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Equitable Occupant Protection - The effect of occupant characteristics on injury severity outcomes

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Executive Summary

Considerable improvements have been made in car occupant protection since regulatory crash tests were first introduced in the UK and Europe in the late 1990s. Nevertheless, car occupants remain by far the largest group of road fatalities and injuries. There is a concern that modern vehicles may not be providing a similar level of crash protection to a wide range of occupant groups who use the car. Previous research has reported that occupant characteristics such as age, sex, height, weight, and body shape all affect the risk of sustaining a serious or fatal injury in a collision.

Real-world collision data from the Road Accident In-Depth Studies (RAIDS) database collected between 2013 and 2023 were used to investigate whether there is any evidence of inequity in injury outcomes for front-seated belted adult occupants due to occupant characteristics in similar crashes. RAIDS is the UK's in-depth collision data collection programme, designed to create an evidence base to support improved road safety. Multinomial logistic regression analyses were conducted to evaluate the role of occupant characteristics on overall and specific body region injury risks for belted adult front seat occupants in similar crashes.

Age was found to have a significant effect on overall maximum AIS injury in both frontal and side impacts. Older occupants were more prone to overall MAIS 2+ outcomes in both impact types. In frontal impacts, ageing increases the risk of sustaining a MAIS 2+ injury risk, in the head, thorax, and abdomen body regions. For side impacts, the thorax was the only body region where age had a significant effect and increased the risk of an injury outcome at MAIS 2+ level. These findings verified the continuing vulnerability of older occupants to moderate-severity injuries in a collision, suggesting that the injury protection assessed through regulatory procedures has to be revisited to consider the effect of ageing.

Occupant sex was found to have a significant effect on overall maximum AIS injury only in side impacts. The risk to females was significantly higher when compared to their male counterparts. Risk of lower extremity injuries to females were significantly higher than males in both frontal and side impacts. This trend of increased lower extremity injury risk to females has been consistently reported in previous research.

The findings of this study shows that occupant characteristics such as age and sex significantly influence injury severity outcomes while controlling for certain crash factors. Age and sex-specific injury risks outcome, particularly to thorax region for older occupants and lower extremity region for female occupants, suggests the need for crashworthiness improvements that can be addressed through regulatory and consumer crash testing programmes.

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1 Introduction

Considerable improvements have been made in car occupant protection since regulatory crash tests were first introduced in the UK and Europe in the late 1990s. Nevertheless, car occupants remain by far the largest group of road fatalities and injuries. It is also clear that occupant characteristics, including sex, age, occupant stature and size, injury tolerance and mechanical response of affected body regions, play an important role in injury severity outcomes. What is not well understood is the extent to which regulatory crash tests ensure equitable protection across these occupant characteristics.

For some time now, the safety community has been questioning the effectiveness of occupant protection for elderly vehicle occupants. The physiological tolerance, injury outcomes and crash exposures varies with age (Kent et al. 2009). Previous studies have shown that the biomechanical tolerance to injury declines with age, reducing the ability for the body to withstand blunt trauma. Using US National Automotive Sampling System - Crashworthiness Data System (NASS-CDS) data, Kent et al. (2005) found that as many as half of older drivers had sustained injuries that proved fatal, but which would likely have been survivable if sustained by a younger driver. The higher rate of thorax injury and associated mortality among older occupants have been reported by several authors (Ridella et al. 2012; Wisch et al. 2019; Ekambaram et al. 2019). Despite the significant improvements in vehicle crash structures and restraint systems, older occupants tend to sustain severe thorax injuries, even in a low/moderate speed crash, and are also increasingly susceptible to rib fractures (Kent et al. 2008; Morris et al. 2003; Ekambaram et al. 2019).

Males and females are physically different: biological and biomechanical properties such as anthropometric size, body composition, and injury tolerance vary between sexes. Females are generally underrepresented in fatal and serious motor vehicle crashes. Despite their lower crash involvement rate, studies have shown that, after adjusting for crash severities and other factors, females are most at risk of being killed or seriously injured in a crash (Welsh et al. 2001, Evans 2001, Bose et al. 2011, Parenteau et al. 2013) – noting that these studies do not include the data from recent vehicle designs. Females are in general smaller in stature compared to the males and they tend to sit closer to the front interior structure of cars and have previously been reported to be at higher risk of sustaining serious head, chest, and lower extremity injury in frontal collisions. In the latest study using NASS-CDS cases collected between 1998 and 2015, Brumbelow and Jermakian (2022) reported that after controlling for vehicle and crash differences, females remained at higher risk of MAIS 2+ injury, particularly to lower extremity injuries. Their study also reported that modern vehicles with improved crashworthiness have benefited females than males for most injury outcomes. However, it is not clear if the European crashes shows the similar trend.

Occupant body habitus can possibly influence the injury severity outcomes in a crash. The use of mid-sized crash test dummies (also known as anthropometric test devices, ATDs) in regulatory tests has significantly improved crash protection; however, the ATDs may represent a small proportion of the population over time due to increased incidence of obesity. Previous studies have examined the influence of BMI on injury risk in motor vehicle crashes, and they have reported differences in the injuries of occupants with obesity attributed to their different interactions with restraint systems and vehicle interiors when compared to non-obese occupants – noting that many studies combine both belted and unbelted occupants. Viano et al. 2008, suggested that obese occupants tend to have higher injury risks as they possess more kinetic energy in a crash, and they need greater restraining forces to reduce excursion. Kent et al. (2010) performed sled tests at 48km/h impact using obese and non-obese cadavers in three-point belted configurations. They reported that the higher excursion of the hip, and concomitant decreased torso pitch may reduce the chance of head striking vehicle interiors. However, this noticed kinematics was suggested to induce rib and pulmonary trauma due to concentrated seatbelts acting on the lower thorax and upper ribs and clavicle. Studies using US crash data have reported higher risks of spinal, thoracic and extremities injuries to obese occupants (Rupp et al. 2013 and Joodaki et al. 2019).

Ensuring transport is safe, reliable, and inclusive is central to the DfT's aim to develop and deliver a transport network that works for everyone. DfT wishes to support the new UN Informal Working Group on Equitable Occupant Protection, maximising the UK's contribution to global efforts to ensure regulations deliver equitable safety outcomes. The objective of this study is to establish whether there is any evidence of inequity in injury outcomes for seat-belted adult occupants due to characteristics such as sex, age, height, and weight in similar frontal and side impact crashes using UK in-depth collision data.

2 Methods

2.1 Road accident in-depth studies (RAIDS)

The UK Road Accident In-Depth Studies (RAIDS)[1] data collected from 2013 was used in this study. RAIDS is the UK's in-depth collision data collection program designed to create the evidence base to support improved road safety. RAIDS is managed by TRL on behalf of the Department for Transport. The study provides detailed evidence on the causes and consequences of road collisions in order to improve road safety outcomes.

RAIDS investigations differ from those of the police because they are designed to understand all factors influencing a collision and its outcome rather than necessarily determine responsibility. Typically, the RAIDS team will investigate around 200 cases per year; these are a mix of investigations carried out at the live collision scene and retrospective investigations based on vehicle examinations and analysis of police collision reports. RAIDS contains over 3000 fields of detailed information about the vehicles involved, the injuries sustained, the circumstances leading up to the collision and the environment of the collision. This information is held in a single comprehensive database, which provides an invaluable evidence-based research tool which is used extensively in road safety improvement programmes, medical research, vehicle standards and design.

The RAIDS data supports a very wide range of road safety analyses such as improved Vulnerable Road User (VRU) protection (e.g. helmet performance, test scenarios for Advanced Emergency Braking (AEB) with pedestrian and cyclist detection, windscreen impacts), safer roadside infrastructure, improved occupant restraint systems, test scenarios for automated vehicles and many others. Since the start of RAIDS, over 100 research studies have accessed RAIDS for research on various topics.

The injury information is recorded within the RAIDS database using the Abbreviated Injury Scale (AAAM 2015). The Abbreviated Injury Scale (AIS) is an anatomically based injury coding technique developed by the Association for the Advancement of Automotive Medicine (AAAM) to classify and describe the severity of injuries. The AIS is a seven-digit numeric code that contains information about the individual injury's severity and the injury location on the body – the first 6 digits uniquely identify each type of injury, and the final digit (the AIS score) indicates the 'threat to life'. The threat to life scale is on a 6-point ordinal scale ranging from minor (AIS 1) to currently untreatable (AIS 6) and are as follows:

- 1 = minor injuries
- 2 = moderate injuries
- 3 = serious injuries
- 4 = severe injuries

[1] https://www.gov.uk/government/publications/road-accident-investigation-road-accident-in-depth-studies/road-accident-in-depth-studies-raids

- 5 = critical injuries
- 6 = untreatable injuries (usually non-survivable)

The AIS is also the basis for the Maximum AIS (MAIS) measure. The MAIS is the highest single AIS injury that a person with multiple injuries has sustained. The MAIS for the occupant is always either equal to or greater than the AIS value for the injury in the individual region.

2.1.1 Selection Criteria

Selection criteria were applied to the RAIDS data to choose a sample containing relevant collisions for frontal and side impacts. This allows to examine the effect of occupant age and sex on overall and specific body region injury risks while controlling the influence of vehicle and crash characteristics on the injury risks.

Frontal impact with the principal direction of force (PDOF) between 11 and 1 o'clock was included for the frontal analysis. The PDOF uses the clock face, where a 12 o'clock impact would be directly into the front of the vehicle, 11 o'clock and 1 o'clock would be angled 30° from the longitudinal vehicle axis on the left and right side respectively. Impacts with the PDOF at 10 or 2 o'clock were not considered because there is a likely chance of the seatbelt slipping from the occupant's shoulder and the occupant missing the airbag due to significant lateral components in the occupant's motion. Side impacts were defined as those with a primary side impact (CDC- Side = L or R) with PDOF 2, 3, 4, 8, 9 or 10. In the case of a multiple impact collision, the impact determined to be the most significant in causing injuries was selected for the frontal or side impact datasets, respectively. If a vehicle sustained multiple impacts in a collision, then the impact which was determined to be the most significant in causing injuries was selected for the study. For this, RAIDS code Phase Significance was set as 'most severe'. Table 1 details the initial filtering applied to RAIDS cases to select occupants in frontal and side impacts.

Table 1: Initial selection criteria applied to frontal and side impact cases

Selection criteria for frontal impact crashes	Selection criteria for side impact crashes
The collision type is either: Car impact with another Car or Car impact with an LGV or a single vehicle car crash	
Principal Direction of Force (PDOF) = 11, 12 or 1 o'clock (i.e. impact point is the front of the occupants' vehicle)	Principal Direction of Force (PDOF) = 2, 3, 4, 8, 9 or 10 (i.e. impact point is the side of the occupants' vehicle)
Collision Deformation Classification = Front	Collision Deformation Classification = Left side or Right side
Phase Significance = Most Severe	

This filtering resulted in 1,442 frontal impact occupants and 413 side impact occupants being selected from the RAIDS database for further consideration.

