GDV
Unfallforschung
der Versicherer

COMPACT ACCIDENT RESEARCH REPORT NO. 134

Analysis of Effects of Vehicle Occupant Characteristics on Injury Severity in GIDAS Data

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Press date
10. April 2026

Editorial work
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Design
zwoplus, Berlin

Photo references
Title: gettyimages/Imgorthand
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1. Introduction

In the context of gender equity, the consideration of differences between females and males in science and research has been claimed by various groups and the public. A so-called "gender gap" was also assumed to exist in the development of crash safety of passenger cars because several analyses of crash data from the U.S. had found a higher risk for moderate and severe injuries for female occupants than for male occupants in certain crash scenarios [1, 2, 3].

Concerns were raised in media and in the political environment that this might be due to the use of a crash test dummy (or anthropomorphic test device ATD) in frontal crash tests that represents the size and weight of an average male. However, the fact was ignored that beside the so-called "50th percentile male" also a "5th percentile female" exists in the Hybrid III ATD family. With a height of 150 cm and a weight of 49 kg, the latter represents the lowest fifth percentile in the female population in terms of body height and mass [4]. It is in use since several years for one of the frontal crash test configurations of EuroNCAP (European New Car Assessment Program) on the driver's seat and on the outboard rear seat. Recently, it was also specified for the front passenger seat in the frontal crash test according to ECE-R137 [5].

Analysis of German crash data by the German Insurers Accident Research (UDV) in 2013 showed that female drivers had benefited to a larger degree than their male counterparts from passive safety improvements of occupant safety, driven primarily through EuroNCAP, even though the 50th percentile male was the only dummy used in frontal tests at that time [6]. More recently, UDV conducted a logistic regression analysis based on injury data of over 1,700 car occupants and related vehicle and crash data from their accident database (Insurers Accident Data Base UDB) [7]. The results indicated that sex-related anatomical differences played a minor role for overall injury severity, as expressed by Maximum Abbreviated Injury Scale (MAIS), in frontal impacts. Instead, the seating position in the vehicle or its mass had a much stronger effect on injury severity. However, reliable evaluation of the effects on injury risk under side impact conditions was not possible due to limited case numbers.

The present study once again aims to identify variables that determine injury severity in a car crash with a similar methodology. This time, the German In-Depth Accident Study (GIDAS) which provides more detail and larger case numbers represents the basis for a statistical analysis that builds mainly on multivariate logistic regression to model the probability of injury for given severity levels.

2. Methods

Our study intends to identify variables that have an effect on the probability that an occupant's injury severity reaches a given level, expressed by the maximum AIS value (MAIS) found in an individual. For this, the dependent variable (or predicted variable) MAIS injury severity has to be dichotomous (i.e. MAIS2+ or MAIS0-1) whereas the independent variables (or predictors), e.g. occupant characteristics, vehicle properties or circumstances of the collision, may be dichotomous, categorial with more than two characteristics or may be of continuous nature.

We developed multivariate logistic regression models combining several independent variables to estimate the probability of an "event" occurring – for instance, an injury severity level of MAIS2 or more (MAIS2+) for the occupant – under given crash conditions. The estimator used in logistic regression models to evaluate the effect of an independent variable is the "odds-ratio" (OR). "Odds" is the probability for each category of the independent variables (e.g. "female") of an event taking place (i.e. an occupant sustaining MAIS2+) divided by the probability of the event not taking place, accordingly (i.e. an occupant presenting MAIS0-1, being uninjured or receiving only minor injury severity). For dichotomous independent variables, odds-ratio (OR) is defined as the ratio of the two odds for the event taking place, one being the odds when the independent variable is of a given category (e.g. "female"), the other being the odds when the independent variable is not the category (e.g. "male"). For instance, for "occupant sex" the OR is the odds of sustaining MAIS2+ when the occupant is female divided by the odds of sustaining MAIS2+ injury severity when the occupant is male. In case of OR > 1, women show higher odds for MAIS2+ injury severity than men; with an OR < 1, the odds are lower. When the odds ratio equals one (OR = 1), the odds for MAIS2+ injury severity are the same for female and male occupants.

When the independent variable is a continuous one the odds ratio can be interpreted as a change in odds for the dependent variable per unit change. For instance, for delta-v (change in vehicle velocity due to the collision) an OR = 1.1 would indicate a 10 % increase in the odds of MAIS2+ per each unit increase, i.e. per +1 km/h. This concept assumes a linear correlation between the probability of the event taking place and the continuous variable. Thus, when interpreting results, it should be kept in mind that these conditions do not necessarily apply to the entire domain of values of the continuous variable. If no linear correlation with the dependent variable exists the domain of continuous values is classified into several categories. In this case or when the independent variable is of categorial nature with more than two categories, a reference category is determined and the reported odds ratios will refer to that reference category.

