. During the 70s and 80s much effort was put into improvements of the car front structures [13]. In the new car models of the 90s, structural changes influencing small overlap collision were introduced [19]. Twenty years later [20] summarized the real-world protection for the car generations with and without these structural advancements providing insight into MAIS2+ injury reduction for full overlap crashes as well as for smaller overlap frontal impacts. Such advancements help reduce foot-well intrusion and thereby address one of the injury mechanisms for lower extremity injuries. However, AIS2+ lower extremity injuries were still relatively frequent in the late 80s, whereby injury mechanisms were studied from real-world crashes and protection guidelines were summarized and addressed

in the next generation cars. General design guidelines were defined for the following areas: geometry, acceleration, pedals and intrusion [21]. Protection systems addressing these guidelines were implemented during the 90s model years and onwards. Recently, the real-world protection for the car generations with and without these advancements were summarized, showing an approximate efficiency of 60% of AIS2+ foot, ankle and leg injury risk [22].

**Side impacts** The advancement steps and the rationale for side impact occupant protection systems in Volvo cars are described in several studies. The first step, in line with to the Circle of Life, was identifying injury mechanisms by analyzing real-world crashes [23]. Implementations include a dedicated side impact structural design, called SIPS – Side Impact Protection System, in 1991 [24], followed by the world-first torso side airbag, called SIPSbag, in 1994 [25], and the world-first IC in 1998 [26].

The advancement steps mainly targeted the occupants on the struck side (near-side). The most important injury mechanism and protection guidelines were reduction of the speed of impact to the occupant, to provide an even dynamic interaction to the body, and to provide efficient support to the head, in addition to minimizing the intrusion as such [23, 24]. This resulted in the structural design of spreading the loads around the occupant absorbing energy elsewhere (SIPS), adding extra cushioning effect by the SIPSbag and covering the broken glass area by the IC to help keep head and extremities into the car and to cushion potential head impacts to the counterpart.

The structural advancements also targeted the occupants on the non-struck side (far-side), mainly by addressing one of their main injury mechanisms, being impacts towards the intruding structure.

In more recent years, further advancements have been made based on new real-world data studies to identify additional injury mechanisms to address, resulting in e.g. improved sensing capabilities to trigger the IC in a larger span of near-side side impacts, so called L-type side impacts [27].

### **Real-World Crash Data Analysis**

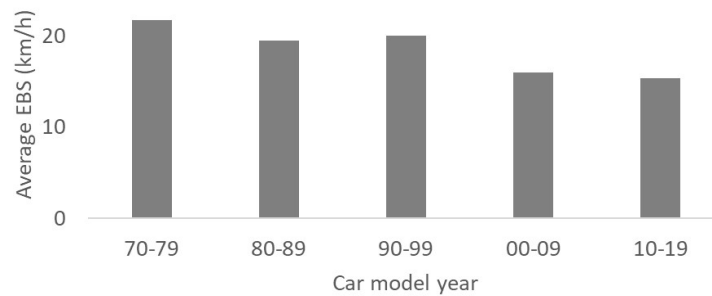
The Volvo Cars Traffic Accident Database (VCTAD) includes data from road traffic crashes occurring in Sweden involving Volvo cars since 1970. Currently, the dataset covers crashes occurring until 2021 with a total of 50,950 cars involving 83,840 occupants.

Volvia (If P&C Insurance) provides notification for cars involved in crashes with estimated repair costs exceeding a certain threshold. All Volvo cars are insured with Volvia for at least the first three years after registration. Photos and technical details of the cars are sent to Volvo Cars' Accident Research Team. The Volvo Cars team sends out a detailed questionnaire to the owner of the car to gather information about the crash, the car and the occupants. The information covers the circumstances of the crash, e.g. weather, road conditions, posted speed limits, sequence of events, and collision objects. Examples of occupant data are age, sex, stature, weight, seat position, restraint use, and injury status. The response rate has varied over the years, currently it is approximately 30%. In addition, the fatally injured cases are enriched with information from governmental investigations.

With the approval from injured occupants, their medical records are requested and coded by a physician within the Volvo Cars Team. Initially, injuries were coded by an in-house body region system and severity coding. When available, the 1985 Abbreviated Injury Scale (AIS) injury severity coding [28] was used, also retrospectively. Since the accident year 2014 all cases are coded in line with the 2015 AIS code book [29].

Based on the photos of the damaged car, and information about the crash from the questionnaire, experts from the Volvo Cars team code the deformation of the car in line with the SAE Standard J224 Collision Deformation Classification [30].

The repair cost limit for the selection and inclusions of cases has been adjusted over the years to reflect and help keep the impact severity comparable. For frontal impacts, the impact severity is estimated using Equivalent Barrier Speed (EBS) [31]. The CDC coding for each case is transformed into the energy matrix for the front structure derived from crash tests for each car model. The EBS is then computed from the total energy dissipation. Figure 2 shows the distribution of average EBS over car model years.



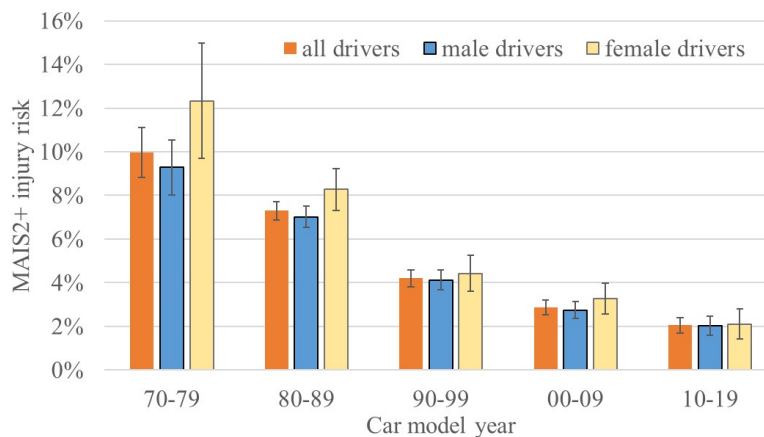
**Figure 2. Average impact severity, EBS (km/h) in frontal impacts per car model year.**

For this study, the occupants were grouped in five groups based on car model year. The car model year groups follow the decades; 1970-1979, 1980-1989, 1990-1999, 2000-2009, and 2010-2019. The sample was limited including seatbelt restrained occupants of age 13 or older. The total dataset selected for analysis included 41,620 drivers, 12,949 front seat occupants and 5,076 rear seat occupants. Details on the total numbers per car model year decade, the distribution of female and males, seat positions and crash types are available in Appendix.