A number of secondary filters were then applied to ensure that the cases included in the final modelling were as comparable as possible and didn't include any missing data. For the current study, only vehicles manufactured from the year 2004 were considered. Those vehicles comply with the international frontal and side impact protection regulations (UN Regulations 94 and 95). Only belted driver and front seat passengers, ages above 16 years, were included. Pregnancy may change how restraint systems interact with the body in the event of a crash and thus influence injury outcomes. Therefore, pregnant females were not included for further analysis.

Vehicles that rolled over in a crash and those coded as underrun or overrun in the RAIDS sample were not included. Only cases with known injury outcomes in terms of AIS were selected for further analysis. In addition, for the frontal impact sample, a crash was included if Energy Equivalent Speed (EES) was known. The EES is equivalent to the energy consumed in a collision to cause vehicle deformation, an energy-based measure of crash severity. Applying this filter to the side impact sample reduced the cases available for modelling by a substantial number; as a result, it was decided to leave this variable as a predictor in the side impact models. A collision was selected from the sample only if the information on injury outcomes in terms of AIS was available. The results of the secondary filtering are detailed in Section 3.1 (for frontal impacts) and Section 3.2 (for side impacts).

Note that the recording rate of occupant height, weight (and therefore BMI) in the medical data was not high enough to support analysis of the effect of these characteristics on injury outcome. Therefore, they are not included in the subsequent analysis. Also, there is no separate analysis for rear impacts data. After applying the relevant selection criteria and filtering for this, only 72 occupants remained in the dataset. This is insufficient for producing statistically robust findings from a multinomial logistic regression model.

2.2 Multinomial Logistic Regression

Regression models enable us to understand the relationships present between a set of *predictor* variables (such as age and sex) and a *response* variable - in this case injury severity. These models can quantify the effect of each individual predictor variable on the response variable (injury severity) and inform us whether this effect is statistically significant[2] or not.

At a simple level, these models represent injury severity as a linear combination of the predictor variables, for example:

$$Injury\ severity\ = \beta_0 + \beta_1\, age + \beta_2\, gender\ + \cdots + \epsilon.$$

In the above equation, the β's are coefficients that capture the size of the effect of each predictor variable while the ϵ is random noise. The model calculates these β coefficients.

[2] Throughout the modelling we use the well-established convention that a result is statistically significant if its p-value is less than 0.05.

In this analysis, the injury severity variable takes values from one of three MAIS categories: 0, 1 and 2+[3]. In other words, it is categorical and must always take one of those discrete values. This requires the use of a different form of regression model: a multinomial logistic regression model.

In multinomial models, a logistic transformation of the odds (referred to as the logit) is used:

$$\log(odds) = logit\ (p) = \ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1\ age + \beta_3 gender + \cdots + \epsilon.$$

In this equation the β's are coefficients as before, ϵ is random noise and p is the probability that the occupant falls into a particular injury severity (MAIS) category.

The research question of interest for this modelling is:

> *When collision involved vehicle occupants are injured (classified using MAIS categories), how do their characteristics (age and sex) affect the injury outcome when controlling for other variables (e.g. impact speed, collision partner), which are also known to affect severity?*

As a result, age and sex are always included in the models, and other variables which are known to affect injury severity have also been considered and included (where they significantly improve the model fit). Full details of these variables for the frontal and side impact modelling are documented in Sections 3.1 and 3.2 respectively. In addition to these variables, an interaction term between age and sex was also tested but was not found to significantly improve the model fit for either of these models.

Statistical modelling is an iterative process to determine the 'best' model for a given set of data. To develop the models, all the independent variables of interest were included in the first model. With the exception of age and sex, if the variable was not contributing significantly to improve the fit of the model (determined using a likelihood ratio test) then this variable was removed in subsequent iterations.

Throughout the modelling iterations, the classification rate (percentage of occupants which were correctly classified by the model into the 'correct' MAIS group) and pseudo-R squared values (a measure of the strength of the relationship between the predictor variables and the response variable) were checked to ensure the decision to include or exclude a variable was based on the fit to the data.

The classification rates for the final models produced are presented in the subsequent sections. Since these models are explanatory (to understand the strength and direction relationship between the predictor variables and injury severity) rather than being used for predictive purposes, these values are for information only.

[3] These are the Maximum Abbreviated Injury Scale (MAIS) groupings used in the models in Section 0 and Appendix A. Based on the sample size of cases, a decision was made to group MAIS scores of 2, 3, 4, 5 and 6 into the category 2+ to ensure the sample size in each category was robust. A MAIS score of 0 represents uninjured occupants.

2.2.1 Body region models

In addition to the main models for the overall occupant MAIS scores (presented in Section 3), additional models for the MAIS in each of the following body regions are presented in Appendix A:

- Head
- Thorax
- Abdomen
- Lower extremities (left and right leg)
- Other regions (neck, pelvis, left arm, right arm and 'other' regions)

These models were not developed in the same way as the main models (i.e. testing combinations of variables to see which ones should be included in the 'best' model), but simply use the variables selected in the final models presented in Section 3 as the predictors, with the relevant MAIS body region score for each occupant as the response. This means that the body region models can easily be compared to the main models to see if different predictors are significant or not. The commentary in the appendix provides this comparison.

3 Results

This section presents the data filtering, exploratory analysis and modelling results for the frontal impacts data (Section 3.1) and the side impacts data (Section 3.2).

3.1 Frontal Impacts

The initial filtering to frontal impacts resulted in 1,442 occupants in the dataset. Table 2 summarises the number of occupants after each of the secondary filters (described in Section 2.1.1) were applied.

Table 2: Secondary filters applied to the frontal impact dataset

Filters applied	Number of occupants
Frontal impact occupants (before secondary filtering):	**1,442**
Remove vehicles from 2003 and earlier	1,232
Remove occupants under 16 (and with unknown age)	1,043
Remove occupants of unknown sex or pregnant females	1,034
Front seated occupants only	962
Remove unbelted occupants	808
Remove cases with any rollover	775
Remove any cases with underrun	709
Known EES value	435
Known Occupant MAIS (0-6) (final sample for modelling)	**376**

3.1.1 Exploratory data analysis

Figure 1 (a) shows the distribution of MAIS scores in the final sample: there are relatively few 2, 3, 4, 5 and 6 scores so a decision was made to group the response variable of interest (MAIS score) into three groups: 0, 1 and 2+ (as shown in Figure 1 (b)).

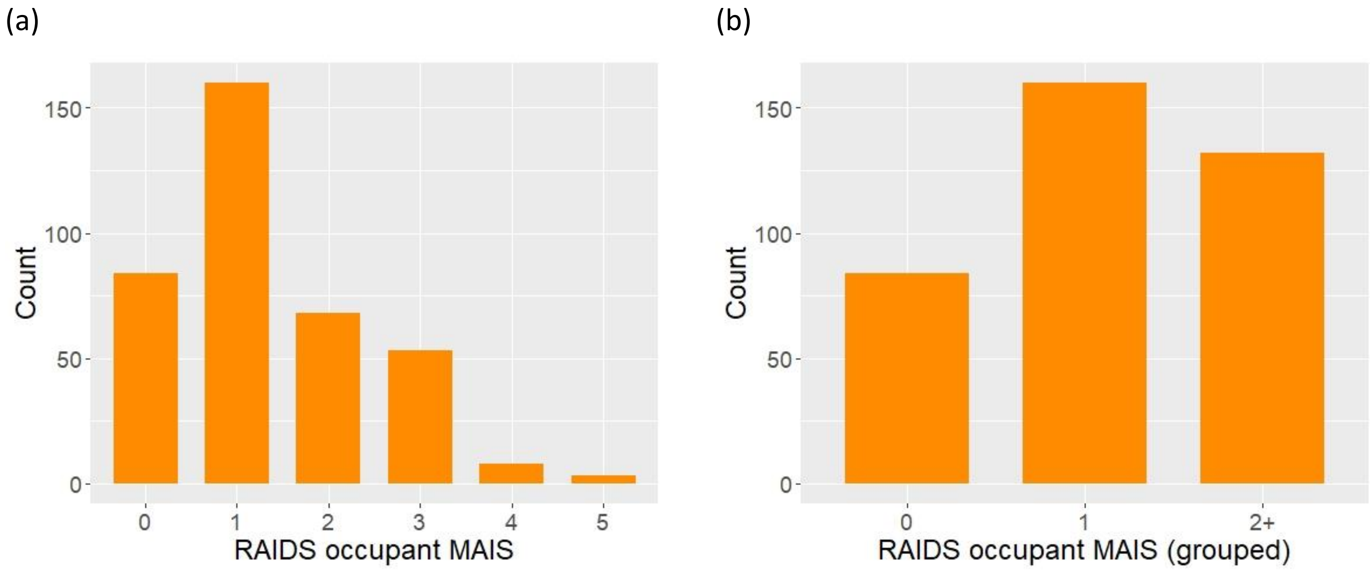

Figure 1: Distribution of (a) raw and (b) grouped MAIS scores for frontal impact occupants included in the final sample (N=376)

Based on the literature and the factors known to influence injury severity, the following variables were considered as predictive variables for the frontal impacts model:

- Age[4] and sex (the key variables of interest) – to investigate differences in injury outcomes for different occupant characteristics.
- Principal direction of force (11, 12 or 1) – to investigate if the angle of impact influences injury outcomes.
- EES – to account for the crash severity on injury outcomes.
- Seating position (driver or front seat passenger) – restraint system and loading can differ between these two positions, so this variable was included to account for any differences in injury outcomes.
- Collision partner type (car/LGV, narrow object, wide object, other) – the mass and dimension of the collision partner determines the forces experienced by the occupants in a crash and hence different injury outcomes.
- Height and weight of the occupant – these variables were considered for inclusion but 56-60% of cases were unknown so these could not be considered further.

Figure 2 shows a boxplot of the distribution of ages by the three MAIS groups. This suggests there may be some effect of increasing age increasing injury severity; for example, the

[4] A linear term for age, a quadratic term for age and a categorical age variable were all tested during the modelling to see which one fitted the data best. The linear age term was found to be the best fit.

median age (horizontal line in the middle of the box) increases across the three MAIS groups (from 36 years (MAIS 0), 41 years (MAIS 1) to 50.5 years (MAIS 2+).