2.1 Univariate statistical analysis

Prior to the multivariate analysis, an univariate analysis of the injury and crash data is conducted in the first step by using univariate logistic regression. It investigates whether a statistically significant correlation exists between a single independent variable, e.g. occupant age, and the dependent variable, i.e. the occurrence of MAIS2+ injury severity. Statistical significance is assumed at a p-level of 0.05 and indicated by an asterisk in data tables hereafter. This is done for all independent variables in the crash database for which a potential effect on injury outcome can be reasonably assumed. The size of valid datasets for analysis may differ when data for an independent variable under investigation are missing for some of the individuals. For instance, body mass, body height or relevant pre-existing diseases may not be reported in all cases.

2.2 Multivariate statistical analysis

In a multivariate logistic regression model the influence of multiple independent variables on the dependent variable can be analysed. From the full list of available independent variables, only those that have shown a significant correlation with injury severity in the univariate analysis are considered for inclusion in the multivariate regression model. The full multivariate regression model will be optimised by subsequently dropping variables that do not contribute to the explanation of the dependent variable. The remaining independent variables are combined and assigned weighting factors, according to the general equation

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k$$

in order to predict the odds of injury severity, e.g. MAIS2+, in the individual datasets to the greatest extent possible (in other words, provides the best explanation of variance in outcome).

The combination of variables requires in theory that there is no interdependence among them, i.e. that they are not interrelated. However, this condition is not fulfilled by all variables in the crash data. Sex and body height, for instance, are not completely independent from each other since adult women are shorter, on average, than adult males. Thus, such variables should not be included in the final model at the same time.

While the concept of a multivariate regression model implies that the smallest number of independent variables from crash data is included that predict the probability of a given injury severity level, one exemption is made for this study. Since occupant sex is of particular interest, this variable will be included in (or "forced into") each multivariate regression model, even if the preceding optimisation process dropped sex from the model initially.

3. Crash and injury data

The analysed real-world crash data comprise GIDAS cases of the years 2000-2019 for belt-restrained adult occupants (aged 18 and over) in passenger cars. Of these passenger cars, only vehicles which were registered for the first time in 2003 or later, or models which were still available on the market in 2003 are included for further analysis since fulfilment of ECE-R94 requirements regarding an offset frontal crash can be assumed. Van-like vehicles are excluded as case vehicles as well as those that had a multi-collision, a rollover or a crash with a vulnerable road user. Furthermore, the collisions are differentiated between frontal impacts, lateral impacts, and rear-impacts. Side crashes are further differentiated between struck-side and non-struck-side impacts – from the perspective of the occupant's seating position – since loading mechanisms on the body may differ and some passive safety components such as side airbags may display their full protective function only in certain impacts.

With the above restrictions, more than 12,000 occupants, both uninjured, injured and a small number of fatally injured, remain for analysis of the effects on injury severity. Documented injuries are coded according to AIS (Abbreviated Injury Scale) Version 2005, Update 2008 [8]. For each occupant, the Maximum AIS is determined to rate the severity, especially, when multiple injuries are present. Occupants with MAIS2+, i.e. involving injuries with a maximum of AIS2 or more, and MAIS3+ (injuries with AIS3 or more) are of primary interest for the analysis. In addition, GIDAS variables related to the vehicle, such as curb mass and airbag deployment, and the kind and severity of the collision, for instance, any crash incompatibility and most importantly, the change in velocity due to the collision (delta-v), are included for the initial consideration.

4. Results

Results for the univariate and the multivariate logistic regression models are presented in the following, both for MAIS2+ and for MAIS3+ outcome in occupants of passenger cars. Body height and mass as well as body mass index BMI are classified into three and two classes, respectively. Variables characterising the vehicle, like year of first registration, curb mass and crash mass (the sum of curb mass and mass of occupants, cargo and half of the fuel tank capacity) are dichotomised. Of the crash characteristics, the change in velocity of the vehicle due to the collision (delta-v) is provided as a continuous variable and the odds ratio given for increments of 1 km/h. Other crash characteristics considered include maximum frontal deformation (dichotomised) and the presence of incompatibility such as impacts against narrow fixed objects or over-running or under-running of vehicle crash structures due to a mismatch with the opponent. Crash opponents are categorised into other passenger cars, heavy vehicles, such as buses or large trucks and fixed objects, such as trees or concrete walls. Lastly, the effect of the occupant position in the vehicle on injury outcome, whether seated in the driver position, on the front passenger seat or on the rear seat, is evaluated.