The injury analysis was based on Maximum AIS per individual or per body region of severity equal to or higher than moderate injury, called MAIS2+. Injury risk is defined as the number of MAIS2+ injured divided by the total number of occupants with known outcome in the group considered. 95% confidence intervals are presented as analysis support in the graphs and to provide input to statistically significant difference between injury risk values. Injury reducing effect (efficiency) is defined as the injury risk in a newer car model year group in relation to the injury risk in an older group with 95% confidence limits ( $C_L$ ,  $C_U$ ).

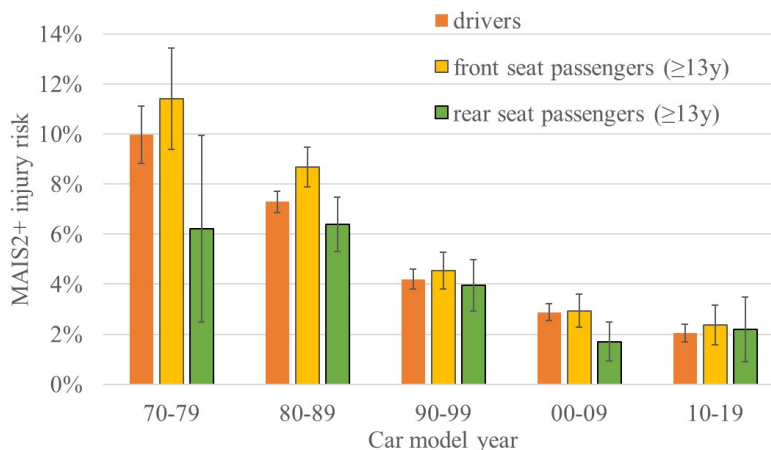
## RESULTS

Figure 3 shows MAIS2+ injury risks for restrained drivers per car model year decade. Overall, a clear MAIS2+ injury risk reduction has been seen over the five decades. Statistically significant differences for all steps are seen overall and for males separately. The MAIS2+ injury risks for female and male drivers are following the same trend and are aligned, especially in the last three decades. Comparing the last decade (2010-2019) with the first (1970-1979) an overall MAIS2+ injury reducing effect of 79% with the confidence limits ( $C_L$ ,  $C_U$ )=(75%, 83%) is seen for all drivers. The corresponding efficiency for male drivers and female drivers, respectively, are 78% ( $C_L$ ,  $C_U$ )=(72%, 83%) and 88% ( $C_L$ ,  $C_U$ )=(75%, 88%).



**Figure 3. MAIS2+ injury risk, including 95% confidence intervals, for the five car model year decades, for all restrained drivers and for female and male drivers separately, all crash types. Background data in Appendix, Table A1.**

Figure 4 compares MAIS2+ injury risks for restrained drivers and restrained front and rear seat passengers 13 years and older, respectively. The same injury-reducing trend observed for drivers is also seen for the two groups of passengers, however with larger confidence intervals due to smaller sample sizes. Although the small samples resulting from low seatbelt use in the rear seat during the first decades, Figure 4 shows that that restrained rear seat passengers benefited from similar level (or better) of protection as the front row occupants. This indicates that the countermeasures introduced in the rear seat during the 70s to 90s were efficient.

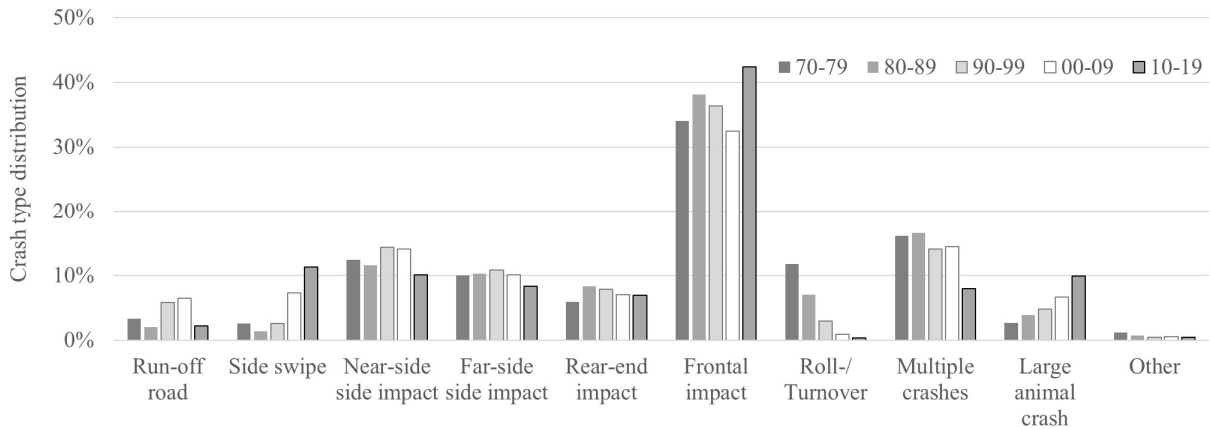


**Figure 4. MAIS2+ injury risk, including 95% confidence intervals, for the five car model year decades, for all restrained drivers and for front and rear seat passengers (≥13y), all crash types. Background data in Appendix, Table A2.**

