TWO CAR FRONTAL COLLISIONS: THE ROLE OF CAR MASS, COLLISION SPEED DISTRIBUTION AND FRONTAL STIFFNESS IN OCCUPANT FATALITY AND INJURY

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ABSTRACT
There is controversy regarding the role of car mass in injury and fatality risk in individual car-to-car collisions and for overall car populations. In addition, the effect of frontal stiffness on both the case and partner cars is disputed, and the role of the distribution of collision closing speed has not been adequately examined. In this paper empirical car crash characteristics derived from onboard crash recorders are combined with risk functions based on mean vehicle acceleration. The model predictions closely match the available real life data for frontal collisions for the US (fatalities), Japan and Germany (AIS3+).

The model is used to predict the roles of case car mass, population car mass, collision closing speed distributions and frontal stiffness in relative vehicle safety. Results show that increasing the 50%*ile* car mass from 1200-1600kg reduces the AIS3+ injury to drivers by 4%, while decreasing the 50%*ile* car mass from 1200-800kg increases overall risk by 15%. By comparison, reducing the 99.99%*ile* collision speed from 200-150km/h reduces injury risk by 14%, but reducing the 50%*ile* collision speed from 60-50km/h reduces injury risk by 31%. Finally, a car population with the structural characteristics of the 'soft' 50%*ile* reduces injury risk by 23%.

Keywords: frontal collision, injury risk, vehicle mass and collision closing speed

RESEARCH INTO TWO CAR COLLISIONS over the past 25 years has shown that injury severity increases as car mass reduces and that car size is a factor even in single vehicle collisions [1-7]. However, it was recently suggested that the mass/size effect is really a surrogate for the frontal stiffness characteristics of cars [8]. No single parameter is responsible for the observed effects, with collision pattern, speed, restraint type, age, health etc. all influencing injury outcome.

Conservation of momentum has long been used to estimate change in vehicle velocity (ΔV), which then became the measure of collision severity. However, Ydenius showed that the mean acceleration experienced by the car is a better predictor of injury risk than ΔV [9]. In recent research [10-12] onboard collision recorders in frontal collisions were used to obtain empirical relations for mean vehicle acceleration as a function of size, mass, structure and collision severity.

Mechanics dictates that occupant acceleration is a key factor in injury risk, and this is the vehicle acceleration transformed by the occupant restraint system. Using this approach, Evans' [13] empirical ΔV versus risk functions derived from the Fatal Accident Reporting System [14] have been re-analysed to yield risk equations as a function of car mean acceleration. These functions, combined in Monte Carlo simulations with empirical equations describing the car population [10-11], yield injury and fatality risk in frontal collisions between pairs of cars within any car population of known mass and collision speed distribution.

INJURY RISK MODEL
The three fundamental factors for injury risk in frontal collisions are (1) structural and crashworthiness characteristics of the vehicles, (2) distribution of collision velocities and (3) injury risk functions.

Structural and crashworthiness characteristics of the vehicles: The fundamental structural parameter for cars is the crumpling stress/density ratio, σ/ρ, which is independent of car size and mass and is equivalent to the specific energy absorption capacity, $\bar{a}L$ [10, 11, 15]. Power regressions of the form

$$\bar{a}.L = \sigma/\rho = C_{da}.(d/L)^{da} \quad [1a]$$

$$\bar{a}.L = C_{va}.\Delta V^{va} \quad [1b]$$

performed on real accident crash recorder data show high statistical correlations, where C_{da} is the key stress/density parameter and is independent of mass, while d_a is a primarily a function of C_{da} [10]. Similarly, mean vehicle acceleration ($\bar{a}$) is related to ΔV [10-11]:

$$\bar{a} = \frac{C_{va}}{L} \cdot \Delta V^{v_a} \quad [2]$$

where L is vehicle length and C_{Va} and v_a are regression parameters which are functions of the crumpling stress/density ratio (σ/ρ) and vehicle mass. Combining these empirical relations with a geometric crush model yielded accurate predictions for the variation of mean vehicle acceleration with collision overlap [12].

Distribution of collision velocities: The independent crash parameter is collision closing speed (*CCS*). However, the available data is in the form of velocity change, Δv, which is a related to mass and *CCS*:

$$\Delta v_{1,2} = \left[\frac{M_{2,1}}{M_1 + M_2}\right] V_{CCS} \quad [3]$$

In countries with in-depth accident research, Δv and mass distributions for tow away-plus collisions are available. Analysis of these for the US vehicle population [13-14] showed that both Δv and mass distributions have approximately log normal distributions and the mean/variance of the *CCS* is therefore

$$\left[\ln(V_{CCS})\right]_{mean/\mathrm{var}} = \left[\ln(\Delta v_{1,2})\right]_{mean/\mathrm{var}} - \left[\ln\left(M_{2,1}/(M_1 + M_2)\right)\right]_{mean/\mathrm{var}} \quad [4]$$

By this means the *CCS* distributions for different countries were derived.