4.1. Results for univariate logistic regression

Univariate regression is shown here only for the frontal collision scenario. A number of investigated variables presented statistically significant correlation with MAIS2+ (Table 1). Among them were sex with an odds ratio of OR = 1.36 for females versus males, and age with an OR = 2.47 for occupants over 50 years of age versus occupants up to 50 years. Shorter persons (height up to 167 cm) showed a greater chance for MAIS2+ in relation to the reference category (height between 173 cm and 180 cm) and adiposity (i.e. BMI over 30) increased the chance, too. Also, being seated on the front passenger seat or the rear seat showed significant effects with OR = 1.74 and OR = 1.61, respectively, in comparision with the driver's seat position. Of the vehicle properties, curb mass and crash mass had a significant effect, with heavier passenger cars being correlated with smaller chances of MAIS2+. Unfavourable crash circumstances, like collisions with heavy vehicles or fixed objects as well as frontal collision incompatibility had strong effects, presenting the largest odds ratios and high statistical significance. Regarding crash-induced change in velocity as a proxy for the overall severity of the collision, the odds for MAIS2+ increased by circa 8 % with each 1 km/h increment of delta-v.

Related to MAIS3+ injury severity, the results of the univariate regression are less clear (Table 2). Sex, body height and mass as well as BMI showed no statistically significant correlation with MAIS3+ outcome. Merely occupant age had a large effect, similar to the effect on MAIS2+. Delta-v, maximum frontal deformation, heavy vehicles and objects as opponents as well as incompatibility were also strongly correlated with MAIS3+. With regard to the occupant seating position, the model suggested a higher chance of MAIS3+ injury severity for the front passenger seat and the rear seat in relation to the driver's seat. However, the former barely reached statistical significance while the latter missed it, possibly due to small case numbers.

Table 1: Univariate logistic regression for MAIS2+ in frontal collisions

Significant OR's for females, advanced age, higher BMI, front passenger seating position and delta-v

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 209/3504 (6.0 %)	female 205/2575 (8.0 %)	1.36 [1.12; 1.67]	0.002 *
occupant age	≤ 50 yrs. 317/5392 (5.9 %)	> 50 yrs. 98/733 (13.4 %)	2.47 [1.93; 3.13]	< 0.001 *
body height	> 173 cm and < 180 cm 63/879 (7.2 %)	> 167 cm and ≤ 173 cm 84/1019 (8.2 %)	1.16 [0.83; 1.64]	0.382
	-	≥ 180 cm 70/1285 (5.4 %)	0.75 [0.53; 1.06]	0.103
	-	≤ 167 cm 110/1126 (9.8 %)	1.4 [1.02; 1.95]	0.040 *
body mass	> 73 kg and < 85 kg 80/1063 (7.5 %)	> 60 kg and ≤ 73 kg 92/1134 (8.1 %)	1.08 [0.79; 1.48]	0.609
	-	≥ 85 kg 94/1341 (7.0 %)	0.93 [0.68; 1.26]	0.628
	-	≤ 60 kg 86/1334 (6.4 %)	0.85 [0.62; 1.16]	0.302
body mass index BMI	≤ 30 249/3564 (7.0 %)	> 30 65/615 (10.6 %)	1.57 [1.17; 2.08]	0.002 *
max. vehicle front deformation	≤ 17 cm 47/2931 (1.6 %)	> 17 cm 352/2756 (12.8 %)	8.98 [6.67; 12.39]	< 0.001 *
delta-v [km/h]	-	-	1.08 [1.08; 1.09]	< 0.001 *
vehicle year of first registration	≤ 2005 211/3236 (6.5 %)	> 2005 204/2878 (7.1 %)	1.09 [0.90; 1.34]	0.378
vehicle curb mass	≤ 1378.5 kg 236/3117 (7.6 %)	> 1378.5 kg 156/2810 (5.6 %)	0.72 [0.58; 0.88]	0.002 *
vehicle crash mass	≤ 1440 kg 209/2789 (7.5 %)	> 1440 kg 158/2729 (5.8 %)	0.76 [0.61; 0.94]	0.011 *
incompatible frontal collision	no 225/5004 (4.5 %)	yes 190/1121 (16.9 %)	4.33 [3.53; 5.32]	< 0.001 *
crash opponent	passenger car 257/5446 (4.7 %)	heavy vehicle 55/198 (27.8 %)	7.77 [5.52; 10.8]	< 0.001 *
	-	object 103/481 (21.4 %)	5.5 [4.27; 7.06]	< 0.001 *
occupant position	driver's seat 288/4832 (6.0 %)	front passenger seat 102/1028 (9.9 %)	1.74 [1.37; 2.19]	< 0.001 *
	-	rear seat 24/259 (9.3 %)	1.61 [1.02; 2.44]	0.032 *

