ESSENTIAL COMPONENTS OF A STATISTICALY VALID CRASHWORTHINESS RATING

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ABSTRACT

The paper mainly deals with methodological foundations of crashworthiness rating procedures based on real world accident material. Most rating methods, especially those for car-to-car crashes, are based on so-called contingency tables containing the injury outcomes for the drivers of the subject and the opponent car. Some light is shed on the assumptions usually made and it is argued that data material, which contains information on the injury severity, is much better suited for rating procedures.

Additionally the paper demonstrates for characteristic real data examples that there exist essential factors, which influence rating results in a non-negligible way.

Finally, the strong relationship between accident severity and injury outcome is investigated.

All theoretical results are underpinned by real accident data taken from the Hanover and Dresden data collected within the German In Depth Accident Study (GIDAS).

1. INTRODUCTION

In this paper we discuss several problems which arise in crashworthiness ratings based on real world accident data. Usually, crashworthiness is understood as the ability of a vehicle to prevent occupant injury in case of an accident. A common measure of crashworthiness of a specific vehicle model is therefore the likelihood or probability of being injured, alternatively severely injured, as e.g. a driver of such a car in case that the vehicle is involved in an accident. Therefore crashworthiness is usually computed in a conditional way. Given that an accident occurs, what is the probability of being injured or severely injured? The probability that the condition, i.e. that an accident occurs, is, in most cases, not considered. This fact has to be stated very clearly in crashworthiness investigations. The probability that the condition, i.e. that an accident occurs, is not easy to estimate. This is a problem of primary or active safety, i.e. the ability of a vehicle to avoid accidents. The probability that an accident happens depends on a large number of influence factors like mileage, driver population, regions where the vehicle is driven and, last but not least, on active safety features of the car like ESP (Electronic Stability Program) or ABS (Antilock Braking System) and so on. Just to make it sure: The probability for a driver of a specific vehicle model to be involved in an accident is not reflected by usual crashworthiness ratings. In statistical language this means that we deal with conditional probabilities. We follow this line throughout the whole paper.

Before one starts to analyse data, one has always to look closely at the underlying database. Is the data reliable? What kind of data has been collected in the database? And so on.

This paper’s analyses are based on data supplied by GIDAS (German In Depth Accident Study). The GIDAS project evolved from the Accident Research Unit of the Hanover Medical University (“Medizinische Hochschule Hannover”, MHH), which has been studying and documenting road accidents since the 1970’s. In 1999 the University of Dresden joined this project. The database used for this paper currently contains as many as 13,000 cases involving 23,000 vehicles and 33,000 people, 18,000 of which were injured. The sampling criteria are as follows:

- road accident
- accident site in Hanover City/ County or Dresden City/ County
- at least one person injured, regardless of severity

The GIDAS database is nearly representative of German national accident statistics, with severe cases being slightly over-represented. The advantages of this database are twofold: (1) the number of cases is high enough to provide statistically significant results, and (2) each case is documented in great detail, so in-depth-analyses are possible as well. The examples used in this paper are an excerpt from this database.

In the following Section 2, we deal with the important question: What is a reasonable measure of safety? Or, more specifically, which safety features can be reflected in crashworthiness ratings from real accident data? Then we turn to a specific type of accidents, namely car-to-car crashes (cf. Section 3). We present in detail the problems arising in this area and the answers given in rating methodology, which are applied.

Section 4 considers several essential factors, which may have a non-negligible influence on the rating results. We will see that the distribution of main factors varies substantially over different subject cars. This fact implies that we have to have a close look on the influence of these factors on injury outcome and on rating results. This is done in Section 5. The influence is sometimes non-linear and needs advanced statistical methods to be measured. Finally, we shed some light on the relationship between accident severity and injury outcome.

2. WHAT IS A REASONABLE MEASURE OF SAFETY?

The question of this section cannot be easily answered. As we will see in detail in the next section, safety is often understood or better measured as a ratio of numbers of accidents with injuries. One example for the case of car-to-car crashes is just the ratio of the number of accidents in which at least the driver of a chosen subject car is injured and the total number of accidents. But what is meant by total number of accidents? Usually we don't have information on *all* accidents. The total number of accidents should not be mixed with the total number of accidents in which at least one person is injured or severely injured or with the number of all tow-away-crashes. Thus the simple ratio mentioned above usually can't be computed from real world accident data. One has to think about alternative quantities which can be computed from usual accident databases and which can be easily interpreted.