Injury risk functions: Evans [13] reported injury risk functions for discrete ΔV intervals for US tow-away accidents for the four cases of AIS3+ injuries and fatalities for belted/unbelted drivers respectively, and included the distribution of ΔV for these accidents. The US car mass distribution obtained from FARS [14] was combined with the ΔV distribution to yield the *CCS* using equations 3&4. The mean car mass for each of Evans' ΔV intervals was determined and equation 1 was then used to convert Evans' equations to $\bar{a}$ versus risk functions. Joksch [16] has proposed an empirical injury risk function given by eq 5a, where $\Delta v_{\mathrm{critical}}$ is the lower limit of Δv for which risk equals 1.0. For $\Delta v > \Delta v_{\mathrm{critical}}$, P_i=1. In this paper it is proposed that injury risk is a function of mean acceleration (eq 5b) in which $\bar{a}_{\mathrm{critical}}$ is now the lower limit of $\bar{a}$ for which risk equals 1.0. The empirical constants $\bar{a}_{\mathrm{critical}}$ and n are derived by regression of real world injury risk data, see table 1. Folksam Research [17] reported risk probability for AIS 2+ belted front seat occupants based on 72 frontal injury collisions, including some cases with airbags. The regression parameters are detailed in table 1.

$$P_i(\Delta v) = \left(\frac{\Delta v}{\Delta v_{critical}}\right)^n \quad [5a], \qquad P_i\left(\bar{a}\right) = \left(\frac{\bar{a}}{\bar{a}_{critical}}\right)^n \quad [5b]$$

Table 1 Injury & Fatality Risk : Regression Parameters: (N = sample size)

Case	$\bar{a}_{critical}$ (g)	n	r^2	N
Belted Driver Fatality	19.72	6.168	0.96	13
Belted Driver AIS 3+ Injury	19.25	3.68	0.93	13
Unbelted Driver Fatality	20.05	4.9	0.96	14
Unbelted Driver AIS 3+ Injury	19.05	3	0.94	12
Folksam Belted AIS 2+ Injury	18.07	1.95	0.96	8

VALIDATION

There are three separate validations of this model.

Vehicle structural model: The structural model used in this paper was previously combined with a geometric crush shape model and generalized full-width barrier characteristics for the car population, the distributions of overlap in frontal collisions, and distributions of crush profiles (segmental and triangular) to predict the frontal collision characteristics of the car population [12,18]. The results correspond closely to the real-accident data obtained from onboard collision recorders for 16 car types in 269 collisions, confirming that the mean and variability obtained from the collision recorders reflects the aggregate effects of car type, collision configuration, collision partner and crush type.

Risk functions in frontal collisions: Comparison of $\bar{a}_{critical}$ for US AIS 3+ injuries with $\bar{a}_{critical}$ from the Folksam AIS 2 + shows no significant difference (t = 0.54), see table 1. Evans [13] reported fatality risk versus Δv for frontal collisions for belted/unbelted drivers from 1982-1991. Using the proportion of belted drivers over this period [19] and the procedures described above the predicted fatality risk was computed using the regression data in table 1. Figure 1 shows the comparison. Correlation analysis shows a coefficient of determination, r^2 = 0.919 with a proportionality coefficient = 1.006 and standard error = 0.09. Figure 2 compares the derived AIS 3+ belted injury relation with recent Folksam AIS 3+ injury risk data derived from 18 AIS 3+ frontal injury collisions. Analysis shows that there is no significant difference between the risk equation and the Folksam data (p> 5%).