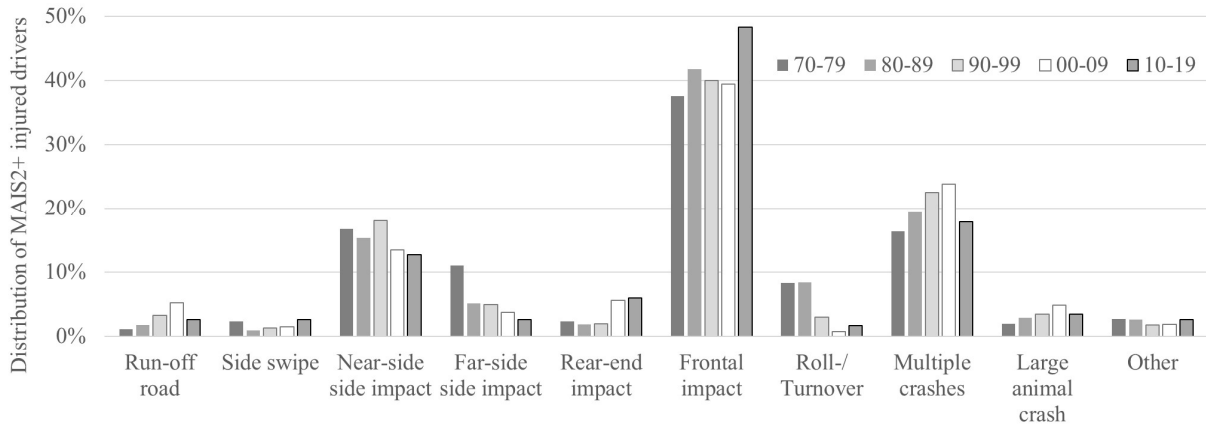
### Crash Types

Crash type distribution for restrained drivers for the five decades is shown in Figure 5a, while the corresponding distribution of the drivers sustaining MAIS2+ injury risks is shown in Figure 5b. Frontal impacts, followed by near-side and far-side side impacts when combined, account for the most frequent crash types. Frontal and side impacts account for high relatively shares of MAIS2+ injuries, respectively, as well, however closely followed by multiple crashes. For the most recent decades, the highest MAIS2+ injury risks are found for multiple crashes (Appendix, Table A4). Multiple crashes are defined as two collisions or more, or roll- or turnover events combined with one or more collision.

Figure 5a shows that the share of roll- and turnovers has become substantially lower, while the opposite is seen for the share of large-animal crashes. The trend for pure roll- and turnover follows the overall trend [32] and is likely to be due to improvements of the chassis, followed by introduction of stability control systems. The increase of share of large-animal crashes corresponds to continued high exposure of large-animal crashes within Sweden. However, a similar increase in the MAIS2+ injured share in such crashes is not seen (Figure 5b). The MAIS 2+ injury risks in those crashes have changed from 7.0% for the 70s, by 5.4% followed by 3.0% and 2.1% to 0.7% for the 10s models (Appendix, Table A4). This injury risk reduction for large-animal crashes follows the occupant protection improvements for the corresponding car model years.



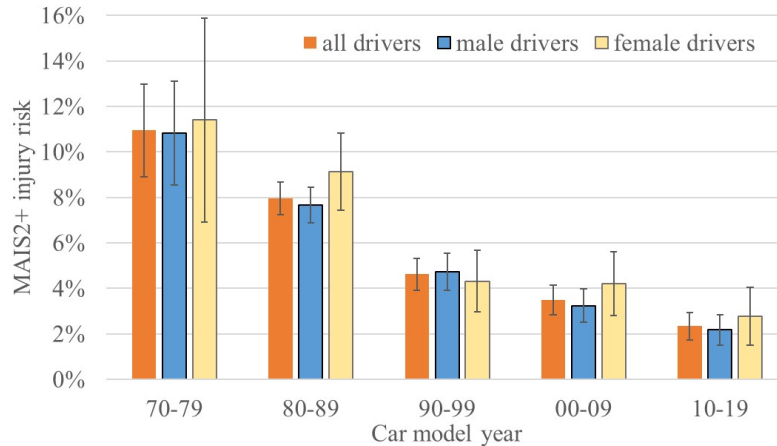
**Figure 5a. Crash type distribution (per driver) for the five car model year decades.**  
Background data in Appendix, Table A3.



**Figure 5b. Crash type distribution of MAIS2+ injured drivers for the five car model year decades.**  
Background data in Appendix, Table A3.

### Frontal Impacts

MAIS2+ injury risks for restrained drivers in frontal impacts follow the same trends as when all crash types were included. Figure 6 shows consistent MAIS2+ injury risk reductions over the five decades, overall and for female and male separately. Similarly to all crash types (Figure 2), the overall MAIS2+ injury reducing effect in frontal impacts for all drivers is 79%, with the confidence limits ( $C_L$ ,  $C_U$ )=(71%, 84%), comparing the last decade (2010-2019) with the first (1970-1979). The corresponding efficiency for male drivers and female drivers, respectively, are 80% ( $C_L$ ,  $C_U$ )=(71%, 86%) and 76% ( $C_L$ ,  $C_U$ )=(56%, 87%).