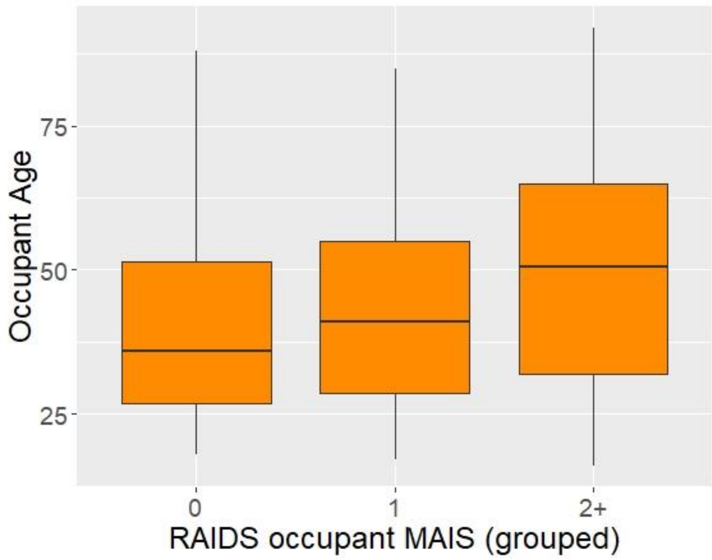

Figure 2: Distribution of occupants in final frontal impacts sample by Age and MAIS (grouped)

Figure 3 shows the count of occupants in the final sample by sex and MAIS (grouped). Proportionately more males were uninjured (MAIS 0) than females (54/204 = 26% of males uninjured, 30/172 = 17% females) and proportionately more females had an injury with MAIS score of 2+ (62/172 = 36% for females, 70/204 = 34% for males), suggesting there may be some effect of sex on injury outcomes.

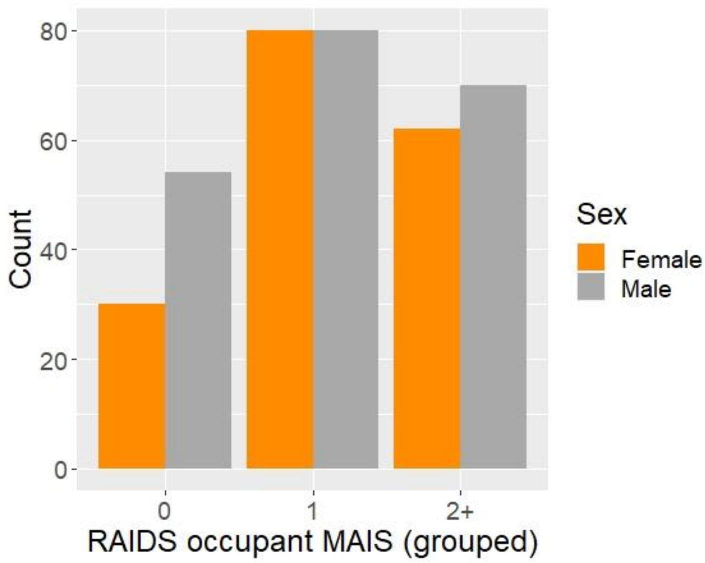

Figure 3: Number of occupants in final frontal impacts sample by Sex and MAIS (grouped)

Figure 4 shows the count of occupants in the final sample by direction of force and MAIS (grouped). Out of 132 MAIS 2+ occupants, 103 (78%) were injured when involved in an impact at 12 o'clock; this proportion was slightly lower for the other groups (68% for MAIS 0 and 58% for MAIS 1).

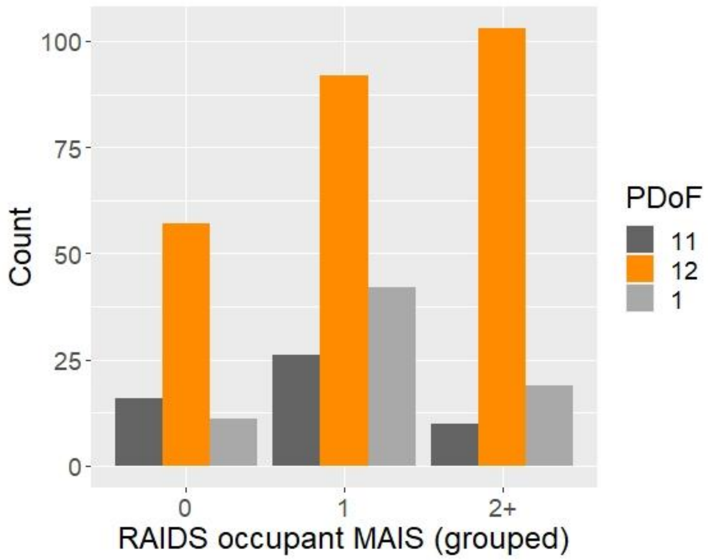

Figure 4: Number of occupants in final frontal impacts sample by Direction of Force and MAIS (grouped)

Figure 5 shows a boxplot of the distribution of EES by the three MAIS groups. The median EES (central line in the orange box) increases across the three MAIS groups (21km/h, 27km/h and 43km/h respectively), suggesting there is a clear pattern of increasing injury severity with increases in EES.

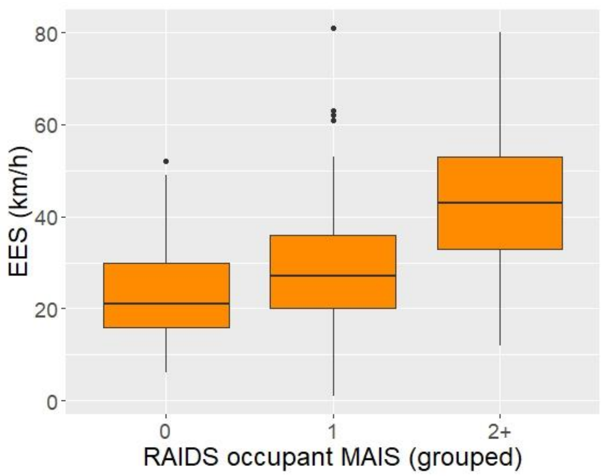

Figure 5: Distribution of occupants in final frontal impacts sample by EES (km/h) and MAIS (grouped)

Figure 6 shows the occupants split by seating position. Between 77% and 85% of occupants in each MAIS group were drivers.

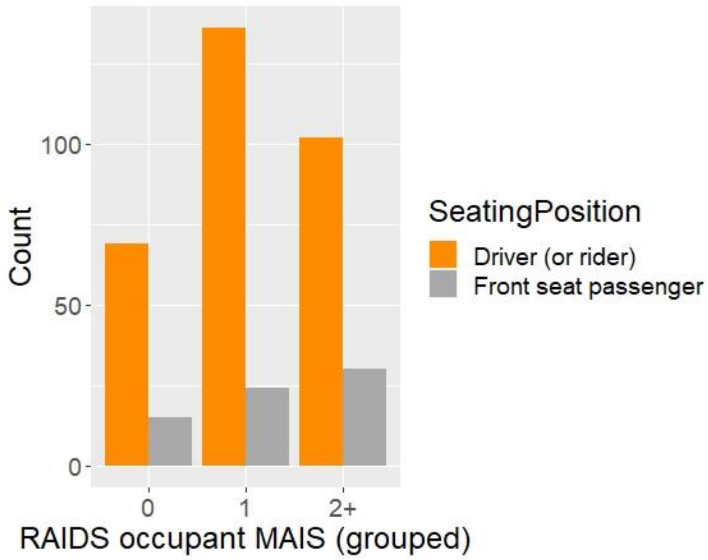

Figure 6: Number of occupants in final frontal impacts sample by Seating Position and MAIS (grouped)

Table 3 shows the distribution of injury severities (MAIS score) by collision partner. There is no clear pattern of injury severity by collision partner for frontal impacts.

Table 3: Number of occupants in final frontal impacts sample by Collision Partner and MAIS (grouped)

Collision Partner	MAIS 0	MAIS 1	MAIS 2+
Car/LGV	62	134	101
Narrow object	10	15	19
Wide object	7	8	10
Other	5	3	2
Total	**84**	**160**	**132**

3.1.2 Modelling results

Modelling results Table 4 outlines the coefficients from the final model for frontal impacts. Since a multinomial regression model was fitted, the coefficients from this model are not as intuitive as the coefficients for a standard linear regression model, and as such these require some interpretation. Table 4 provides the coefficients in two forms; firstly, the coefficients from the regression in their raw form, and in addition, in parentheses, the odds ratios are provided. The odds ratios are helpful in terms of interpreting the output from the model.

Table 4: Coefficients and odds ratios from the final model for frontal impacts [response variable = occupant MAIS (grouped)]

	Coefficients (odds ratios)		
Variable in the model	**MAIS 1**	**MAIS 2+**	**Significant variable?**
Intercept	-0.591 (0.554)	-4.284 (0.014)	N/A
Age	0.006 (1.006)	0.031 (1.032)	Yes (p < 0.001)
Sex: Male	-0.563 (0.570)	-0.576 (0.562)	No (p = 0.12)
EES	0.047 (1.048)	0.125 (1.134)	Yes (p < 0.001)
PDOF: 11	-0.151 (0.860)	-1.536 (0.215)	Yes (p < 0.001)
PDOF: 1	0.668 (1.951)	-0.774 (0.461)	

Age, impact speed (EES) and the principal direction of force (PDOF) were significant variables in the final model (i.e. they have a significant impact on the injury outcomes). Sex was not significant but is included in the model as this was one of the key variables of interest.

The positive coefficients for age show that as age increases, occupants are more likely to be injured (MAIS 1 or MAIS 2+) relative to the reference group (MAIS 0 or uninjured). Using odds ratios, we can be more specific.

For age, if we compare MAIS 1 occupants with MAIS level 0 (uninjured) occupants, the odds ratio of 1.006 means that for each year that an occupant ages, there is a 0.6% increase in the odds of the occupant being injured to a MAIS 1 level, rather than being left uninjured (MAIS level 0).

Similarly for age, if we compare MAIS 2 occupants with MAIS level 0 (uninjured) occupants, the odds ratio of 1.032 means that for each year that an occupant ages, there is a 3.2% increase in the odds of the occupant being injured to a MAIS 2+ level, rather than being left uninjured (MAIS level 0).

The positive coefficients for EES show that as crash severity increases, occupants are more likely to be injured (MAIS 1 or MAIS 2+) relative to the reference group (MAIS 0 or uninjured). More specifically, the odds ratios of 1.048 and 1.134 mean that for each km/h increase in EES in the collision, there is a 4.8% and a 13.4% increase in the odds of the occupant being injured to a MAIS 1 level and a MAIS 2+ level respectively, rather than being left uninjured (MAIS level 0).

Three of the coefficients for PDOF are negative suggesting that relative to the reference level (12 o'clock), impacts at 11 o'clock and 1 o'clock are less likely to result in serious injury. More specifically, for PDOF 11 o'clock, the odds ratios of 0.860 and 0.215 mean that there is a 14% and a 78.5% decrease in the odds of the occupant being injured to a MAIS 1 level and a MAIS 2+ level respectively, compared to a collision with PDOF 12 o'clock. For PDOF 1 o'clock, the results are mixed. The odds ratios of 1.951 and 0.461 mean that there is a 95.1% increase and a 53.9% decrease in the odds of the occupant being injured to a MAIS 1 level and a MAIS 2+ level respectively, compared to a collision with PDOF 12 o'clock.