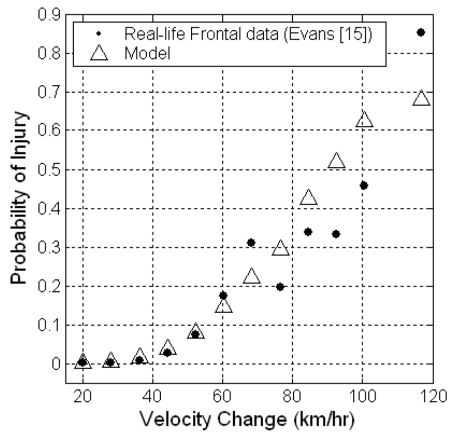


Figure 1: Risk versus Δv

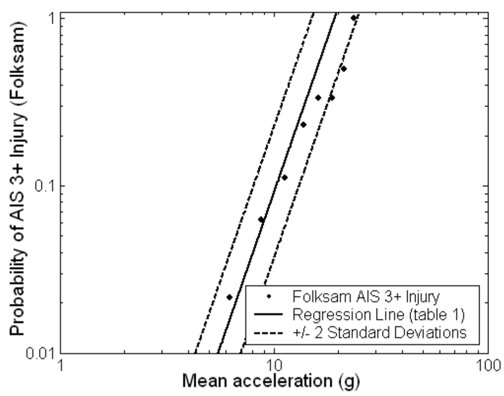


Figure 2: Risk versus $\bar{a}$

Model comparison with real life population data: Figure 3 compares the relative fatality risk to drivers as a function of car to car mass ratio in frontal collisions for 1991-1994 for the US [20] with the predictions using the fatality risk functions in table 1 and the ratio of reported seatbelt use [19]. Mass ratio is the defined as the ratio of heavier vehicle mass to the lighter vehicle mass. The predicted injury risk versus mass ratio and the real world data closely match (t = -1.06). Figure 4 compares the relative AIS 3 + injury risk to drivers as a function of car to car mass ratio in Japan [21] from 1992-1995 with the model predictions, showing close correspondence (t = 0.95).