Table 2: Univariate logistic regression for MAIS3+ in frontal collisions

Significant OR's for advanced occupant age and crash-related variables like delta-v, frontal deformation and crash compatibility

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 56/3504 (1.6 %)	female 46/2575 (1.8 %)	1.12 [0.75; 1.66]	0.573
occupant age	≤ 50 yrs. 76/5392 (1.4 %)	> 50 yrs. 27/733 (3.7 %)	2.68 [1.68; 4.12]	< 0.001 *
body height	> 173 cm and < 180 cm 15/879 (1.7 %)	> 167 cm and ≤ 173 cm 15/1019 (1.5 %)	0.86 [0.42; 1.78]	0.683
	-	≥ 180 cm 16/1285 (1.2 %)	0.73 [0.36; 1.49]	0.377
	-	≤ 167 cm 28/1126 (2.5 %)	1.47 [0.79; 2.84]	0.234
body mass	> 73 kg and < 85 kg 16/1063 (1.5 %)	> 60 kg and ≤ 73 kg 16/1134 (1.4 %)	0.94 [0.46; 1.90]	0.854
	-	≥ 85 kg 24/1341 (1.8 %)	1.19 [0.64; 2.30]	0.589
	-	≤ 60 kg 27/1334 (2.0 %)	1.35 [0.73; 2.58]	0.343
body mass index BMI	≤ 30 55/3564 (1.5 %)	> 30 14/615 (2.3 %)	1.49 [0.79; 2.61]	0.190
max. vehicle front deformation	≤ 17 cm 5/2931 (0.2 %)	> 17 cm 93/2756 (3.4 %)	20.44 [9.20; 58.04]	< 0.001 *
delta-v [km/h]	-	-	1.10 [1.08; 1.11]	< 0.001 *
vehicle year of first registration	≤ 2005 53/3236 (1.6 %)	> 2005 50/2878 (1.7 %)	1.06 [0.72; 1.57]	0.763
vehicle curb mass	≤ 1378.5 kg 56/3117 (1.8 %)	> 1378.5 kg 43/2810 (1.5 %)	0.85 [0.57; 1.27]	0.425
vehicle crash mass	≤ 1440 kg 54/2789 (1.9 %)	> 1440 kg 41/2729 (1.5 %)	0.77 [0.51; 1.16]	0.217
incompatible frontal collision	no 51/5004 (1.0 %)	yes 52/1121 (4.6 %)	4.72 [3.19; 7.00]	< 0.001 *
crash opponent	passenger car 46/5446 (0.8 %)	heavy vehicle 22/198 (11.1 %)	14.67 [8.5; 24.65]	< 0.001 *
	-	object 35/481 (7.3 %)	9.21 [5.84; 14.41]	< 0.001 *
occupant position	driver's seat 71/4832 (1.5 %)	front passenger seat 24/1028 (2.3 %)	1.60 [0.98; 2.52]	0.048 *
	-	rear seat 7/259 (2.7 %)	1.86 [0.77; 3.82]	0.121

4.2. Results for multivariate logistic regression

Multivariate regression was performed not only for frontal crashes, but also for side crashes and rear-impact collision scenarios. Except for rear-impacts, separate models for the outcome of the dependent variable, MAIS2+ and MAIS3+, were developed. As explained above, each model comprises different sets of variables that have remained after the optimisation process.

4.2.1 Multivariate logistic regression for frontal collisions

Results for the model for all frontal collisions and MAIS2+ injury severity are provided in Table 3. Female sex showed an OR = 1.43 in comparison with male sex and was statistically significant. Occupants over 50 years of age presented an even higher odds ratio (OR = 2.14) in comparison to those aged 50 and under, also statistically significant. Other occupant-related variables, like body height or weight and BMI were dropped in the final model. The seating position in the vehicle, namely the front passenger, had an effect on MAIS2+ (OR = 1.48) in relation to the driver position as the reference category. Crash circumstances like delta-v (OR = 1.08 per 1 km/h), crashes involving heavy vehicles and objects or incompatibility presented significant effects whereas vehicle properties, such as year of first registration or curb weight, played no role in the model. The variance explained by the model amounted to circa 27 %.