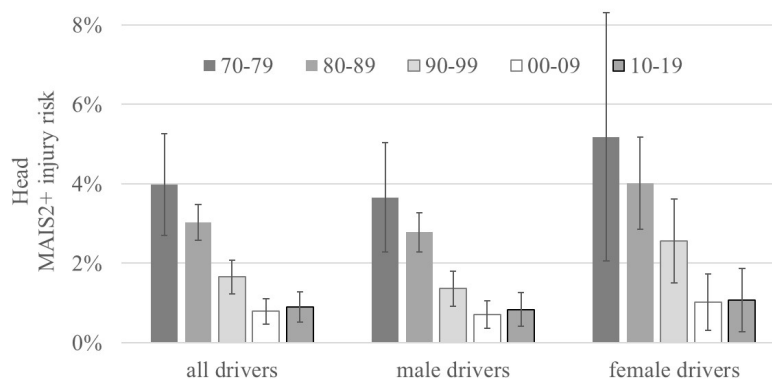


**Figure 6. MAIS2+ injury risk, including 95% confidence intervals for the five car model year decades, for all restrained drivers and for female and male drivers separately in frontal impacts. Background data in Appendix, Table A5.**

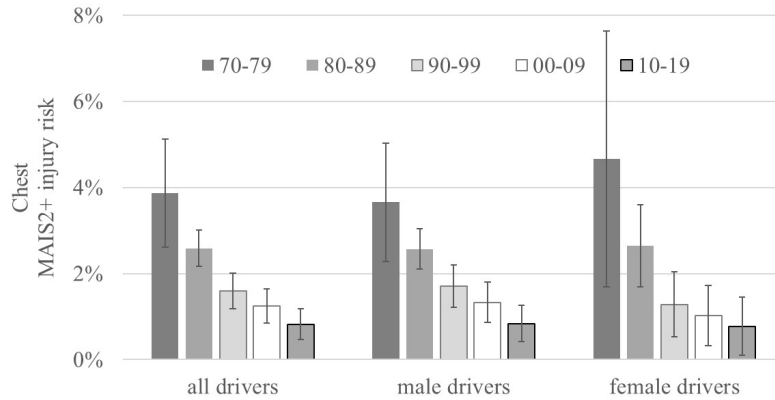
As seen in Figure 6, a statistically significant step was taken between the 80s' model years and the 90s. Per body region, this step is statistically significant for all body regions except abdomen, spine and upper extremities. Figures 7a-c show MAIS2+ for head, chest and lower extremities for restrained drivers in frontal impacts.

Structural improvements and the driver airbag including the energy absorbing steering column are early advancement steps having impact on MAIS2+ head and chest injuries reductions during the 70s and 80s (Figures 7a-b).

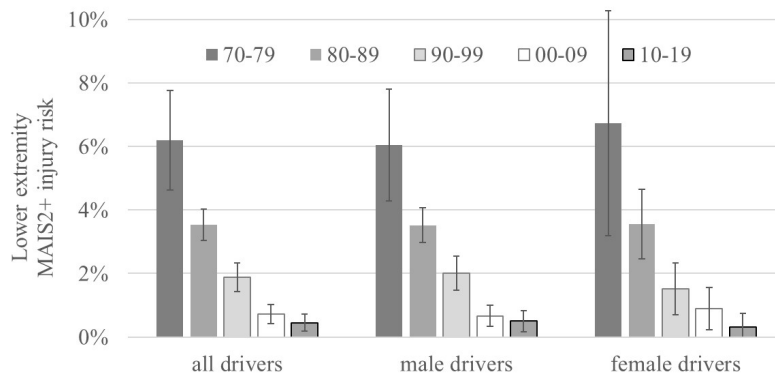
Small overlap crashes pose high risk for footwell intrusion. The measures addressing this, in addition to the measures addressing the guidelines for foot, ankle and leg injuries as in [21] are reflected in Figure 7c with reductions of MAIS 2+ lower extremity injury risks between the 80s and 00s car models. This applies to both sexes. This is further elaborated in [22].



**Figure 7a. Head MAIS2+ injury risk, including 95% confidence intervals, for the five car model year decades, for all restrained drivers and for female and male drivers separately, in frontal impacts. Background data in Appendix, Table A6.**



**Figure 7b. Chest MAIS2+ injury risk, including 95% confidence intervals, for the five car model year decades, for all restrained drivers and for female and male drivers separately, in frontal impacts. Background data in Appendix, Table A7.**

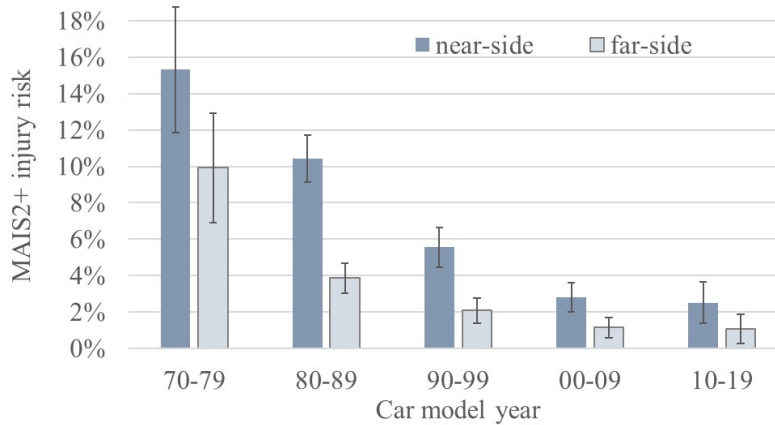


**Figure 7c. Lower extremity MAIS2+ injury risk, including 95% confidence intervals, for the five car model year decades, for all restrained drivers and for female and male drivers separately in frontal impacts. Background data in Appendix, Table A8.**