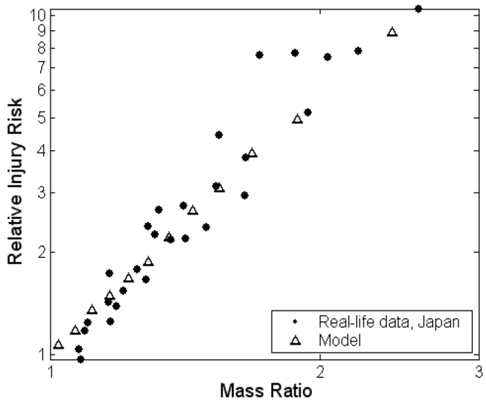


Figure 3: Relative Injury risk versus mass ratio

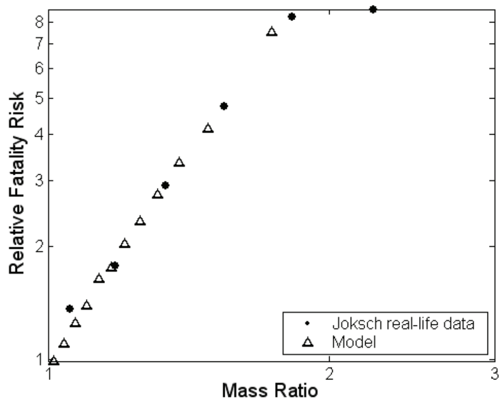


Figure 4: Relative Fatality risk versus mass ratio

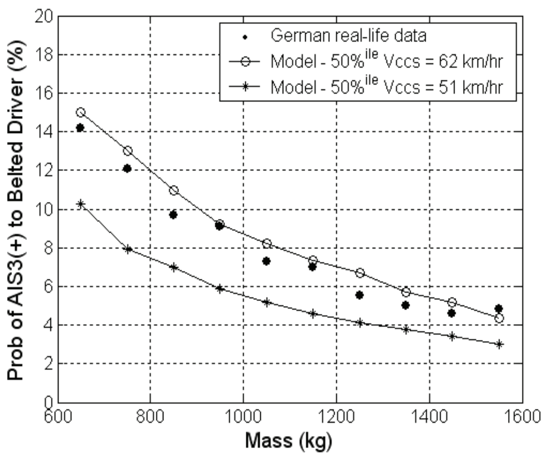


Figure 5: Driver risk versus vehicle mass

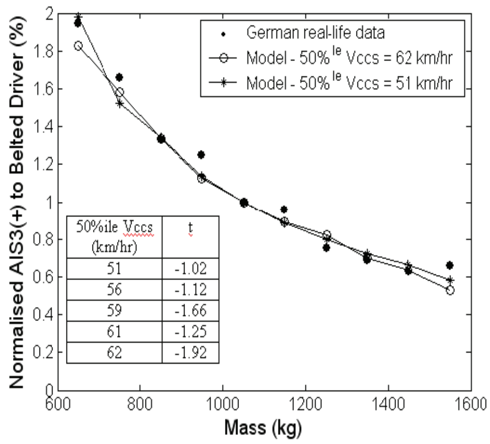


Figure 6: Normalised Driver risk versus vehicle mass

Ernst et al [22] reported on the variation in AIS 3+ injury car mass in rural two car frontal collisions in Rhine Westphalia between 1984 and 1988. The V_{CCS} distribution for Rhine Westphalia was not available, so instead overall data for West Germany for the period 1973-1988 was used [23]. Figure 5 shows the real world variation in AIS 3+ risk with car mass compared with the predicted results for 50%^{ile} collision closing speeds between 51 km/hr and 62 km/hr. The absolute risk is very sensitive to the magnitude of the 50%^{ile} V_{CCS}. A 50% increase in injury risk for all cars results from a 20% increase in 50%^{ile} Vccs - from 52km/h to 62 km/h. Figure 5 shows that predicted risk varies with mass in a similar manner to the real world data and bounds the data. Figure 6 shows the close match between real world variation in risk with mass normalized for the 50%^{ile} German car mass (1050 kg). Statistical analysis of the normalised data for different 50%^{ile} closing speeds shows no significant difference between the real world data and the model predictions, see figure 6.

INFERENCES FROM INJURY RISK MODEL

The close correlation between the model predictions and the available test data means that the model can be used to investigate the influence of vehicle and crash characteristics on injury risk.

Variation in Mean Risk with Velocity Change, ΔV: Figure 7 shows the mean probability of AIS3+ as a function of car mass and ΔV. This is the mean acceleration data for the car population transformed by the injury risk functions (see table 1) [10 12 18].

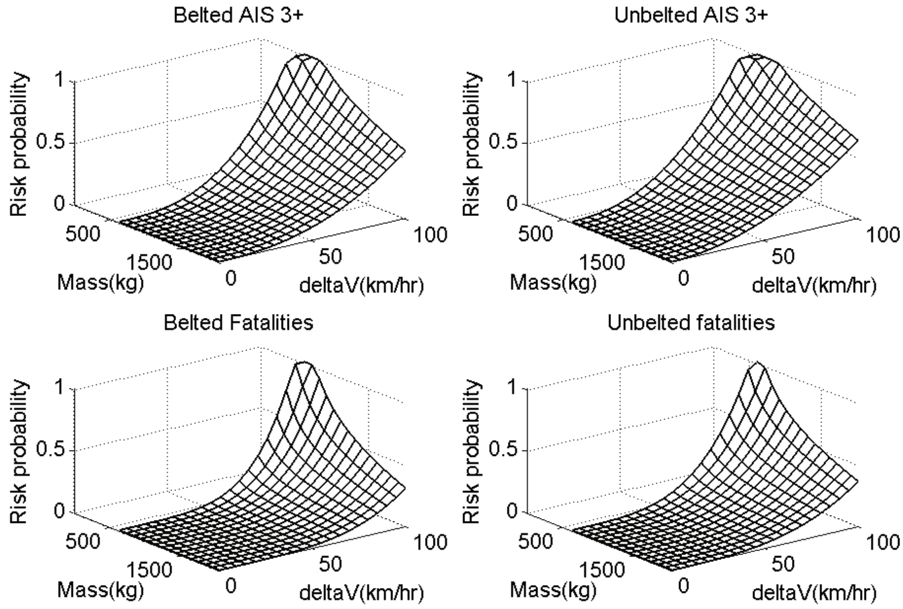


Figure 7: Risk as a function of mass and ΔV.

Variation in Mean Risk with Mass and Collision Closing Speed: For the sake of brevity, the remaining analysis considers only the AIS 3+ injury risk for belted drivers. Similar trends are easily shown for AIS3+ unbelted, and for belted / unbelted fatalities. Figure 8 shows the variation in injury risk with mass of car and partner car for $V_{CCS} =$ 60/120 km/h respectively.

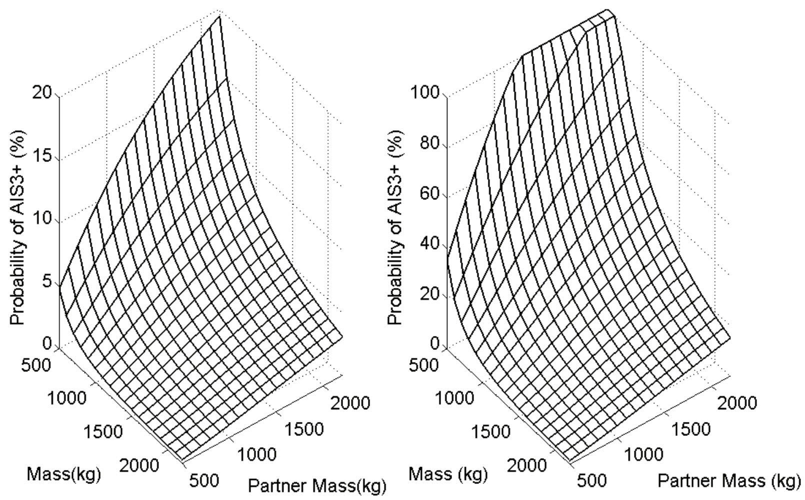


Figure 8: AIS3+ probability versus car/partner car mass for fixed V_{CCS}.
(a) V_{CCS} = 60km/h, (b) V_{CCS} = 120km/h

Variation in Relative Risk with Mass Ratio: Figure 9 shows AIS3+ risk for belted drivers as a function of case and partner car mass (50th percentile V_{CCS} = 60km/h, 99.99%^{ile} V_{CCS} = 200km/h.