Table 5 presents the classification of each of the cases in the final model. Those occupants in the green cells across the diagonal were correctly classified: 58% of occupants.

Table 5: Classification table for the final model for frontal impacts [response variable = occupant MAIS (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	21	56	7
MAIS 1	21	106	33
MAIS 2+	3	38	91

The model results for MAIS scores for each of the body regions are presented in Appendix A.1, along with a commentary on any differences from the main model (for overall occupant MAIS) presented here.

3.1.3 Additional model with four categories for injury severity

For frontal impacts, an additional model was fitted that included the following four categories for the response variable, injury severity: MAIS level 0, 1, 2, and 3+. Any injury classed as MAIS level 3 or higher, was placed in the MAIS 3+ category. The purpose of this model was to determine if the use of this additional category would reveal any additional insights from the data. *Note that no such models were fitted for side impacts or for the separate body regions due to insufficient sample sizes.*

The same multinomial logistic regression model to that fitted in Section 3.1.2 was fitted, using the same predictor variables: age, sex, impact speed (EES) and the principal direction of force (PDOF). The only difference to the previous model of Section 3.1.2 was the four categories, (rather than three categories), response variable for injury severity.

As for the previous model, age ($p < 0.001$), EES ($p < 0.001$) and PDOF ($p < 0.001$) were significant variables in the final model (i.e. they were found to have a significant impact on the injury outcomes). Sex ($p = 0.219$) was not significant but was again included in the model because this was one of the key variables of interest. This model correctly classified the injury severity category for 50.5% of occupants. Table 6 presents the odds ratios for this additional model and compares these with the original model of Section 3.1.2.

Table 6: Odds ratios for the additional model, compared with the original model for frontal impacts

Original model (3 categories)						
	Intercept	Age	Sex: Male	EES	PDOF:11	PDOF:1
MAIS 1	0.554	1.006	0.570	1.048	0.860	1.951
MAIS 2+	0.014	1.032	0.562	1.134	0.215	0.461
Additional Model (4 categories)						
	Intercept	Age	Sex: Male	EES	PDOF:11	PDOF:1
MAIS 1	0.533	1.007	0.571	1.048	0.852	1.943
MAIS 2	0.036	1.013	0.535	1.113	0.260	0.592
MAIS 3+	0.000	1.068	0.631	1.175	0.163	0.262

From Table 6, the additional model has enabled the following observations:

- Age: For age, in the original model we were able to conclude that for each year that an occupant ages, there are 0.6% and 3.2% increases in the odds of the occupant being injured to a MAIS 1 level and a MAIS 2+ level respectively, rather than being left uninjured (MAIS level 0). Using insights from the additional model, we can now refine this further and state the following: For each year that an occupant ages, there are 0.7%, 1.3% and 6.8% increases in the odds of the occupant being injured to a MAIS 1 level, a MAIS 2 level and a MAIS 3+ level respectively, rather than being left uninjured (MAIS level 0). The latter of these figures is the most important, because the effect of age is most prominent for the most severe injury category.
    - In the previous model, for the most severe injury category (MAIS 2+ level) there was a 3.2% increase in the odds for each year an occupant ages, rather than being left uninjured (MAIS level 0). Now from the additional model, for the most severe injury category (MAIS 3+ level), there is a (considerably greater) 6.8% increase in the odds for each year that an occupant ages.
- PDOF: For the additional model, as the injury severity increases to MAIS 1, 2, and 3+ levels, there is a clear trend in that PDOF 11 o'clock becomes less likely to result in more serious injuries, compared to the baseline of PDOF 12 o'clock. This was also the case for the original model but is more noticeable here with the additional injury severity category of the additional model. The results are again mixed for PDOF 1 o'clock. PDOF 1 o'clock is more likely to result in a MAIS 1 level injury compared to

the baseline of PDOF 12 o'clock but is then less likely to result in a MAIS 2 level or MAIS 3+ level injury, compared to the baseline of PDOF 12 o'clock.

- More specifically, for PDOF 11 o'clock, there are 14.8%, 74.0% and 83.7% decreases in the odds of the occupant being injured to a MAIS 1 level, MAIS 2 level and MAIS 3+ level respectively, compared to a collision with PDOF 12 o'clock. For PDOF 1 o'clock, although there is a 94.3% increase in the odds of the occupant being injured to a MAIS 1 level, there are also 40.8% and 73.8% decreases in the odds of the occupant being injured to a MAIS 2 level and MAIS 3+ level respectively, compared to a collision with PDOF 12 o'clock.

3.2 Side Impacts

The initial filtering to side impacts resulted in 413 occupants in the dataset. Table 7 summarises the number of occupants after each of the secondary filters (described in Section 2.1.1) were applied.

Table 7: Secondary filters applied to the side impact dataset

Filters applied	Number of occupants
Side impact occupants (before secondary filtering):	**413**
Remove vehicles from 2003 and earlier	336
Remove occupants under 16 (and with unknown age)	294
Remove occupants of unknown sex or pregnant females	292
Front seated occupants only	276
Remove unbelted occupants	215
Remove cases with any rollover	199
Known occupant MAIS (0-6) (final sample for modelling)	**177**

Note: Known EES was excluded as filter because this reduced the cases available for modelling by a substantial number; as a result, it will not be possible to include this variable as a predictor in the side impact models.

3.2.1 Exploratory data analysis

Figure 7 (a) shows the distribution of MAIS scores in the final sample: there are relatively few 2, 3, 4, 5 and 6 scores so a decision was made to group the response variable of interest (MAIS score) into three groups: 0, 1 and 2+ (as shown in Figure 7 (b)).

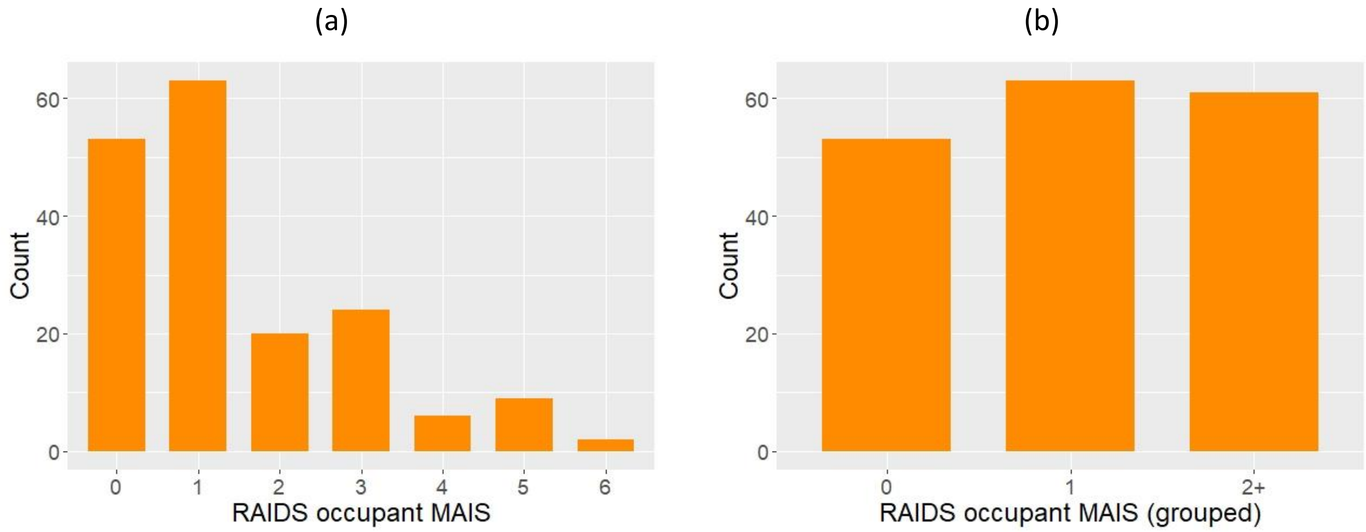

Figure 7: Distribution of (a) raw and (b) grouped MAIS scores for side impact occupants included in the final sample (N=177)

Based on the literature and the factors known to influence injury severity, the following variables were considered as predictive variables for the side impacts model:

- Age[5] and sex (the key variables of interest) – to investigate differences in injury outcomes for different occupant characteristics.
- Seating position (driver or front seat passenger) – restraint systems can differ between these two positions, so this variable was included to account for any differences in injury outcomes.
- Collision partner type (car/LGV, narrow object, wide object, other/unknown) – Collision partner type (car/LGV, narrow object, wide object, other) - the mass and dimension of the collision partner determines the forces experienced by the occupants in a crash and hence different injury outcomes.
- Whether the impact was on the occupant's side of the vehicle (yes or no) – this is to account for the fact that the occupant closest to the impact may be more likely to be severely injured.
- Height and weight of the occupant – these variables were considered for inclusion but 56-60% of cases were unknown so these could not be considered further.

Figure 8 shows a boxplot of the distribution of ages by the three MAIS groups. The median age (central line in the orange box) does not differ substantially between MAIS groups (47 years, 43 years and 45 years respectively). However, the taller box for MAIS 2+ suggests

[5] A linear term for age, a quadratic term for age and a categorical age variable were all tested during the modelling to see which one fitted the data best. The linear age term was found to be the best fit.

there may be some effect of increasing age increasing injury severity; this will be investigated further in the modelling.

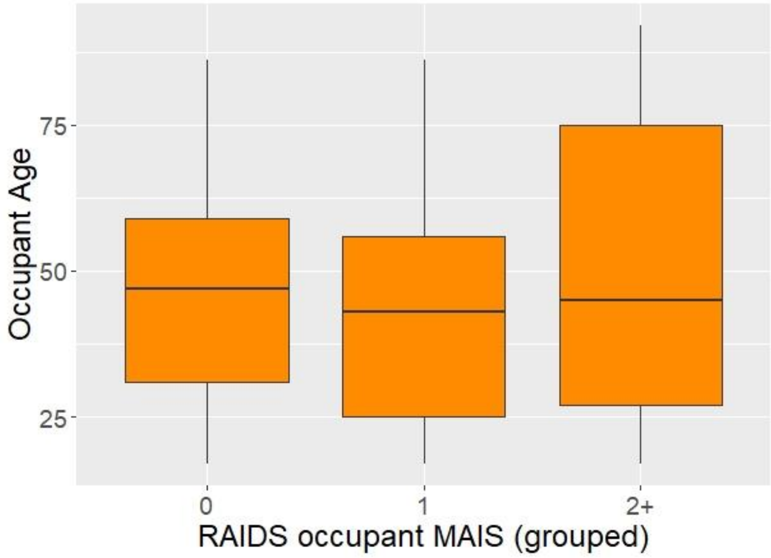

Figure 8: Distribution of occupants in final side impacts sample by Age and MAIS (grouped)

Figure 9 shows the count of occupants in the final sample by sex and MAIS (grouped). The injury pattern is not clear from this chart: more males were uninjured (MAIS 0) or with a MAIS 2+ injury than females, but the opposite is true for the MAIS 1 (slight bruising/laceration type) injuries.