Table 3: Multivariate logistic regression for MAIS2+ in frontal collisions

Significant OR's for females, advanced occupant age and the front passenger position, but also for crash-related variables

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 209/3414 (6.1 %)	female 204/2497 (8.2 %)	1.43 [1.12; 1.81]	0.004 *
occupant age	≤ 50 yrs. 315/5191 (6.1 %)	> 50 yrs. 98/720 (13.6 %)	2.14 [1.60; 2.83]	< 0.001 *
delta-v [km/h]	-	-	1.08 [1.07; 1.08]	< 0.001 *
incompatible frontal collision	no 224/4801 (4.7 %)	yes 189/1110 (17.0 %)	2.41 [1.90; 3.05]	< 0.001 *
crash opponent	passenger car 257/5251 (4.9 %)	heavy vehicle 53/192 (27.6 %)	1.55 [1.02; 2.33]	0.038 *
	-	object 103/468 (22.0 %)	2.14 [1.57; 2.88]	< 0.001 *
occupant position	driver's seat 287/4663 (6.2 %)	front passenger seat 102/996 (10.2 %)	1.48 [1.11; 1.97]	0.007 *
	-	rear seat 24/252 (9.5 %)	1.31 [0.77; 2.12]	0.294
Total cases (occupants): 5,911, explained variance: 27.3 %				

For MAIS3+ injury severity, the model included only four variables after optimisation, but sex was forced in deliberately (Table 4). With OR = 1.29, its effect was smaller than for MAIS2+ injury severity. Moreover, the result clearly missed statistical significance. Occupant age, however, remained in the model as a strong predictor (OR 2.35) while seating position was dropped. Delta-v, heavy vehicles as opponents and collisions with an object and incompatibility were significantly correlated with MAIS3+ injury severity. The percentage of explained variance was comparatively high with approximately 36 %.

Table 4: Multivariate logistic regression for MAIS3+ in frontal collisions

Significant OR's for advanced age, the crash opponent and incompatibilty, but not for sex and the occupant's seating position

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 56/3417 (1.6 %)	female 46/2500 (1.8 %)	1.29 [0.82; 2.03]	0.270
occupant age	≤ 50 yrs. 75/5197 (1.4 %)	> 50 yrs. 27/720 (3.8 %)	2.35 [1.38; 3.90]	0.001 *
delta-v [km/h]	-	-	1.09 [1.07; 1.10]	< 0.001 *
incompatible frontal collision	no 51/4807 (1.1 %)	yes 51/1110 (4.6 %)	2.26 [1.43; 3.55]	< 0.001 *
crash opponent	passenger car 46/5254 (0.9 %)	heavy vehicle 21/195 (10.8 %)	2.08 [1.07; 3.91]	0.026 *
	-	object 35/468 (7.5 %)	2.53 [1.49; 4.23]	< 0.001 *
Total cases (occupants): 5,917, explained variance: 36.3 %				

Since the results of the multivariate logistic regression for all frontal collisions suggest that seating position affects injury outcome, at least at MAIS2+ level, logistic regression models were also run separately for drivers and for front seat passengers, respectively, in frontal collisions. For the model of drivers in frontal collisions, sex was forced in, both for MAIS2+ and MAIS3+ injury severity (Table 5, Table 6). With OR = 1.15 and not being statistically significant, the model provided no evidence that female drivers have higher odds than men to sustain MAIS2+. Similar to the results for all frontal collisions with MAIS2+ outcome, the final model comprised driver age and variables that reflect crash severity. For the first time, vehicle crash mass was included, but the OR missed statistical significance by a small margin.

For MAIS3+ injury severity of drivers, sex and age had no effect at all. Only delta-v (OR = 1.10), collisions with a fixed object and incompatibility showed statistical significance. Despite the small number of predictors remaining in the model, the variance was captured well (nearly 41 %).

Table 5: Multivariate logistic regression for MAIS2+ in frontal collisions, driver

Significant OR's only for advanced occupant age and crash-related variables when focusing on driver's seat

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 154/2677 (5.8 %)	female 95/1539 (6.2 %)	1.15 [0.84; 1.58]	0.370
occupant age	≤ 50 yrs. 197/3757 (5.2 %)	> 50 yrs. 52/459 (11.3 %)	2.13 [1.45; 3.08]	< 0.001 *
delta-v [km/h]	-	-	1.07 [1.07; 1.08]	< 0.001 *
vehicle crash mass	≤ 1440 kg 164/2262 (7.3 %)	> 1440 kg 85/1954 (4.4 %)	0.73 [0.53; 1.00]	0.054
incompatible frontal collision	no 137/3440 (4.0 %)	yes 112/776 (14.4 %)	2.37 [1.75; 3.20]	< 0.001 *
crash opponent	passenger car 152/3762 (4.0 %)	heavy vehicle 27/118 (22.9 %)	1.41 [0.79; 2.43]	0.229
	-	object 70/336 (20.8 %)	2.22 [1.52; 3.21]	< 0.001 *
Total cases (occupants): 4,216, explained variance: 27.4 %				

Table 6: Multivariate logistic regression for MAIS3+ in frontal collisions, driver

No effect of sex and age, significant OR's only for crash-related variables like delta-v and collisions with a fixed object when focusing on driver's seat