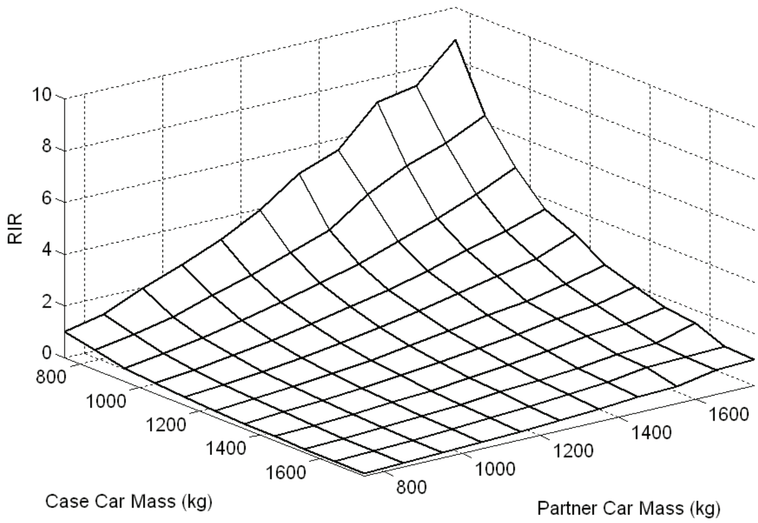
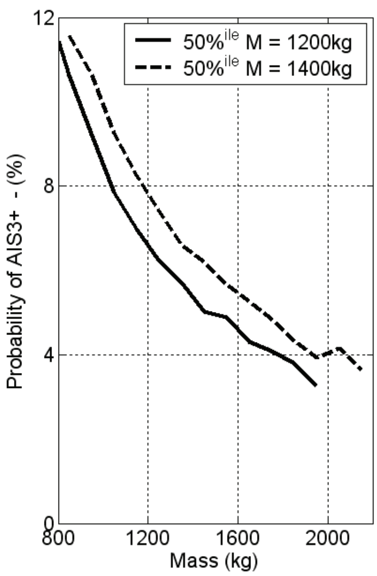


Figure 9: Relative Injury risk as a function of case car mass versus partner car mass

Variation in Overall Mean Risk with Car Mass: For each population car mass distribution, cars in each car mass category collide with cars of all other masses. The overall risk to each mass category is the sum of the risks from colliding with all other cars in the population and figure 10 shows the variation in overall risk of AIS3+ injury for belted drivers (50%^{ile} mass = 1200/1400kg, 50%^{ile} V_{CCS} = 60km/h, 99.99%^{ile} V_{CCS} = 200km/h. Figure 11 shows the change in overall AIS3+ injury risk for belted drivers as a function of the mass distribution of the car population. (50%^{ile} V_{CCS} = 60km/h, 99.99%^{ile} V_{CCS} = 200km/h, (see Appendix for the mass distributions used).



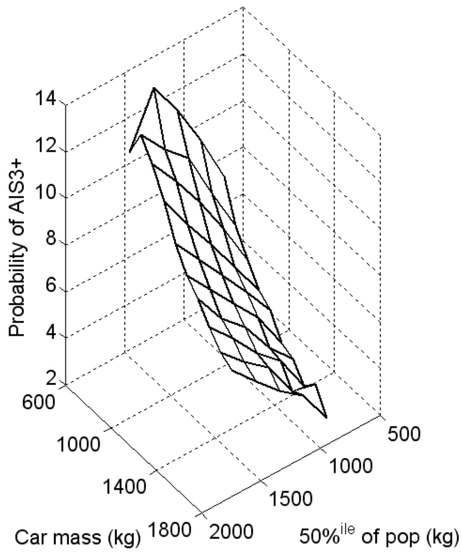


Figure 10: Effect of population mass on individual mass

Figure 11. Effect of population mass

Variation in Population Injury Risk with Mass and Collision Closing Speed: The overall injury risk in a car population is the total number of drivers injured divided by the total number of colliding cars. Figure 12 shows the variation in overall AIS3+ probability for belted drivers as a function of 50%^{ile} population mass and 50%^{ile} collision closing speed. (99.99%^{ile} V_{CCS} = 200km/h, see Appendix for further V_{CCS} distribution details. Figure 13 shows the variation in AIS 3+ injury with 50%^{ile} and 99.99%^{ile} V_{CCS} (see Appendix for details).