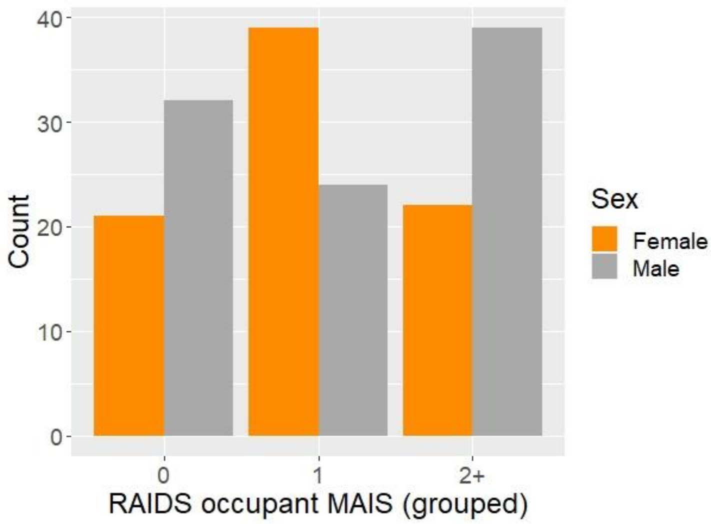

Figure 9: Number of occupants in final side impacts sample by Sex and MAIS (grouped)

Figure 10 shows the occupants split by seating position. Around 80% of occupants in each MAIS group were drivers.

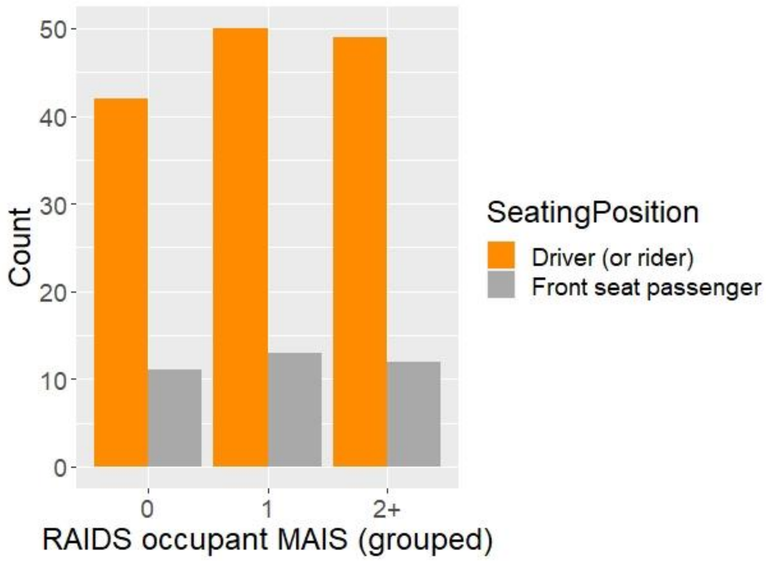

Figure 10: Number of occupants in final side impacts sample by Seating Position and MAIS (grouped)

Table 8 shows the distribution of injury severities (MAIS score) by collision partner. There is some indication that collision with a narrow or wide object tends to result in higher severity (more 2+) injuries.

Table 8: Number of occupants in final side impacts sample by Collision Partner and MAIS (grouped)

Collision Partner	MAIS 0	MAIS 1	MAIS 2+
Car/LGV	49	59	43
Narrow object	0	0	12
Wide object	1	1	5
Other/unknown	3	3	1
Total	**53**	**63**	**61**

Figure 11 shows the occupants split by whether the impact occurred on the occupant's side of the vehicle or not. This trend is as expected: if the impact is on the occupant's side, a larger number of the injuries are 2+ compared with 0 and 1.

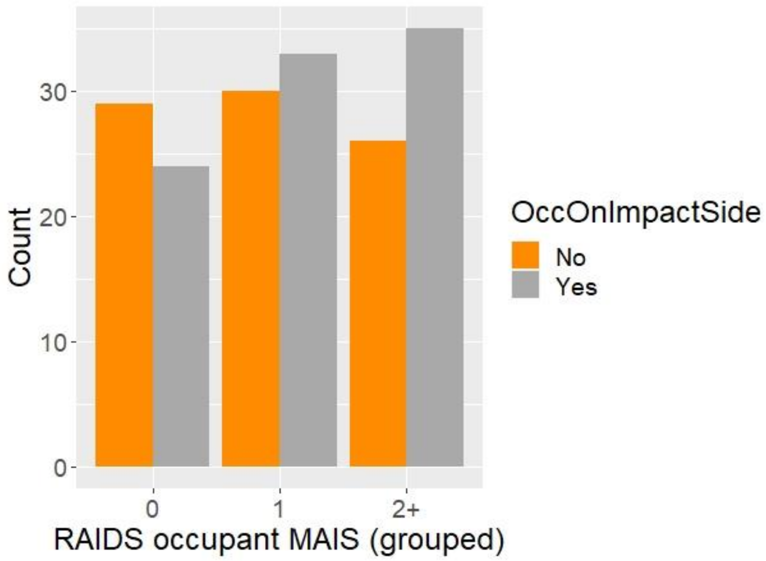

Figure 11: Number of occupants in final side impacts sample by whether the impact was on the occupant's side of the vehicle or not and MAIS (grouped)

3.2.2 Modelling results

Table 9 outlines the coefficients and odds ratios from the final model for side impacts. Age, sex and the collision partner were significant variables in the final model (i.e. they have a significant impact on the injury outcomes).

Table 9: Coefficients and odds ratios from the final model for side impacts [response variable = occupant MAIS (grouped)]

	Coefficients (odds ratios)		
Variable in the model	**MAIS 1**	**MAIS 2+**	**Significant variable?**
Intercept	1.037 (2.822)	-1.193 (0.303)	N/A
Age	-0.009 (0.991)	0.021 (1.021)	Yes (p = 0.012)
Sex:Male	-0.853 (0.426)	-0.057 (0.945)	Yes (p = 0.048)
CollisionPartner:NarrowObject	-2.312 (0.099)	14.283 (1595832)	Yes (p < 0.001)
CollisionPartner:WideObject	-0.162 (0.851)	2.074 (7.955)	
CollisionPartner:OtherUnknown	-0.460 (0.631)	-0.369 (0.692)	

The positive coefficients for age (MAIS 2+) show that as age increases, occupants are more likely to be injured relative to the reference group (MAIS 0 or uninjured); the opposite is true for MAIS 1 (as shown by the negative coefficient). The odds ratios of 0.991 and 1.021 mean that for each year that an occupant ages, there is a 0.9% decrease and a 2.1% increase in the odds of the occupant being injured to a MAIS 1 level and a MAIS 2+ level respectively, rather than being left uninjured (MAIS level 0).The negative coefficient for sex shows that females tend to be in the higher MAIS levels (1 and 2+) relative to uninjured (MAIS 0) more frequently than males (i.e. male occupants are less likely to be injured than female occupants). The odds ratios of 0.426 and 0.945 mean that there is a 57.4% decrease and a 5.5% decrease in the odds of a male occupant being injured to a MAIS 1 level and a MAIS 2+ level respectively, compared to a female occupant.

The large and positive coefficient for narrow collision partners (MAIS 2+) shows that relative to the reference level (collisions with cars/LGVs), occupants are more likely to be severely injured when involved in a collision with a narrow object (such as a lighting column, tree, or road sign). The large odds ratio for narrow collision partners of 1595832 means that there is more than a 150 million % increase in the odds of an occupant being injured to a MAIS 2+ level, compared to collisions with cars/LGVs. Severe caution should be taken when interpreting this result though as this is only based on a sample of 12 occupants who were injured in collisions with a narrow object.

Wide objects (e.g. barriers, bridges, fences, walls, and buildings) also result in more severe injury outcomes (MAIS 2+) relative to a collision with a car or LGV, although this effect is smaller than for narrow objects. The odds ratio for wide collision partners of 7.955 means that there is a 695.5% increase in the odds of an occupant being injured to a MAIS 2+ level, compared to collisions with cars/LGVs. Again, severe caution should be taken with interpretation here since only 7 occupants were in a collision with a wide object in the final sample.

Table 10 presents the classification of each of the cases in the final model. Those occupants in the green cells across the diagonal were correctly classified: 53% of occupants.

Table 10: Classification table for the final model for side impacts [response variable = occupant MAIS (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	22	20	11
MAIS 1	16	35	12
MAIS 2+	10	14	37

The model results for MAIS scores for each of the body regions are presented in Appendix A.2, along with a commentary on any differences from the main model (for overall occupant MAIS) presented here.

4 Summary of the Findings

4.1 Frontal Impact

- The overall occupant MAIS model for frontal impacts presented in Section 3.1.2 is the main model – this was used to decide on the variables to include in the body region models (included in Appendix A.1).
- Age was significant in this model (see Table 11) but sex was not, meaning that sex does not have a significant effect on injury severity.
- EES and PDOF were also significant in this model.
- The EES coefficients were positive: as impact speed increases, occupants are more likely to be injured (MAIS 1 or MAIS 2+) relative to the reference group (MAIS 0 or uninjured).
- There was a more mixed picture for PDOF coefficients but on balance, most were negative suggesting that relative to the reference level (12 o'clock), impacts at 11 o'clock and 1 o'clock are less likely to result in serious injury.
- Table 11 shows whether the age and sex variables were significant or not in each of the body region models.

Table 11: Summary of the frontal impact model results

Model	Significance of age variable (direction of coefficient)	Significance of sex variable (direction of coefficient)
Overall occupant MAIS	**Significant (as age increases, occupants are more likely to be injured)**	**Not significant**
MAIS for head region	Significant (as age increases, occupants are more likely to be injured)	Significant (male occupants are more likely to have a serious (MAIS 2+) head injury than females)
MAIS for thorax region	Significant (as age increases, occupants are more likely to be injured)	Not significant
MAIS for abdomen region	Significant (as age increases, occupants are more likely to be injured)	Not significant
MAIS for lower extremities	Not significant	Significant (male occupants are less likely to be injured with a lower extremity injury than female occupants)
MAIS for other regions	Not significant	Not significant

4.2 Side Impact

- The overall occupant MAIS model for side impacts presented in Section 3.2.2 is the main model – this was used to decide on the variables to include in the body region models (included in Appendix A.2).
- Age and sex were both significant in this model, meaning that they both have a significant effect on injury severity (see Table 12).
- Collision partner was also significant in this model.
- The collision partner coefficients for narrow objects and wide objects were positive: relative to the reference level (collisions with cars/LGVs), occupants are more likely to be severely injured when involved in a collision with these objects.
- Table 12 shows whether the age and sex variables were significant or not in each of the body region models.