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 47/2967 (1.6 %)	female 23/1696 (1.4 %)	0.98 [0.54; 1.76]	0.955
delta-v [km/h]	-	-	1.10 [1.08; 1.11]	< 0.001 *
incompatible frontal collision	no 32/3789 (0.8 %)	yes 38/874 (4.3 %)	2.78 [1.59; 4.88]	< 0.001 *
crash opponent	passenger car 30/4161 (0.7 %)	heavy vehicle 12/137 (8.8 %)	1.74 [0.73; 3.93]	0.195
	-	object 28/365 (7.7 %)	2.79 [1.49; 5.14]	0.001 *
Total cases (occupants): 4,663, explained variance: 40.7 %				

In analogy to the driver's seat, the front passenger position was evaluated regarding variables with a potential effect on the odds of sustaining MAIS2+ and MAIS3+, respectively (Table 7, Table 8). The odds ratio OR = 2.01 indicated that with female sex the chance to sustain MAIS2+ injury severity is approximately twice as high in comparison with male front seat passengers, the result being statistically significant. With OR = 2.25, age over 50 years had an even larger effect. The results for the variables delta-v, the presence of an incompatible frontal collision and crashes into an object were similiar to those found for the driver position (Table 5). Again, the odds ratio when the opponent was a heavy vehicle was not significant, possibly due to small case numbers. With approximately 23 %, the explained variance of the model was the lowest of all frontal collision models.

For MAIS3+ injury severity of front seat passengers, merely occupant age and delta-v were of significance. Front seat passengers over 50 years showed a nearly five-fold chance (OR = 4.88) for MAIS3+ in comparison with those aged up to 50. Again, sex was forced into the model, but the OR = 1.76 did not come close to statistical significance. Generally, the case numbers for front seat passengers sustaining MAIS3+ were small. The captured variance was 24 %.

Table 7: Multivariate logistic regression for MAIS2+ in frontal collisions, front passenger

Results similar to those for the driver when focusing on passenger seat, except for females with a chance twice as large as for males

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 24/342 (7.0 %)	female 78/654 (11.9 %)	2.01 [1.17; 3.58]	0.014 *
occupant age	≤ 50 yrs. 64/807 (7.9 %)	> 50 yrs. 38/189 (20.1 %)	2.25 [1.35; 3.71]	0.002 *
delta-v [km/h]	-	-	1.06 [1.05; 1.08]	< 0.001 *
incompatible frontal collision	no 57/806 (7.1 %)	yes 45/190 (23.7 %)	2.49 [1.52; 4.06]	< 0.001 *
crash opponent	passenger car 70/880 (8.0 %)	heavy vehicle 13/39 (33.3 %)	1.33 [0.55; 3.08]	0.510
	-	object 19/77 (24.7 %)	2.25 [1.12; 4.36]	0.019 *
Total cases (occupants): 996, explained variance: 22.5 %				

Table 8: Multivariate logistic regression for MAIS3+ in frontal collisions, front passenger

Only two variables with an effect on injury outcome: age with particularly high odds ratio and delta-v

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 5/342 (1.5 %)	female 19/654 (2.9 %)	1.76 [0.64; 5.74]	0.303
occupant age	≤ 50 yrs. 11/807 (1.4 %)	> 50 yrs. 13/189 (6.9 %)	4.88 [2.02; 12.09]	< 0.001 *
delta-v [km/h]	-	-	1.07 [1.05; 1.09]	< 0.001 *
Total cases (occupants): 996, explained variance: 24.1 %				

4.2.2 Multivariate logistic regression for side-impact collisions

Separate models were fit, both for MAIS2+ and MAIS3+ injury severity, for occupants seated on the struck side of the vehicle and for those seated on the non-struck-side, the latter also including any occupants on center seats. Tables 9 and 10 provide the results for the struck side and MAIS2+ and MAIS3+ outcome, respectively. For MAIS2+, occupant age and impact severity, expressed by delta-v, had the greatest effect. Sex had little effect, but most importantly, the result was not significant. Curb mass as a variable indicated that heavier vehicles were associated with smaller chances of MAIS2+, but the result (OR = 0.46) barely missed statistical significance. The case numbers for MAIS3+ injury severity were very small, but suggested that occupant age and delta-v had a particularly large effect on injury outcome. For sex, the odds ratio was high with a nearly four-fold chance for females, however, this result was missing significance. Still, the captured variance was greater than 50 %.