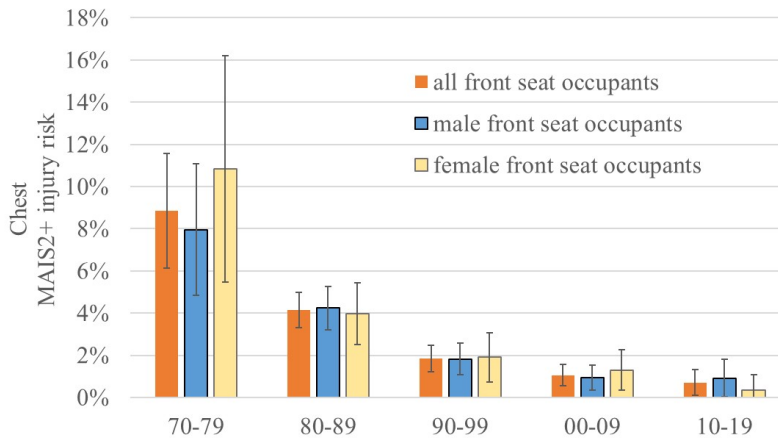
### Side Impacts

For the side impact analysis, the drivers and front seat passengers are grouped together as front seat occupants and analyzed with respect to being seated on the struck side (near-side) or non-struck side (far-side) at impact. MAIS2+ injury risks for these two groups are shown for the five car model year decades in Figure 8. For both, a general reduction in injury risk is seen over the years. Comparing the last decade (2010-2019) with the first (1970-1979), injury reducing effects of 84% (73% - 90%) for near-side and 89% (76% - 95%) for far-side front seat occupants are seen. Consistently over the decades, there are lower injury risks when seated on the non-struck side as compared to the struck side.

Addressing near-side side impacts, Figure 9 shows the chest MAIS2+ injury risk for the five car model year decades, for all front seat occupants and for female and males separately. The chest injury reduction follows in line with the introduction of advancement steps during the 90s, taking a significant step from the 80s to the 00s model year cars.



**Figure 8. MAIS2+ injury risk, including 95% confidence intervals for the five car model year decades, for front seat occupants in near-side and far-side side impacts, respectively. Background data in Appendix, Table A9.**



**Figure 9. Chest MAIS2+ injury risk, including 95% confidence intervals for the five car model year decades, for all front seat occupants and for male and female separately in near-side side impacts. Background data in Appendix, Table A10.**

## DISCUSSIONS

To provide equal occupant protection, the heterogeneous population of people and the diversity of crashes need to be included and addressed. This study included a variation of crash types (such as frontal, side and car-to-large animal crashes), seat positions (front versus rear seat, struck versus non-struck side) and occupant characteristics, represented by sex. The rationale for this approach was to provide examples from a range of aspects illustrating the feasibility of the Circle of Life, leading up to the aggregated progress of occupant protection over the car model years, as exemplified by driver MAIS2+ injury risks in Figure 3.

The principles of the Circle of Life are not unique. The working process follows the principles of PDSA (plan, do, study, act) cycle, also called Deming cycle, introduced by Edwards Deming a century ago. This is a continual improvement process commonly used for quality improvements within product development industries, emphasizing the importance of consumer research for guiding the redesigning of products or services. When applied in car safety developments in general, and occupant protection specifically, the core is to understand the injury mechanisms and to identify protection principles based on those. With such a human-centric approach using the Circle of Life, novel

solutions may be found and leverage the next car generation, this more than if just adhering to standardized targets in legal or third-party testing.

With the purpose of learning from the past, moving forward, the objective of this study was to present and discuss a working process that can generate equal occupant protection. When addressing injury mechanisms and protection principles derived from real-world crashes, they naturally include heterogeneity of the occupants and their seating. An example of a decision, for which real-world understanding was essential, was the placement of the SIPSbag. The choice of positioning it in the side of the seatback, instead of in the door panel, was because it would then be in a better position for a larger group of occupant sizes and their selected seat positions [25]. With such an understanding and mindset, equal occupant protection can be achieved, as illustrated by comparable chest AIS2+ injury risks for females and males in Figure 9. Similar female versus male trends is also seen in Figures 3, 6 and 7, providing examples that a human-centric and real-world crash data driven process like the Circle of Life may representatively address the occupant population.

The large and statistically significant step in near-side side impact MAIS2+ injury reductions seen between the car model years 80s to the 00s are due to the stepwise integration of the SIPS, SIPSbag and IC during the 1990s. The current study may not provide injury reducing effects of these steps of introduction, since the data selection is based on year model decades. Instead, homogeneous generation-based car models groups matching the introduced side impact systems need to be compared. This was done in [33] showing that compared to the baseline (car models just prior to SIPS introduction), the MAIS2+ injury reducing effects of the SIPS was 54%, followed by 61% when combining SIPS and SIPSbag, and 72% for the first car generation including IC together with refined SIPS and SIPSbag. SIPS most likely also contributed to statistically significant reduced MAIS2+ injury risks for the occupants on the non-struck side between car model years 80s to the 00s, as well. The main injury mechanisms for those occupants are impacts into the interior. Especially for car models prior to SIPS, extensive deformations of the struck side were seen in side impacts, with an increased risk also for the occupant on the non-struck side. Other countermeasures include activation of seatbelt pre-tensioners in side impacts. However, the recent introduction of airbags between the front seats cannot be assessed by the dataset included in the current study.

The evolution in frontal impacts is only covered briefly in this study, pointing out some important steps of countermeasures and structural improvements. This is likely the crash type which is most influenced by legal requirements and third-party test assessment. It is beyond the scope of the current study to try to assess this degree of influence. However, an example of the Circle of Life process is the introduction of countermeasures for small overlap crashes already in the 90s [19], while it wasn't until 20 years later that such standardized method was implemented by the Insurance Institute of Highway Safety as third-party testing. This influences MAIS2+ injury risks in Figure 6 as well as seen for the lower extremity injury risks in Figure 7c for the step between 80s to 90s. Another example is the continued focus on the foot, ankle and leg injuries, introducing several countermeasures to address the protection principles as listed in [21], confirmed by [22] and also seen in Figure 7c for the step between the 90s and 00s.