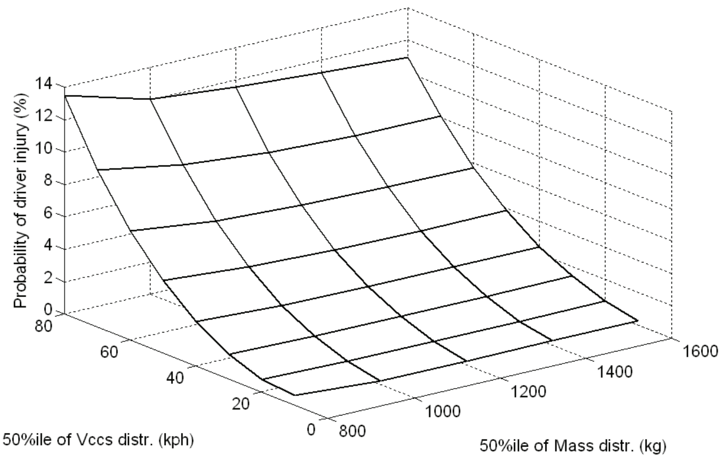


Figure 12: AIS3+ versus V_{CCS} and mean Mass

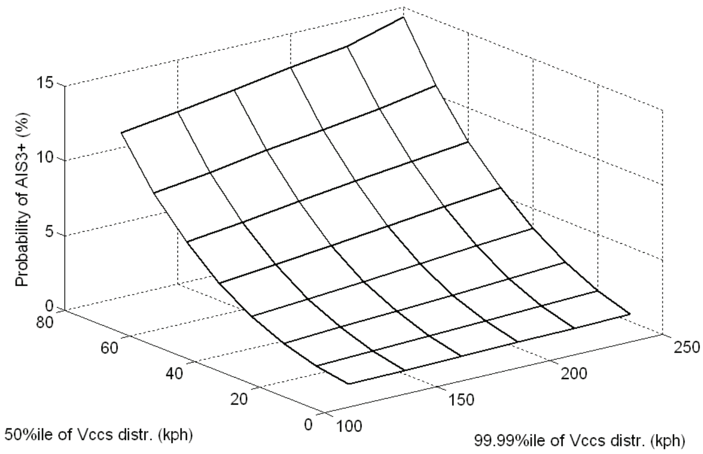


Figure 13: AIS3+ versus mean and max V_{CCS}.

Effect of Car Characteristics: Analysis of the onboard collision recorder data showed that individual car types have different crumpling stress/density (σ/ρ) characteristics [10-11] and figure 14 shows the influence of constraining the car population to having 'soft' or 'hard' structural characteristics.

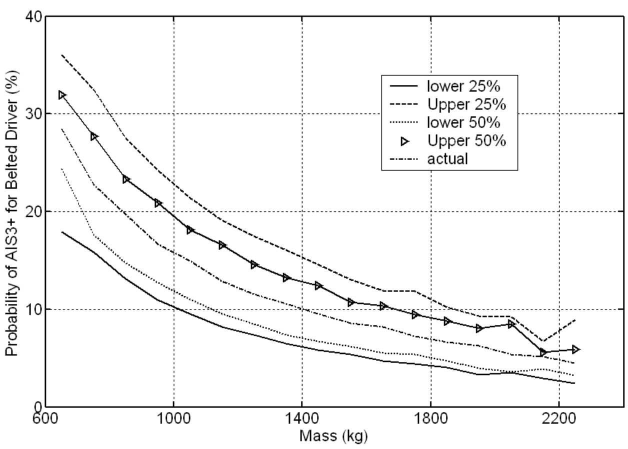


Figure 14: Vehicle stiffness effects showing percentages of stiffness pop used

DISCUSSION

Model background: The vehicle model derives from an analysis by Wood et al [10,11] of collision data from crash recorders [9] in which 269 single and two-car collisions were extracted (overlap > 25% and impact orientation within ±30 degrees of pure frontal). It has been shown [10, 15] that the fundamental structural parameter is the crumpling stress/density (σ/ρ) ratio, which is independent of car size and mass and is equivalent to the specific energy absorption capacity ($\overline{a}L$). Power regressions for 12 individual and also for a 'mean' car type of the form show high statistical correlation, where C_{da} and da are empirical parameters in which C_{da} is the key (σ/ρ) parameter which is independent of mass, while da is a primarily a function of C_{da}, with a secondary mass influence [11]. The mean $\overline{a}L$ versus ΔV function has been previously reported and is of the form given in equation 1. These equations have been applied to successfully predict peak barrier force versus vehicle mass characteristics reported by Edwards et al [8, 11]. In addition, analysis of the distribution of $\overline{a}$ with collision severity using the overall full-width barrier characteristics of the car population combined with the distribution of overlap in frontal collisions and geometric crush behaviour confirmed that the characteristics derived from on board collision recorders reflect the distribution of overlap in frontal collisions [12].