Table 12: Summary of the side impact model results

Model	Significance of age variable (interpretation of coefficient)	Significance of sex variable (interpretation of coefficient)
Overall occupant MAIS	**Significant (as age increases, occupants are more likely to be injured)**	**Significant (male occupants are less likely to be injured than female occupants)**
MAIS for head region	Not significant	Not significant
MAIS for thorax region	Significant (as age increases, occupants are more likely to be injured)	Not significant
MAIS for abdomen region	Not significant	Not significant
MAIS for lower extremities	Not significant	Significant (male occupants are less likely to be injured with a lower extremity injury than female occupants)
MAIS for other regions	Not significant	Not significant

5 Discussion

Real-world UK in-depth collision data from the Road Accident In-Depth Studies (RAIDS) database, collected from 2013, were analysed to understand the effect of occupant characteristics on injury outcomes for front seat occupants. From the crash sample, vehicles involved in non-rollover frontal impacts with a PDOF 11, 12 and 1 o'clock and side impacts with PDOF 2, 3, 4, 8, 9 or 10 o'clock were chosen. To further include cars that comply with the UN Regulations 94 and 95, only vehicles manufactured after the calendar year 2004 were selected. The data sample was further narrowed to belted adult front seat occupants (16+ years). The recording rate of occupant height, weight (and therefore BMI) in the medical data was not high enough to support analysis of the effect of these characteristics on injury outcome.

The findings of this study have shown that the risk of sustaining a moderate severity (MAIS2+) injury in frontal impacts increases with EES for all body regions. In side impact models, EES wasn't included as a predictor due to a reduced number of cases. In the frontal crash sample, impacts at the 12 o'clock direction showed a higher risk of overall MAIS and injuries to most body regions except the head, compared to 11 o'clock and 1 o'clock. This trend requires further understanding as lateral components in other impact types (11 and 1 o'clock) may create unfavourable interaction of occupants with the restraint system, resulting in higher injury risks, which is not the case in this study. However, the findings suggest that current frontal regulatory test requirements (12 o'clock) may cover a range of oblique frontal impacts (i.e. ±30°). Further studies including real world testing with advanced crash test dummies may be required to confirm the findings.

Age was determined to be one of the significant predictors of overall maximum injury in both frontal and side impacts. The older occupants were more prone to overall MAIS 2+ outcomes in both impact types. For frontal impacts, where there was sufficient data to model up to the MAIS 3+ level, the effect of age was even more prominent than the MAIS 2+ model, with older occupants being even more prone to the most severe injury category of MAIS 3+ level. These results verify the continuing vulnerability of older occupants to serious injuries, concurring with previous real-world studies using UK (Morris et al. 2003) and US (Carter et al. 2014; Ridella et al. 2012) collision data. In frontal impacts, age was a significant predictor of MAIS injury risk in the head, thorax, and abdomen body regions. In the side impact sample, the thorax was the only body region where age had a significant effect on the MAIS injury outcome.

The relationship between age and increased risk of MAIS 2+ head injury in frontal impacts is similar to the findings of Mallory (2010), who analysed the NASS-CDS collision data to report a higher risk of head injury risk to older occupants, even in low-severity frontal impacts. The author indicated that change in head injury outcome may be age specific. In the frontal impact, ageing also increased the risk of a MAIS 2+ abdomen injury. An age-related increase in injury risk to the abdomen in frontal impacts has been reported in previous studies (Frampton et al. 2012; Lamielle et al. 2006).

Results from the regression models showed that the risk of moderate severity thorax injury (MAIS 2+) increases with ageing in both frontal and side impacts. The higher risk of thorax injury to older front seat occupants is well reported, and they tend to sustain serious thorax injuries even in low/moderate speed crashes (Wisch et al. 2019; Ekambaram et al. 2019).

Several studies have linked this variation in the collision outcome to the biomechanical changes related to ageing. Including age-related occupant protection, especially to the thorax region, in regulatory and consumer test procedures may be beneficial.

Unlike frontal impacts, sex was a significant predictor of overall maximum AIS in side impacts. The injury risk to females was significantly higher when compared to their male counterparts. In frontal impacts, females were less likely to sustain a MAIS 2+ head injury. However, this result is based on a limited sample size and should be treated with caution; only 4 females and 9 males in the dataset sustained a MAIS 2+ level head injury. This result also disagrees with the findings of some previous studies based on US data (Ridella et al. 2012; Carter et al. 2014). Including belted-only occupants and relatively modern vehicles, usually fitted with airbags, in the present study may explain the reduced sex-based disparity. Analysing compatible frontal crashes involving modern vehicles and belted occupants from the NASS CDS dataset, Brumbelow et al. (2022) reported that the estimated odds ratio between males and females for sustaining a MAIS 3+ head injury was similar. They also reported that some disparity noted in the previous study was not due to physiological differences between sexes but to variations in vehicle and crash characteristics.

In this analysis, results showed that females are more susceptible to lower extremity injuries than males in frontal and side impacts. Previous studies have also reported a higher risk of lower extremity injury for females (Brumbelow et al. 2022; Kahane 2013). Researchers have related a higher risk of lower extremity injuries among females to physiological differences (Forman et al. 2019) and stature (Welsh et al. 2001; Crandall et al. 1996). Crandall et al. (1996) postulated that the position of the foot/ankle during the crash is highly associated with an increase in lower extremity injuries for shorter drivers. This consistent reporting of increased lower extremity risk for females, even in relatively modern vehicles, requires further understanding.

The collision partner wasn’t a significant predictor in frontal impacts; however, it was found to be significant for side impacts. Collision with a narrow object such as trees and crash bollards was found to have a higher overall MAIS 2+ injury risk relative to collision with a car or LGV. Similarly, collision with wide objects such as barriers, bridges, fences, walls, and buildings also resulted in more severe injury outcomes (MAIS 2+) than a collision with a car or LGV. A similar trend was observed in injury risks to all body regions except for injuries to the abdomen. However, these results for both narrow and wide objects should be treated with severe caution as they are based on very limited sample sizes.

This study controlled for several crash factors to best examine the difference in injury risk for variation in age and sex. However, several other factors, such as intrusion, distribution of overlap, seat postures, deployment of airbags, and height and weight of the occupants, were unable to be included due to a large number of missing variables. More caution is required while interpreting the side impact model results as the number of cases is low, and EES or other predictors to control for crash severity variations were not included in the models as this would have resulted in too few cases for analysis. The number of rear impact cases that fit the inclusion criteria was too low for conducting a robust analysis; therefore, they weren't investigated. Despite these limitations, the study's findings can show the influence of occupant characteristics such as age and sex on injury outcomes and identify areas where further research and change in vehicle regulations may benefit.

6 References

Association for the Advancement of Automotive Medicine (AAAM, 2015). Abbreviated Injury Scale – 2015 Edition. Barrington, Illinois, USA.

Bose D, Segui-Gomez M and Crandall JR (2011). Vulnerability of female drivers involved in motor vehicle crashes: an analysis of US population at risk. American journal of public health, 101(12), pp.2368–73.

Brumbelow M and Jermakian J (2022). Injury risks and crashworthiness benefits for females and males: Which differences are physiological? Traffic Injury Prevention, 23:1, 11-16, DOI: 10.1080/15389588.2021.2004312

Carter PM, Flannagan CA, Reed MP, Cunningham RM, and Rupp JD (2014). Comparing the effects of age, BMI and gender on severe injury (AIS 3+) in motor-vehicle crashes. Accident Analysis & Prevention. Nov 1;72:146-60.

Crandall JR, Martin PG, Bass CR, Pilkey WD, Dischinger PC, Burgess AR, O'Quinn TD, and Schmidhauser CB (1996). Foot and ankle injury: the roles of driver anthropometry, footwear and pedal controls. In Annual proceedings of the Association for the Advancement of Automotive Medicine (Vol. 40, pp. 1-18). Association for the Advancement of Automotive Medicine.

Evans L (2001). Female compared to male fatality risk from similar impacts. J Trauma. 200;:50(2). 281–288. doi:10.1097/00005373-200102000-00014.

Ekambaram K, Frampton R and Lenard J (2019). Factors associated with chest injuries to front seat occupants in frontal impacts, Traffic Injury Prevention, 20:sup2, S37-S42, 2019, DOI: 10.1080/15389588.2019.1654606

Forman J, Poplin GS, Shaw CG, McMurry TL, Schmidt K, Ash J, and Sunnevang C (2019). Automobile injury trends in the contemporary fleet: Belted occupants in frontal collisions. Traffic injury prevention.20(6):607-12.

Frampton R, Lenard J and Compigne S (2012). An in-depth study of abdominal injuries sustained by car occupants in frontal crashes. In Annals of Advances in Automotive Medicine/Annual Scientific Conference (Vol. 56, p. 137). Association for the Advancement of Automotive Medicine.

Joodaki H, Gepner B, McMurry T and Kerrigan J (2020). Comparison of injuries of belted occupants among different BMI categories in frontal crashes. Int J Obes (Lond). 2020 Jun;44(6):1319-1329. doi: 10.1038/s41366-019-0481-2. Epub 2019 Nov 18. PMID: 31740724.

Kahane CJ (2013). Injury vulnerability and effectiveness of occupant protection technologies for older occupants and women (No. DOT HS 811 766).

Kent R, Sang-Hyun L, Darvish K and Wang S (2005). Structural and material changes in the aging thorax and their role in crash protection for older occupants. Stapp car Crash journal. 2005 Nov 1;49:231.

Kent R, Trowbridge M, Lopez-Valdes FJ, Ordoyo RH, and Segui-Gomez M (2009). How many people are injured and killed as a result of aging? Frailty, fragility, and the elderly risk-exposure trade off assessed via a risk saturation model. In Annals of Advances in Automotive medicine/Annual Scientific Conference 2009 Oct 5 (Vol. 53, p. 41). Association for the Advancement of Automotive Medicine.

Lamielle S, Cuny S, Foret-Bruno JY, Petit P, Vezin P, Verriest JP, and Guillemot H (2006). Abdominal injury patterns in real frontal crashes: influence of crash conditions, occupant seat and restraint systems. In Annual Proceedings/Association for the Advancement of Automotive Medicine (Vol. 50, p. 109). Association for the Advancement of Automotive Medicine.