As seen in Figure 4, early introduction of rear seat countermeasures, with no external driving force, helped to keep the rear seat protection on par with the front seat occupants, for which the external drivers such as legal requirements and third-party assessment were more available. The lack of external drivers for rear seat protection was reflected on by [34]. Using NASS data, they compared restrained front and rear seat occupants and calculated a relatively higher MAIS3+ injury risk for rear seat passengers (aged 16-50) for model years 1997-2007, while equal risk for the model years 1990-1996, proposing that the rear seat occupant protection has not kept pace with front seat safety improvements.

Another example of occupant protection going beyond the standardized testing context is the car-to-large animal crashes. Especially in parts of North America, northern Asia and northern Europe, crashes with large animals, like moose, elk and large deer, are frequent. There are also other large animals like horses, cattle and camels, making these types of crashes globally relevant. In the current study, the most frequent large animal crash type was that with a moose. The typical characteristic of a moose is a high center of gravity due to its long and slim legs. These legs will have limited interaction with the car front. Therefore, the speed reduction is very low, and the header and A-pillar area is where the bulk of the moose body is engaging. This special load case and the potential consequences of head, neck and upper extremity injuries due to interaction with intruding roof structures, or direct interaction with the body of the

moose into the compartment, were identified in early real-world data studies. Since then, continuous structural performance of the header and A-pillars were made to Volvo cars and large-animal test methods have been developed [17]. These improvements are reflected by the MAIS2+ injury risk reductions seen over the five car model year decades from 7% during the 70s to less than 1% for the 10s (Appendix, Table A4).

One strength in the present study is the access to a crash dataset that is collected consistently over all these years, including well-controlled car models. Over the years, the variations between the concurrent Volvo models have been small. They may vary somewhat in size, weight and height, but they all adhere to similar internal safety standards, meaning that learnings are implemented in new models, irrespective of size/type.

Limitations include the difficulties of comparable data collection over this long range of years. The selection criterion based on repair cost limit was chosen to reflect a crash severity level, enabling injury risk comparisons. Obviously, it is challenging over time to calibrate the repair cost limit to crash severity, especially during more recent years as more advanced technologies have been introduced that may be costly to repair if damaged. In addition, the changes in frequency of the different crash types over the years skew the total severity in the data, exemplified by the reduction of roll- and turnover crashes. The lack of good severity measures for all crash types of such a long-time span is also challenging, thereby the only comparison possible to make for all these years was for frontal impacts, using EBS (Figure 2). As seen, there is a slight trend towards reduced crash severity in frontal impacts, in more recent years, which should be kept in mind in the analysis.

The data is based on one car brand and crashes in one country only. Thereby it is difficult to generalize the results from the real-world data graphs. The traffic situations in Sweden may differ from other countries. In addition, the traffic situation has also changed over the 50 years of the data in this study. Hence, overall safety improvements of the traffic system may account for part of the injury reduction over the years, however this is difficult to estimate using the graphs since accident years are not consistent with car model years. This study does not provide generalized conclusions regarding the safety of the whole car fleet. From that perspective this may be perceived as a limitation, however with the objective and focus of this study, a well-controlled car model set was a prerequisite.

Another limitation is that the results in this study are difficult to compare with other datasets, spanning for over 50 years and with a unique set-up with respect to car models and country. Using a national Swedish dataset, [5] could observe similar injury reducing trends over parts of the time span covered in the current study. However, as mentioned by [5] the high market share of Volvo cars in Sweden, and hence their data, may have influenced the results.

Significant real-world occupant protection steps were taken throughout the 50 years covered in this study. The development and implementation of standardized crash testing have increased over these years. However, the standardized tests reflect only a limited part of the whole spectrum of crash situations, occupant characteristics and injury mechanism. They cannot alone explain the substantial and wide reduction of injury risks seen in this study. Instead, the human-centric and real-world crash driven process, the Circle of Life, has helped to address the heterogeneous population and the diversity of crashes. This was done through analysis of the injury mechanisms, understanding and focusing on the most vulnerable combination of occupant and crash characteristics. The analyses were supported by exposure-based methodologies addressing and assessing varieties in crash severity and occupant characteristics [14, 15]. By addressing those combinations and adhering to defined protection principles, the other combinations were addressed as well, enhancing equal occupant protection.

The five decades of crash data provided evidence of continuous MAIS2+ injury risk reduction, overall as well as for females and males separately. Exemplified by car safety advancement steps and the background for those steps, the Circle of Life was shown to be efficient. The advancements were driven by understanding the injury mechanisms, defining the protection principles and assessed using a variety of methodologies.

The challenges ahead, in addition to changes in the demographics, such as an aging population and a trend of people with higher BMI, include an even higher focus on more complex crashes as well as more unique combinations [11]. This is supported by the data in Figure 5b for the last decades which show that occupant protection in multiple event crashes has not been addressed in line with the other crash types. This is a highly variable group of crashes, with the common denominator of being exposed to more than one impact or event. This makes them complicated, varied and

not easily assessed by singular tests. That is, optimizing towards a number of singular individual sizes in singular sitting postures and crash situations, such as most current standardized crash tests, may not help in driving such car safety developments forward. The challenge with more unique cases is a result of efficient safety work over the years. To address this, tools and methods replicating a larger variety of crash characteristics and occupant variability are necessary. In addition, the rapid implementation of collision mitigation technologies calls for methods and tools encompassing the whole crash events, including maneuvers as well as multiple events. This, however, adds to the complexity of car safety assessment. Fortunately, this information can be found in the real-world data and by applying the principles of Circle of Life more complex crashes can be addressed step by step in car safety developments. Moving forward, targeting even further needs of robust protection for a variation of individuals in different seating and crashes, such a car safety development working process using real-world data is deemed suitable.