Table 9: Multivariate logistic regression for MAIS2+ in side collisions (struck side)

Large and significant effects for advanced occupant age and delta-v, but no significant effect of sex

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 23/526 (4.4 %)	female 21/456 (4.6 %)	1.17 [0.58; 2.37]	0.670
occupant age	≤ 50 yrs. 31/859 (3.6 %)	> 50 yrs. 13/123 (10.6 %)	3.15 [1.44; 6.62]	0.003 *
delta-v [km/h]	-	-	1.10 [1.07; 1.13]	< 0.001 *
vehicle curb mass	≤ 1378.5 kg 34/549 (6.2 %)	> 1378.5 kg 10/433 (2.3 %)	0.46 [0.19; 1.00]	0.061
Total cases (occupants): 982, explained variance: 24.8 %				

Table 10: Multivariate logistic regression for MAIS3+ in side collisions (struck side)

Side crashes with occupants on struck side based on very few cases with large and significant effects only for occupant age and delta-v

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 7/540 (1.3 %)	female 8/466 (1.7 %)	3.97 [0.95; 21.05]	0.073
occupant age	≤ 50 yrs. 10/880 (1.1 %)	> 50 yrs. 5/126 (4.0 %)	6.78 [1.60; 29.02]	0.008 *
delta-v [km/h]	-	-	1.16 [1.11; 1.22]	< 0.001 *
Total cases (occupants): 1,006, explained variance: 51.3 %				

For the non-struck side, occupant sex (OR = 2.53) and age (OR = 3.69) and delta-v were the only variables in the model and had a considerable effect on MAIS2+ probability (Table 11).

For MAIS3+ outcome, the case numbers were particularly small (Table 12). Only nine occupants out of a total of 761 receiving a far-side impact sustained MAIS3+. The odds ratio for sex was OR = 1.56, but not significant. Delta-v had a large effect and was the only variable with statistical significance. Yet, with nearly 54 %, the explained variance was the largest among all models.

Table 11: Multivariate logistic regression for MAIS2+ in side collisions (non-struck side)

Side crashes with occupants on struck side based on very few cases with large and significant effects only for occupant age and delta-v

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 12/424 (2.8 %)	female 19/337 (5.6 %)	2.53 [1.10; 6.16]	0.033 *
occupant age	≤ 50 yrs. 18/643 (2.8 %)	> 50 yrs. 13/118 (11.0 %)	3.69 [1.51; 8.78]	0.003 *
delta-v [km/h]	-	-	1.15 [1.10; 1.19]	< 0.001 *
Total cases (occupants): 761, explained variance: 30.6 %				

Table 12: Multivariate logistic regression for MAIS3+ in side collisions (non-struck side)

Delta-v the only significant variable, having a particularly large effect

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 5/424 (1.2 %)	female 4/337 (1.2 %)	1.56 [0.27; 9.60]	0.611
delta-v [km/h]	-	-	1.23 [1.15; 1.36]	< 0.001 *
Total cases (occupants): 761, explained variance: 53.6 %				

4.2.3 Multivariate logistic regression for rear-impact collisions

Due to the small number of occupants with MAIS2+, altogether, 17 in the GIDAS dataset, an evaluation is not considered meaningful. Instead, a multivariate logistic regression model was fit for MAIS1+ outcome, i.e. occupants with any coded injury severity after a rear impact, as opposed to uninjured occupants (MAIS0) (Table 13).

Table 13: Multivariate logistic regression for MAIS1+ in rear-impact collisions

Model for MAIS1+ with several significant variables, among them sex, seating position and delta-v, but the overall model captures the variance poorly

Independent variable	Reference category	Effect category	Odds Ratio with confidence interval	p-value
occupant sex	male 692/1417 (48.8 %)	female 862/1281 (67.3 %)	1.92 [1.63; 2.28]	< 0.001 *
occupant age	≤ 50 yrs. 1473/2520 (58.5 %)	> 50 yrs. 81/178 (45.5 %)	0.49 [0.35; 0.68]	< 0.001 *
delta-v [km/h]	-	-	1.05 [1.04; 1.07]	< 0.001 *
vehicle crash mass	≤ 1440 kg 842/1275 (66.0 %)	> 1440 kg 712/1423 (50.0 %)	0.57 [0.48; 0.67]	< 0.001 *
crash opponent	passenger car 1469/2587 (56.8 %)	heavy vehicle 80/97 (82.5 %)	2.83 [1.67; 5.06]	< 0.001 *
	-	object 5/14 (35.7 %)	0.45 [0.13; 1.43]	0.188
occupant position	driver's seat 1058/1910 (55.4 %)	front passenger seat 381/598 (63.7 %)	1.32 [1.08; 1.63]	0.007 *
	-	rear seat 115/190 (60.5 %)	1.28 [0.93; 1.78]	0.131
Total cases (occupants): 2,698, explained variance: 7.7 %				

Sex had a significant effect with an odds ratio of OR = 1.92, i.e. nearly twice the chance for injury, i.e. MAIS1+, in females in relation to males. Interestingly, the odds ratio for occupant age (OR = 0.49) suggested that the probability of injury for occupants over 50 years was only half of that for younger occupants. This is in strong contrast to the results from the other collision scenarios. Lower vehicle (crash) mass and heavy vehicles as well as higher delta-v speed significantly increased the probability of injury. In comparison with the driver's seat, only the front passenger position was associated with a significantly greater chance of injury. However, with less than 8 %, the captured variance was by far the poorest of all models.