For the injury risk functions, the suitability of the US accident data (containing some side/rear impact cases) for application in frontal collisions was statistically analysed. Comparison of $\bar{a}_{\text{critical}}$ for US AIS 3+ injuries with $\bar{a}_{\text{critical}}$ from the Folksam AIS 2 + shows no significant difference (t = 0.54), see table 1. The regression exponent for the Folksam AIS 2 + risk is, as expected, less than that for the AIS 3+ unbelted which is less than the AIS 3+ belted, both being less than the exponents for fatalities. Correlation with Evans [24] reported fatality risk versus Δv for frontal collisions for belted and unbelted drivers between 1982 and 1991 shows a coefficient of determination, r^2 = 0.919 with a proportionality coefficient = 1.006 and standard error = 0.09. Finally, figure 2 shows that the derived AIS 3+ belted injury relation compares well with recent Folksam AIS 3+ injury risk data derived from 18 AIS 3+ frontal injury collisions. The resulting car size and injury risk model predicts the available real life data for three separate frontal collision data sets very well: US [20], German [22] and Japanese [21].

The sensitivity analysis used in this paper utilised a log-normal form for the distribution of mass and V_{CCS} because this matched the real life data well. The use of an alternative distribution form would yield somewhat different predictions.

Model predictions: Figure 7 shows that the increase in injury and fatality risk with decreasing car mass is only significant at moderate and high ΔV's. For the AIS3+ belted case, at ΔV's below 40km/h the probability of AIS3+ in any mass category is small (<10=%). The distribution of V_{CCS} is a function of the ratio of differentiated / undifferentiated roads, speed limits and human factors. Figure 8 shows the dramatic influence of doubling V_{CCS} on belted AIS3+ risk in nearly all car-to-car mass combinations. Specifically, for a 2:1 mass ratio in favour of the partner car, say 800:1600kg, risk is 8% for a 60km/h V_{CCS}, but this rises to 55% risk at the higher V_{CCS} of 120km/h.

The influence of mass ratio of the colliding vehicles is well established and figure 9 shows the relative risk increasing from 1.0 at a mass ratio of 1.0 to 6.3 at a mass ratio of 2.0 (800:1600kg). However, cars in each car mass category collide with cars of all other mass categories and further consideration of the influence of reducing the mean vehicle population mass on a car belonging to a particular mass category shows that risk probability to drivers in all car mass categories decreases. This is to be expected because as the 50%^{ile} car mass decreases, so does the mean mass of the collision partner for all car mass categories. Paradoxically, as the mean mass is reduced, the overall population risk increases. Figure 10 shows that as an individual car mass reduces from 1800 to 900kg (for a fixed mean population mass = 1200kg), the AIS3+ risk increases from 4 to 10% - an increase in risk of a factor of 2.5 for a 2:1 mass change.

Changing 50%^{ile} Mass 50%^{ile} V_{CCS} = 60kph 99.99%^{ile} V_{CCS} = 200kph Overall C_{da} distribution		**Changing C_{da}** 50%^{ile} Mass = 1200kg 50%^{ile} V_{CCS} = 60kph 99.99%^{ile} V_{CCS} = 200 kph	
50%^{ile} Mass (kg)	Relative Risk	C_{da} distr.	Relative Risk
1600	0.96	Upper 50%	1.24
1200	**1**	**Overall**	**1**
800	1.15	Lower 50%	0.77

Table 2: Sensitivity analysis results for AIS3+ belted simulations: influence of mass and stiffness

Changing 50%^{ile} V_{CCS} 50%^{ile} Mass = 1200kg 99.99%^{ile} V_{CCS} = 200kph Overall C_{da} distribution		**Changing 99.99%^{ile} V_{CCS}** V_{ccs} 50%^{ile} Mass = 1200kg 50%^{ile} V_{CCS} = 60kph Overall C_{da} distribution	
50%^{ile} V_{CCS} (km/h)	Relative Risk	99.99%^{ile} V_{CCS} (km/h)	Relative Risk
70	1.38	225	1.06
60	**1**	**200**	**1**
50	0.69	175	0.93