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## APPENDIX A

*Table A1.*

*Data for Figure 3. Restrained drivers per car model year decade, and corresponding MAIS2+ injury risks (95% confidence intervals) in %.*

	All drivers		Male drivers		Female drivers	
	N	MAIS2+ injury risk	N	MAIS2+ injury risk	N	MAIS2+ injury risk
<b>70s</b>	2647	10.0 (± 1.14)	2047	9.3 (± 1.26)	600	12.3 (± 2.63)
<b>80s</b>	14185	7.3 (± 0.43)	11065	7.0 (± 0.48)	3120	8.3 (± 0.97)
<b>90s</b>	9642	4.2 (± 0.40)	7266	4.1 (± 0.46)	2376	4.4 (± 0.83)
<b>00s</b>	9381	2.9 (± 0.34)	6931	2.7 (± 0.38)	2450	3.3 (± 0.70)
<b>10s</b>	5765	2.0 (± 0.37)	4153	2.0 (± 0.43)	1612	2.1 (± 0.70)
<b>Total</b>	<b>41620</b>		<b>31462</b>		<b>10158</b>	

*Table A2.*

*Data for Figure 4. Restrained drivers, front seat passengers and rear seat passengers per car model year decade, and MAIS2+ injury risks (95% confidence intervals) in %.*

	Drivers		Front seat passengers		Rear seat passengers	
	N	MAIS2+ injury risk	N	MAIS2+ injury risk	N	MAIS2+ injury risk
<b>70s</b>	2647	10.0 (± 1.14)	955	11.4 (± 2.02)	161	6.2 (± 3.73)
<b>80s</b>	14185	7.3 (± 0.43)	4903	8.7 (± 0.79)	1942	6.4 (± 1.09)
<b>90s</b>	9642	4.2 (± 0.40)	3034	4.5 (± 0.74)	1416	4.0 (± 1.02)
<b>00s</b>	9381	2.9 (± 0.34)	2618	2.9 (± 0.65)	1057	1.7 (± 0.78)
<b>10s</b>	5765	2.0 (± 0.37)	1439	2.4 (± 0.78)	500	2.2 (± 1.29)
<b>Total</b>	<b>41620</b>		<b>12949</b>		<b>5076</b>	

**Table A3.**  
**Data for Figures 5a and 5b. Number of cases and number of MAIS2+ injured for restrained drivers per car model year decade and crash type.**

	70s		80s		90s		00s		10s	
	Total	MAIS2+ injured	Total	MAIS2+ injured	Total	MAIS2+ injured	Total	MAIS2+ injured	Total	MAIS2+ injured
Run-off road	88	3	288	18	561	13	611	14	128	3
Side swipe	69	6	194	9	252	5	688	4	652	3
Near-side side impact	331	44	1653	158	1393	73	1336	36	586	15
Far-side side impact	266	29	1470	53	1052	20	955	10	484	3
Rear-end impact	159	6	1182	19	759	8	663	15	401	7
Frontal impact	908	99	5432	431	3521	162	3070	106	2449	57
Roll-/turnover	313	22	1005	87	283	12	83	2	20	2
Multiple crashes	431	43	2368	201	1367	91	1367	64	460	21
Large animal	71	5	551	30	462	14	631	13	573	4
Other	32	7	99	27	42	7	47	5	28	3
<b>Total</b>	<b>2668</b>	<b>264</b>	<b>14242</b>	<b>1033</b>	<b>9692</b>	<b>405</b>	<b>9451</b>	<b>269</b>	<b>5781</b>	<b>118</b>

**Table A4.**  
**MAIS2+ injury risks (95% confidence intervals) in % for restrained drivers per car model year decade and crash type, same cases as in Table A3.**

	70s	80s	90s	00s	10s
Run-off road	3.4 (± 3.79)	6.3 (± 2.80)	2.3 (± 1.25)	2.3 (± 1.19)	2.3 (± 2.62)
Side swipe	8.7 (± 6.65)	4.6 (± 2.96)	2.0 (± 1.72)	0.6 (± 0.57)	0.5 (± 0.52)
Near-side side impact	13.3 (± 3.66)	9.6 (± 1.42)	5.2 (± 1.17)	2.7 (± 0.87)	2.6 (± 1.28)
Far-side side impact	10.9 (± 3.75)	3.6 (± 0.95)	1.9 (± 0.83)	1.0 (± 0.65)	0.6 (± 0.70)
Rear-end impact	3.8 (± 2.96)	1.6 (± 0.72)	1.1 (± 0.73)	2.3 (± 1.13)	1.7 (± 1.28)
Frontal impact	10.9 (± 2.03)	7.9 (± 0.72)	4.6 (± 0.69)	3.5 (± 0.65)	2.3 (± 0.60)
Roll-/turnover	7.0 (± 2.83)	8.7 (± 1.74)	4.2 (± 2.35)	2.4 (± 3.30)	10.0 (± 13.15)
Multiple crashes	10.0 (± 2.83)	8.5 (± 1.12)	6.7 (± 1.32)	4.7 (± 1.12)	4.6 (± 1.91)
Large animal	7.0 (± 5.95)	5.4 (± 1.89)	3.0 (± 1.56)	2.1 (± 1.11)	0.7 (± 0.68)

**Table A5.**

**Data for Figure 6. Restrained drivers in frontal impacts per car model year decade, and corresponding MAIS2+ injury risks (95% confidence intervals) in %.**