Mallory A (2010). Head injury and aging: the importance of bleeding injuries. In Annals of Advances in Automotive Medicine/Annual Scientific Conference 2010 Jan (Vol. 54, p. 51). Association for the Advancement of Automotive Medicine.

Morris A, Welsh R and Hassan A (2003). Requirements for the crash protection of older vehicle passengers. In Annual Proceedings/Association for the Advancement of Automotive Medicine, vol. 47, p. 165. Association for the Advancement of Automotive Medicine, 2003

Parenteau CS, Zuby D, Brolin K, Svensson MY, Palmertz C and Wang SC (2013). Restrained Male and Female Occupants in Frontal Crashes: Are We Different?. IRCOBI Conference Proceedings, paper number IRC-13-98.

Ridella SA, Rupp JD and Poland K (2012). Age-related differences in AIS 3+ crash injury risk, types, causation and mechanisms. IRCOBI Conference Proceedings, paper number IRC-12-14.

Rupp JD, Flannagan CA, Leslie AJ, Hoff CN, Reed MP, and Cunningham RM (2013). Effects of BMI on the risk and frequency of AIS 3+ injuries in motor-vehicle crashes. Obesity. 2013 Jan;21(1):E88-97.

Viano DC, Parenteau CS, and Edwards ML (2008). Crash injury risks for obese occupants using a matched-pair analysis. Traffic injury prevention. 9(1):59-64.

Welsh R and Lenard J (2001). Male and female car drivers--differences in collision and injury risks. Annual proceedings / Association for the Advancement of Automotive Medicine. Association for the Advancement of Automotive Medicine, 45, pp.73–91.

Wisch M, Lerner M, Vukovic E, Schäfer R, Hynd D, Fiorentino A and Fornells A (2019). Road traffic crashes in Europe involving older car occupants, older pedestrians or cyclists in crashes with passenger cars–Results from SENIORS. Dostupno na adresi: https://wwwesv. nhtsa. dot. gov/Proceedings/25/25ESV-000398. pdf. Datum pristupa. 2019;27.

Appendix A Modelling results for body regions

A.1 Frontal impact models

A.1.1 Head region

This section presents the results of the model for the MAIS scores on the head region for each occupant, using the same variables as in the final model for frontal impacts (presented in Section 3.1.2).

Table 13: Coefficients and odds ratios from the final model for frontal impacts [response variable = MAIS for Head region (grouped)]

	Coefficients (odds ratios)		
Variable in the model	**MAIS 1**	**MAIS 2+**	**Significant variable?**
Intercept	-1.967 (0.140)	-9.875 (0.000)	N/A
Age	0.008 (1.008)	0.048 (1.049)	Yes (p = 0.017)
Sex:Male	-0.699 (0.497)	0.588 (1.800)	Yes (p = 0.029)
EES	0.009 (1.009)	0.094 (1.099)	Yes (p < 0.001)
PDOF:11	0.322 (1.380)	0.582 (1.790)	No (p = 0.492)
PDOF: 1	-0.253 (0.776)	-1.146 (0.318)	

Table 14: Classification table for the final model for frontal impacts [response variable = MAIS for Head region (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	304	0	1
MAIS 1	58	0	0
MAIS 2+	13	0	0

Summary of the findings (compared to the overall MAIS model results for frontal impacts):

- Age and EES were also significant in this model, with coefficients in the same direction (positive).
- Sex was significant in this model unlike in the overall MAIS model for frontal impacts. The positive coefficient for sex shows that males tend to be in the highest MAIS level (2+) relative to uninjured (MAIS 0) more frequently than females (i.e. male occupants are more likely to have a serious (MAIS 2+) head injury than females).
- PDOF was not significant in this model.
- The classification rate for this model was 81% which was better than for the overall model (58%), although most of the misclassification was in the injured (MAIS 1 and 2+) occupants being classified as uninjured. As a result, caution should be taken when using this model for predictive purposes.
- The classification table also shows that no occupants were predicted a MAIS score of 1 using this model, suggesting that the model form could benefit from better specification.

A.1.2 Thorax region

This section presents the results of the model for the MAIS scores on the thorax region for each occupant, using the same variables as in the final model for frontal impacts (presented in Section 3.1.2).

Table 15: Coefficients and odds ratios from the final model for frontal impacts [response variable = MAIS for Thorax region (grouped)]

	Coefficients (odds ratios)		
Variable in the model	MAIS 1	MAIS 2+	Significant variable?
Intercept	-2.093 (0.123)	-6.628 (0.001)	N/A
Age	0.015 (1.015)	0.055 (1.057)	Yes ($p < 0.001$)
Sex:Male	-0.047 (0.954)	0.220 (1.246)	No ($p = 0.74$)
EES	0.016 (1.016)	0.084 (1.088)	Yes ($p < 0.001$)
PDOF:11	-0.616 (0.540)	-1.124 (0.325)	Yes ($p = 0.03$)
PDOF: 1	-0.084 (0.919)	-1.039 (0.354)	

Table 16: Classification table for the final model for frontal impacts [response variable = MAIS for Thorax region (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	206	0	18
MAIS 1	65	0	10
MAIS 2+	35	0	45

Summary of the findings (compared to the overall MAIS model results for frontal impacts):

- As with the overall model, sex was not significant, but the other variables were.
- Age, EES and PDOF were significant in this model, with coefficients in the same direction as the overall model.
- The classification rate for this model was 67% which was better than for the overall model (58%), although most of the misclassification was in the injured (MAIS 1 and 2+) occupants being classified as uninjured. As a result, caution should be taken when using this model for predictive purposes.
- The classification table also shows that no occupants were predicted a MAIS score of 1 using this model, suggesting that the model form could benefit from better specification.

A.1.3 Abdomen region

This section presents the results of the model for the MAIS scores on the abdomen region for each occupant, using the same variables as in the final model for frontal impacts (presented in Section 3.1.2).

Table 17: Coefficients and odds ratios from the final model for frontal impacts [response variable = MAIS for Abdomen region (grouped)]

	Coefficients (odds ratios)		
Variable in the model	**MAIS 1**	**MAIS 2+**	**Significant variable?**
Intercept	-2.660 (0.070)	-5.894 (0.003)	N/A
Age	0.013 (1.013)	0.025 (1.025)	Yes (p = 0.016)
Sex:Male	-0.582 (0.559)	0.078 (1.081)	No (p = 0.12)
EES	0.027 (1.027)	0.086 (1.090)	Yes (p < 0.001)
PDOF:11	0.210 (1.234)	-2.297 (0.101)	Yes (p = 0.014)
PDOF: 1	-0.109 (0.897)	-0.980 (0.375)	

Table 18: Classification table for the final model for frontal impacts [response variable = MAIS for Abdomen region (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	225	0	12
MAIS 1	56	0	4
MAIS 2+	31	0	18

Summary of the findings (compared to the overall MAIS model results for frontal impacts):

- As with the overall model, sex was not significant, but the other variables were.
- Age, EES and PDOF were significant in this model, with coefficients in the same direction as the overall model.
- The classification rate for this model was 73% which was better than for the overall model (58%), although most of the misclassification was in the injured (MAIS 1 and 2+) occupants being classified as uninjured. As a result, caution should be taken when using this model for predictive purposes.

- The classification table also shows that no occupants were predicted a MAIS score of 1 using this model, suggesting that the model form could benefit from better specification.

A.1.4 Lower extremities

This section presents the results of the model for the MAIS scores on the lower extremities for each occupant, using the same variables as in the final model for frontal impacts (presented in Section 3.1.2). The MAIS value for lower extremities were calculated for each occupant as the maximum of the MAIS for the left and right leg.

Table 19: Coefficients and odds ratios from the final model for frontal impacts [response variable = MAIS for Lower Extremities (grouped)]

	Coefficients (odds ratios)		
Variable in the model	**MAIS 1**	**MAIS 2+**	**Significant variable?**
Intercept	-1.614 (0.199)	-5.679 (0.003)	N/A
Age	0.005 (1.005)	0.018 (1.018)	No (p = 0.18)
Sex:Male	-0.747 (0.474)	-0.778 (0.459)	Yes (p = 0.008)
EES	0.020 (1.020)	0.100 (1.105)	Yes (p < 0.001)
PDOF:11	-0.305 (0.737)	-0.919 (0.399)	Yes (p = 0.016)
PDOF: 1	-0.431 (0.650)	-1.790 (0.167)	

Table 20: Classification table for the final model for frontal impacts [response variable = MAIS for Lower Extremities (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	250	0	6
MAIS 1	65	0	7
MAIS 2+	29	0	19

Summary of the findings (compared to the overall MAIS model results for frontal impacts):

- Age was not significant in this model unlike in the overall MAIS model.
- Sex, however, was significant. The negative coefficient for sex shows that females tend to be in the higher MAIS levels (1 and 2+) relative to uninjured (MAIS 0) more frequently than males (i.e. male occupants are less likely to be injured with a lower extremity injury than female occupants).
- EES and PDOF were also significant in this model, with coefficients in the same direction as the overall model.
- The classification rate for this model was 72% which was better than for the overall model (58%), although most of the misclassification was in the injured (MAIS 1 and 2+) occupants being classified as uninjured. As a result, caution should be taken when using this model for predictive purposes.
- The classification table also shows that no occupants were predicted a MAIS score of 1, suggesting that the model form could benefit from better specification.

A.1.5 Other regions

This section presents the results of the model for the MAIS scores on other regions for each occupant, using the same variables as in the final model for frontal impacts (presented in Section 3.1.2). The MAIS value for other regions was calculated for each occupant as the maximum of the MAIS for the neck, pelvis, left arm, right arm and 'other' regions combined.

Table 21: Coefficients and odds ratios from the final model for frontal impacts [response variable = MAIS for Other regions (grouped)]

	Coefficients (odds ratios)		
Variable in the model	**MAIS 1**	**MAIS 2+**	**Significant variable?**
Intercept	-0.541 (0.582)	-3.704 (0.025)	N/A
Age	0.004 (1.004)	0.011 (1.011)	No (p = 0.43)
Sex:Male	-0.219 (0.803)	-0.575 (0.563)	No (p = 0.22)
EES	-0.005 (0.995)	0.061 (1.063)	Yes (p < 0.001)
PDOF:11	0.493 (1.637)	-0.353 (0.703)	Yes (p < 0.001)
PDOF: 1	1.057 (2.878)	-0.560 (0.571)	

Table 22: Classification table for the final model for frontal impacts [response variable = MAIS for Other regions (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	149	31	8
MAIS 1	93	41	3
MAIS 2+	32	8	11

Summary of the findings (compared to the overall MAIS model results for frontal impacts):

- Neither age nor sex were significant in this model.
- EES and PDOF were significant with mixed results on the direction (sign) of this effect.
- The classification rate for this model was 53% which was slightly worse than for the overall model (58%).