5. Discussion and conclusions

The results of this study underline the importance of occupant age and – as could be expected – impact severity as variables that determine the probability of moderate (MAIS2+) and serious (MAIS3+) injuries. Interestingly, vehicle metrics, such as mass or year of first registration, played no role in the large majority of multivariate models. Likely, these characteristics are reflected already in the change of velocity (delta-v) due to the impact. In most of the frontal collision models, incompatible collisions and crashes into objects presented a greater chance of MAIS2+ than collisions with other passenger cars and with compatible structures. The model fit for all frontal collisions showed a greater chance (OR = 1.48) to sustain MAIS2+ on the front seat passenger seat in comparison to the driver's seat whereas the differences were not significant for passengers on the rear seat, possibly due to a relatively small number of occupants there.

Therefore, separate models for frontal collisions were fit for the driver and the front passenger position. Both models presented similar effects on MAIS2+ for the variables occupant age, delta-v, incompatibility and type of crash opponent, whereas their results differed considerably for the effect of sex. While the odds ratio for female drivers in comparison with male drivers was close to 1 (OR = 1.15) and failed to reach statistical significance, sex had a considerable effect on MAIS2+ injury probability for the front passenger position: the results suggested that the chance for MAIS2+ on the front passenger seat was twice as great for females as for males. The reasons are unknown, e.g. whether the difference is caused by anatomical differences, variation in body height or mass or potential differences in seating posture. Interestingly, while body height and body mass index showed a moderate relationship with MAIS2+ in the univariate regression analysis, these variables were dropped for the final multivariate frontal collision models. When only MAIS3+ injury severity was considered, the number of variables in the frontal collision models that had a significant effect on injury outcome became smaller. Variables characterising crash severity such as delta-v and incompatibility then dominated with even larger effects than for MAIS2+ injury severity. In contrast, sex showed no significant effect on MAIS3+ outcome. Occupant age was not incorporated in the driver model for MAIS3+ whereas it displayed a strong effect (OR = 4.88) in the front passenger model.

The multivariate regression models for side impact collisions consisted of only a few variables that had a larger effect on MAIS2+ and MAIS3+ than in most of the frontal collision models. Essentially, occupant age and delta-v appeared to determine the probability of moderate and serious injuries. Occupant sex showed a considerable effect for MAIS2+ (OR = 2.53) for occupants on the non-struck side. With OR = 3.97, the effect was even stronger for MAIS3+ for occupants on the struck side, but statistical significance was just missed, possibly due to merely 15 occupants, altogether, who were seated on the struck side and sustained MAIS3+.

Generally, the results for frontal and side collisions suggested that, with higher injury severity level, fewer variables determined the outcome. These were mainly metrics that characterise the severity or incompatibility of a crash and occupant age which is likely a proxy for the vulnerability of the occupant. Yet, it is remarkable that these models presented the highest level of explanation of variance, i.e. despite their small number, these variables contributed to a meaningful model. Other variables relating to the occupant, such as BMI or pre-existing diseases were either dropped during the model optimisation or provided too few individuals with documentation of these variables so that fitting a multivariate model was not meaningful.

Analysis of rear-impact collisions had to be extended to MAIS1+ injury severity because of very few occupants with AIS2+ injuries in GIDAS. While the results demonstrated that several variables, among them sex and delta-v significantly affected the probability of an injury occurring, even if minor, the poor level of explanation of variance suggested that injury outcome in these types of collisions was determined to a large degree by other, mostly unknown variables that were not reflected in GIDAS.

While building on a large database, controlling for variables like belt status and focusing on modern vehicles, our study has limitations, still. Namely, some variables, such as body height and mass, were missing in several datasets which prevented more detailed analysis of the possible effect of occupant stature on injury severity. Sex appears to be of significance much more on the front passenger seat than on the driver's seat and should be reason to further investigate into the types of AIS2+ injuries sustained in frontal crashes and whether differences can be attributed to stature, anatomy, seating posture and/or restraint system layout. Physical crash test dummies cannot reflect details of individual occupants sufficiently. Human body models which allow such variations in numerical crash simulation, in principle, should be used to gain further insights before new ATD sizes, based on current designs, are demanded.

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