	All drivers		Male drivers		Female drivers	
	N	MAIS2+ injury risk	N	MAIS2+ injury risk	N	MAIS2+ injury risk
<b>70s</b>	904	11.0 (± 2.04)	711	10.8 (± 2.28)	193	11.4 (± 4.48)
<b>80s</b>	5414	8.0 (± 0.72)	4319	7.7 (± 0.79)	1095	9.1 (± 1.71)
<b>90s</b>	3503	4.6 (± 0.70)	2646	4.7 (± 0.81)	857	4.3 (± 1.36)
<b>00s</b>	3037	3.5 (± 0.65)	2254	3.2 (± 0.73)	783	4.2 (± 1.41)
<b>10s</b>	2441	2.3 (± 0.60)	1793	2.2 (± 0.68)	648	2.8 (± 1.27)
<b>Total</b>	<b>15299</b>		<b>11723</b>		<b>3576</b>	

**Table A6.**

**Data for Figure 7a. Restrained drivers in frontal impacts per car model year decade, and corresponding MAIS2+ head injury risks (95% confidence intervals) in %.**

	All drivers		Male drivers		Female drivers	
	N	MAIS2+ head injury risk	N	MAIS2+ head injury risk	N	MAIS2+ head injury risk
<b>70s</b>	904	4.0 (± 1.27)	711	3.7 (± 1.38)	193	5.2 (± 3.13)
<b>80s</b>	5414	3.0 (± 0.46)	4319	2.8 (± 0.49)	1095	4.0 (± 1.16)
<b>90s</b>	3503	1.7 (± 0.42)	2646	1.4 (± 0.44)	857	2.6 (± 1.06)
<b>00s</b>	3037	0.8 (± 0.31)	2254	0.7 (± 0.35)	783	1.0 (± 0.70)
<b>10s</b>	2441	0.9 (± 0.37)	1793	0.8 (± 0.42)	648	1.1 (± 0.80)
<b>Total</b>	<b>15299</b>		<b>11723</b>		<b>3576</b>	

**Table A7.**

**Data for Figure 7b. Restrained drivers in frontal impacts per car model year decade, and corresponding MAIS2+ chest injury risks (95% confidence intervals) in %.**

	All drivers		Male drivers		Female drivers	
	N	MAIS2+ chest injury risk	N	MAIS2+ chest injury risk	N	MAIS2+ chest injury risk
<b>70s</b>	904	3.9 (± 1.26)	711	3.7 (± 1.38)	193	4.7 (± 2.97)
<b>80s</b>	5414	2.6 (± 0.42)	4319	2.6 (± 0.47)	1095	2.6 (± 0.95)
<b>90s</b>	3503	1.6 (± 0.42)	2646	1.7 (± 0.49)	857	1.3 (± 0.75)
<b>00s</b>	3037	1.3 (± 0.40)	2254	1.3 (± 0.47)	783	1.0 (± 0.70)
<b>10s</b>	2441	0.8 (± 0.36)	1793	0.8 (± 0.42)	648	0.8 (± 0.67)
<b>Total</b>	<b>15299</b>		<b>11723</b>		<b>3576</b>	

**Table A8.**

*Data for Figure 7c. Restrained drivers in frontal impacts per car model year decade, and corresponding MAIS2+ lower extremity (LX) injury risks (95% confidence intervals) in %.*

	All drivers		Male drivers		Female drivers	
	N	MAIS2+ LX injury risk	N	MAIS2+ LX injury risk	N	MAIS2+ LX injury risk
<b>70s</b>	904	6.2 (± 1.57)	711	6.0 (± 1.75)	193	6.7 (± 3.54)
<b>80s</b>	5414	3.5 (± 0.49)	4319	3.5 (± 0.55)	1095	3.6 (± 1.10)
<b>90s</b>	3503	1.9 (± 0.45)	2646	2.0 (± 0.53)	857	1.5 (± 0.82)
<b>00s</b>	3037	0.7 (± 0.30)	2254	0.7 (± 0.34)	783	0.9 (± 0.66)
<b>10s</b>	2441	0.5 (± 0.27)	1793	0.5 (± 0.33)	648	0.3 (± 0.43)
<b>Total</b>	<b>15299</b>		<b>11723</b>		<b>3576</b>	

**Table A9.**

*Data for Figure 8. Restrained front seat occupants in side impacts per car model year decade. and corresponding MAIS2+ injury risks (95% confidence intervals) in %.*

	Near-side front seat occupants		Far-side front seat occupants	
	N	MAIS2+ injury risk	N	MAIS2+ injury risk
<b>70s</b>	418	15.3 (± 3.45)	383	9.9 (± 2.99)
<b>80s</b>	2121	10.4 (± 1.30)	2098	3.9 (± 0.82)
<b>90s</b>	1730	5.5 (± 1.08)	1543	2.1 (± 0.71)
<b>00s</b>	1605	2.8 (± 0.81)	1397	1.1 (± 0.56)
<b>10s</b>	717	2.5 (± 1.15)	656	1.1 (± 0.79)
<b>Total</b>	<b>6591</b>		<b>6077</b>	

**Table A10.**

*Data for Figure 9. Restrained near-side front seat occupants in side impacts per car model year decade and corresponding MAIS2+ chest injury risks (95% confidence intervals) in %.*

	Near-side front seat occupants		Males		Females	
	N	MAIS2+ chest injury risk	N	MAIS2+ chest injury risk	N	MAIS2+ chest injury risk
<b>70s</b>	418	8.9 (± 2.72)	289	8.0 (± 3.12)	129	10.9 (± 5.37)
<b>80s</b>	2121	4.1 (± 0.85)	1440	4.2 (± 1.04)	681	4.0 (± 1.47)
<b>90s</b>	1730	1.8 (± 0.63)	1205	1.8 (± 0.76)	525	1.9 (± 1.17)
<b>00s</b>	1605	1.1 (± 0.50)	1066	0.9 (± 0.58)	539	1.3 (± 0.96)
<b>10s</b>	717	0.7 (± 0.61)	440	0.9 (± 0.89)	277	0.4 (± 0.71)
<b>Total</b>	<b>6591</b>		<b>4440</b>		<b>2151</b>	