Table 3: Sensitivity analysis results for AIS3+ belted simulations: influence of mean and maximum Collision Closing Speed

The influence on risk probability of varying the mean mass of the vehicle population and the mean V_{CCS} is shown in figure 12. This clearly shows the principal prediction outcome from this model: the negative influence of speed on injury probability far outweighs the relative protection afforded by increased relative vehicle mass. Conversely, the increased population risk of introducing a car fleet of lighter mass can be more than offset by reducing the distribution of V_{CCS}. By comparison, research by Buzeman-Jewkes *et al* [25] drew a similar conclusion that vehicle fleet downsizing is not detrimental if the mass ratio of colliding pairs is not affected, and that impact speed reductions strongly reduce risk. Further, the current model shows that it is the mean rather than the maximum V_{CCS} which is much more important in determining overall risk, see figure 13. The influence of reducing the maximum V_{CCS} is somewhat masked by the log-normal analysis used, see Appendix.

Figure 14 shows a higher risk probability for occupants of vehicles with a stiffer frontal structure. This is an inevitable consequence of the increased acceleration associated with the reduced deformation occurring in stiffer vehicles [26].

In conclusion, a model for frontal collisions is presented which has been successfully validated against the available experimental data. The model has been used to predict the role of vehicle mass, closing speed and frontal stiffness in injury and fatality risk. The predictions are summarised in tables 2&3 showing that increasing the 50%^{ile} car mass from 1200 to 1600kg reduces the AIS3+ injury to drivers by 4%, while decreasing the 50%^{ile} car mass to 800kg increases the overall risk by 15%. By comparison, reducing the 99.99%^{ile} V_{CCS} from 200 to 150km/h reduces the injury risk by 14%, while reducing the 50%^{ile} collision speed from 60 to 50km/h reduces the injury risk by 31%. Finally, a car population with the structural characteristics of the ‘soft’ 50%^{ile} reduces injury risk by 23%.

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Appendix

Mass distribution in case countries

Country	50%^{ile} Mass (kg)	Std deviation ($\log_e$ form)	2.5%^{ile}	97.5%^{ile}
United States [14]	1298	0.181	913	1846
Japan [21]	1071	0.29	609	1892
Germany [23]	1028	0.226	661	1593

Collision Closing Speed Distribution in case countries

Country	50%^{ile} V_{CCS} (km/h)	Std deviation ($\log_e$ form)	2.5%^{ile}	97.5%^{ile}
United States [14]	41.5	0.421	17.9	93.0
Japan [21]	70	0.405	31.8	153.7
Germany [23]	51.7	1.167(lower 50%^{ile}) 0.401(upper 50%^{ile})	5.2	111.7

Mass distribution for sensitivity analysis

Form of distribution is log normal. Standard Deviation ($\log_e$ form) is 0.199.

50%^{ile} Mass	2.5%^{ile}	97.5%^{ile}
800	542	1182
1000	677	1477
1200	812	1772
1400	948	2068
1600	1083	2363

Collision Closing Speed distribution for sensitivity analysis: Changes in 50%^{ile} V_{CCS}

Form of distribution is log normal

99.99%^{ile} V_{CCS} is 200km/h

50$^{\%ile}$ V_{CCS}	0.1$^{\%ile}$ V_{CCS}	2.5$^{\%ile}$ V_{CCS}	97.5$^{\%ile}$ V_{CCS}	99.9$^{\%ile}$ V_{CCS}	99.99$^{\%ile}$ V_{CCS}
10	0.8	2.1	48.5	120.5	200
20	3.0	5.9	67.3	135.4	200
30	6.2	11.0	81.5	145.1	200
40	10.5	17.1	93.4	152.4	200
50	15.8	24.1	103.9	158.3	200
60	22.0	31.8	113.2	163.3	200
70	29.3	40.3	121.7	167.3	200
80	37.3	49.4	129.6	171.2	200

Collision Closing Speed distribution for sensitivity analysis: Changes in 99.99%^{ile} V_{CCS}
Form of distribution is log normal
t values for 0.01%ile = ± 3.719

Case 1: 50%^{ile} V_{CCS} = 40km/h

99.99%^{ile} V_{CCS}	0.01%^{ile}	2.5%^{ile}	97.5%^{ile}
150	10.7	19.9	80.3
175	9.1	18.4	87.1
225	7.1	16.1	99.4
250	6.4	15.2	105.1

Case 2: 50%^{ile} V_{CCS} = 80km/h

99.99%^{ile} V_{CCS}	0.01%^{ile}	2.5%^{ile}	97.5%^{ile}
150	42.7	57.4	111.4
175	36.6	53.0	120.9
225	28.4	46.4	138.0
250	25.6	43.9	145.8