A.2 Side impact models

A.2.1 Head region

This section presents the results of the model for the MAIS scores on the head region for each occupant, using the same variables as in the final model for side impacts (presented in Section 3.2.2).

Table 23: Coefficients and odds ratios from the final model for side impacts [response variable = MAIS for the Head region (grouped)]

	Coefficients (odds ratios)		
Variable in the model	MAIS 1	MAIS 2+	Significant variable?
Intercept	-0.942 (0.390)	-3.195 (0.041)	N/A
Age	-0.006 (0.994)	0.016 (1.017)	No (p = 0.46)
Sex:Male	-0.485 (0.616)	-0.692 (0.500)	No (p = 0.32)
CollisionPartner:NarrowObject	0.901 (2.463)	3.044 (20.996)	Yes (p = 0.014)
CollisionPartner:WideObject	1.107 (3.026)	2.600 (13.466)	
CollisionPartner:OtherUnknown	-0.522 (0.593)	-9.310 (0.000)	

Table 24: Classification table for the final model for side impacts [response variable = MAIS for Head region (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	127	1	2
MAIS 1	32	0	1
MAIS 2+	12	0	2

Summary of the findings (compared to the overall MAIS model results for side impacts):

- Neither age nor sex were significant in this model; this differs from the overall MAIS model where both were significant.
- The coefficients for narrow and wide object collision partners for MAIS 2+ injury were both positive (similar to the overall model), indicating that these objects present a high risk of severe injury than cars/LGVs.
- The classification rate for this model was 81% which was better than for the overall model (53%), although most of the misclassification was in the injured (MAIS 1 and 2+) occupants being classified as uninjured. As a result, caution should be taken when using this model for predictive purposes.

A.2.2 Thorax region

This section presents the results of the model for the MAIS scores on the thorax region for each occupant, using the same variables as in the final model for side impacts (presented in Section 3.2.2).

Table 25: Coefficients and odds ratios from the final model for side impacts [response variable = MAIS for the Thorax region (grouped)]

	Coefficients (odds ratios)		
Variable in the model	**MAIS 1**	**MAIS 2+**	**Significant variable?**
Intercept	-1.958 (0.141)	-2.758 (0.063)	N/A
Age	0.015 (1.015)	0.031 (1.031)	Yes (p = 0.008)
Sex:Male	-0.737 (0.479)	-0.117 (0.890)	No (p = 0.300)
CollisionPartner:NarrowObject	-11.051 (0.000)	2.435 (11.416)	Yes (p = 0.004)
CollisionPartner:WideObject	0.831 (2.296)	1.654 (5.228)	
CollisionPartner:OtherUnknown	0.057 (1.059)	-11.315 (0.000)	

Table 26: Classification table for the final model for side impacts [response variable = MAIS for Thorax region (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	109	0	5
MAIS 1	23	0	0
MAIS 2+	30	0	10

Summary of the findings (compared to the overall MAIS model results for side impacts):

- Similarly, to the overall model, age is significant and positive suggesting as age increases, occupants are more likely to be injured.
- Sex was not significant in this model unlike in the overall MAIS model for side impacts.
- The coefficients for narrow and wide object collision partners for MAIS 2+ injury was both positive (similar to the overall model), indicating that these objects present a high risk of severe injury than cars/LGVs.

- The classification rate for this model was 67% which was better than for the overall model (53%), although most of the misclassification was in the injured (MAIS 1 and 2+) occupants being classified as uninjured. As a result, caution should be taken when using this model for predictive purposes.
- The classification table also shows that no occupants were predicted a MAIS score of 1 using this model, suggesting that the model form could benefit from better specification.

A.2.3 Abdomen region

This section presents the results of the model for the MAIS scores on the abdomen region for each occupant, using the same variables as in the final model for side impacts (presented in Section 3.2.2).

Table 27: Coefficients and odds ratios from the final model for side impacts [response variable = MAIS for the Abdomen region (grouped)]

	Coefficients (odds ratios)		
Variable in the model	**MAIS 1**	**MAIS 2+**	**Significant variable?**
Intercept	-1.036 (0.355)	-1.505 (0.222)	N/A
Age	-0.016 (0.984)	-0.005 (0.995)	No (p = 0.49)
Sex:Male	-0.481 (0.618)	-0.215 (0.807)	No (p = 0.63)
CollisionPartner:NarrowObject	-12.011 (0.000)	1.078 (2.939)	No (p = 0.22)
CollisionPartner:WideObject	0.566 (1.761)	1.173 (3.232)	
CollisionPartner:OtherUnknown	-12.111 (0.000)	-0.075 (0.928)	

Table 28: Classification table for the final model for side impacts [response variable = MAIS for Abdomen region (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	135	0	0
MAIS 1	17	0	0
MAIS 2+	25	0	0

Summary of the findings (compared to the overall MAIS model results for side impacts):

- None of the variables were significant in this model.
- The classification rate for this model was 76% which was better than for the overall model (53%), although most of the misclassification was in the injured (MAIS 1 and 2+) occupants being classified as uninjured. As a result, caution should be taken when using this model for predictive purposes.
- The classification table also shows that no occupants were predicted a MAIS score of 1 or 2+ using this model, suggesting that the model form could benefit from better specification.

A.2.4 Lower extremities

This section presents the results of the model for the MAIS scores on the lower extremities for each occupant, using the same variables as in the final model for side impacts (presented in Section 3.2.2). The MAIS value for lower extremities were calculated for each occupant as the maximum of the MAIS for the left and right leg.

Table 29: Coefficients and odds ratios from the final model for side impacts [response variable = MAIS for Lower Extremities (grouped)]

	Coefficients (odds ratios)		
Variable in the model	**MAIS 1**	**MAIS 2+**	**Significant variable?**
Intercept	-1.944 (0.143)	-3.882 (0.021)	N/A
Age	0.017 (1.017)	0.029 (1.029)	No (p = 0.11)
Sex:Male	-1.297 (0.273)	-1.111 (0.329)	Yes (p = 0.008)
CollisionPartner:NarrowObject	1.368 (3.927)	1.819 (6.166)	Yes (p = 0.010)
CollisionPartner:WideObject	1.203 (3.330)	3.595 (36.416)	
CollisionPartner:OtherUnknown	-11.903 (0.000)	-8.334 (0.000)	

Table 30: Classification table for the final model for side impacts [response variable = MAIS for Lower Extremities (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	138	0	1
MAIS 1	27	0	0
MAIS 2+	9	0	2

Summary of the findings (compared to the overall MAIS model results for side impacts):

- Age was not significant in this model unlike in the overall MAIS model for side impacts.
- Similarly to the overall model, sex was significant in this model. The negative coefficient for sex shows that females tend to be in the higher MAIS levels (1 and 2+) relative to uninjured (MAIS 0) more frequently than males (i.e. male occupants' legs are less likely to be injured than female occupants).
- The coefficients for narrow and wide object collision partners for MAIS 2+ injury were both positive (similar to the overall model), indicating that these objects present a high risk of severe injury than cars/LGVs.
- The classification rate for this model was 79% which was better than for the overall model (53%), although most of the misclassification was in the injured (MAIS 1 and 2+) occupants being classified as uninjured. As a result, caution should be taken when using this model for predictive purposes.
- The classification table also shows that no occupants were predicted a MAIS score of 1 using this model, suggesting that the model form could benefit from better specification.

A.2.5 Other regions

This section presents the results of the model for the MAIS scores on other regions for each occupant, using the same variables as in the final model for side impacts (presented in Section 3.2.2). The MAIS value for other regions was calculated for each occupant as the maximum of the MAIS for the neck, pelvis, left arm, right arm and 'other' regions combined.

Table 31: Coefficients and odds ratios from the final model for side impacts [response variable = MAIS for Other regions (grouped)]

	Coefficients (odds ratios)		
Variable in the model	MAIS 1	MAIS 2+	Significant variable?
Intercept	-0.009 (0.991)	-1.315 (0.268)	N/A
Age	-0.007 (0.993)	0.004 (1.004)	No (p = 0.58)
Sex:Male	-0.163 (0.850)	0.075 (1.078)	No (p = 0.85)
CollisionPartner:NarrowObject	0.282 (1.326)	2.556 (12.884)	Yes (p = 0.001)
CollisionPartner:WideObject	1.085 (2.959)	2.490 (12.061)	
CollisionPartner:OtherUnknown	-0.670 (0.512)	-10.871 (0.000)	

Table 32: Classification table for the final model for side impacts [response variable = MAIS for Other regions (grouped)]

	MAIS 0	MAIS 1	MAIS 2+
MAIS 0	81	0	3
MAIS 1	51	0	4
MAIS 2+	26	0	12

Summary of the findings (compared to the overall MAIS model results for side impacts):

- Neither age nor sex were significant in this model; this differs from the overall MAIS model where both were significant.
- The coefficients for narrow and wide object collision partners for MAIS 2+ injury were both positive (similar to the overall model), indicating that these objects present a high risk of severe injury than cars/LGVs.
- The classification rate for this model was 53% which was the same as the overall model.
- The classification table also shows that no occupants were predicted a MAIS score of 1 using this model, suggesting that the model form could benefit from better specification.

Equitable Occupant Protection - The effect of occupant characteristics on injury severity outcomes

Ensuring transport is safe, reliable, and inclusive is central to the UK Department for Transport's (DfT) aim to develop and deliver a transport network that works for everyone. DfT commissioned this study to examine whether there is any evidence of inequity in injury outcomes for seat-belted adult occupants due to characteristics. Real-world collision data from the Road Accident In-Depth Studies (RAIDS) database collected between 2013 and 2023 were used for this study. Multinomial logistic regression analyses were conducted to evaluate the role of occupant characteristics on overall and specific body region injury risks for belted adult front-seat occupants in similar frontal and side-impact crashes. Age was a significant predictor of overall maximum AIS injury in both frontal and side impacts. The older occupants were more prone to overall MAIS 2+ outcomes in both impact types. In frontal impacts, ageing increases the risk of sustaining a MAIS 2+ injury risk in the head, chest, and abdomen body regions. The thorax was the only body region where age significantly influenced the MAIS injury outcome in the side impacts. Occupant sex was a significant predictor of overall MAIS injury only in side impacts. The risk to female was significantly higher when compared to their male counterparts. In both frontal and side impacts, lower extremity injuries to females were significantly higher than males. The study suggests that physiological differences between age and sex have a significant influence on injury severity outcomes. Age and sex-specific injury risk outcomes, particularly to the thorax region for older occupants and lower extremity region for female occupants, suggest the need for crashworthiness improvements that can be addressed through regulatory and consumer crash testing programmes.

Other titles from this subject area

PPR2015	**Pedal Misapplication Study – characteristics of collision relating to pedal misapplication. Karthikeyan Ekambaram, Bethany Frox, Niamh Bull, Emma Lyndon and Hannah Wright. 2023**
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