It is worth mentioning that this inevitable fact, that we have to work with conditional probabilities or frequencies, i.e. the frequency of a (severe) injury given that an accident occurs which is reported upon in the underlying database, is really a dilemma. This dilemma necessarily leads to the fact that a variation of the likelihood of entering into the database (e.g. changes of the make and model which lead to a lower or higher rate of tow-away crashes of this vehicle) have an influence on the conditional probability or frequency of having a (severe) injury, even if the total number of accidents with (severe) injuries is not changed. This implies that progress in active or primary safety, which is not reflected by crashworthiness investigations on passive safety, has an influence on crashworthiness ratings. And of course the avoidance of accidents is an essential feature of safety of vehicles.

Another problem one has to face is that we want to measure and finally rate the passive safety or crashworthiness of a vehicle model only. We don't want to measure crashworthiness of this vehicle model under the conditions that a driver from a specific driver population has driven the car, that an opponent of a specific type was involved in the accident, specific exposure factors like region and road and /or weather conditions take specific values and so on. Of course that is what we usually observe, namely accidents under very specific circumstances. We are completely unable to observe accidents in well-defined and pre-specified situations. The non-trivial task we have to face is to abstract from all the occurring and disturbing factors, which influence the measured quantities in part substantially. In some cases this task seems to be nearly impossible, because we can't control all factors. E.g., sometimes we are simply unable to observe accidents for a specific make and model under some given exposure conditions. If, for example, one vehicle model (subject car A) is more or less only driven by much older drivers than another make and model (subject car B), then it is very difficult to distinguish between the influence of *age* on the injury outcome and the influence of *crashworthiness of the specific car* on the injury outcome. We only observe a mixture of both and we can't produce accidents with young drivers in subject car A and older drivers in subject car B. But we want to estimate the influence of the *crashworthiness of the specific car* on the injury outcome, only! Exactly the same holds true for makes and models that are more or less only driven in rural than in urban areas or driven more often by female than male drivers (in case that there is an influence of *sex* to injury outcome) and so on. As far as possible, one has to try to eliminate the influence of such unwanted external influence factors on the injury outcome.

A further problem is that we have to be careful not to mix up the injury outcome of the subject car with the injury outcome of the opponent car. If we, for example, use a ratio, e.g. the ratio of the number of accidents with at least the driver of a subject car injured and the number of accidents in which at least the opponent car driver is injured, then we are completely unable to differentiate between crashworthiness and aggressivity of the subject car. The use of such a ratio may easily lead to the strange situation in which a very aggressive car appears, only because of its high aggressivity, to be very safe with respect to passive safety.

3. RATINGS FOR CAR-TO-CAR CRASHES BASES ON CONTINGENCY TABLES

Many of the existing safety rating methods for car-to-car crashes based on real accident data rely on accident material from mass databases, which can be represented in a condensed form as so-called 2x2 contingency tables. For a real accident data example consider Table 1. The underlying data has been taken from the GIDAS database for a specific subject car.

Table 1.
Accident data for car-to-car crashes for a specific subject car A (complete 2x2 table)

Driver of opponent car	Driver of subject car		
	Not Injured	Injured	
Not Injured	$N_{1,1} = 79$	$N_{1,2} = 97$	$N_{1,+} = 176$
Injured	$N_{2,1} = 90$	$N_{2,2} = 85$	$N_{2,+} = 175$
	$N_{+,1} = 169$	$N_{+,2} = 182$	$N = 351$

Given a table like Table 1 one has to first ask, what is the entry criterion into the database used. It may be that all tow-away crashes have been included or, as is the case for the GIDAS data, all crashes with at least one injured person are included. Since almost all databases in use do not include *all* accidents, the value N=351, cf. Table 1, does not coincide with the total number of accidents and the value $N_{1,1} = 79$ should not be used. The reason is that the number of accidents in which both drivers are not injured is much larger than $N_{1,1} = 79$ and therefore the total number of accidents is much larger than N=351. In Table 1, accidents in which both drivers are not injured are included only if there is another person involved in the accident who suffers an injury (e.g. a back seat passenger or a pedestrian). All crashes in which nobody is injured are missing. Thus one has to live with an incomplete 2x2 table, cf. Table 2, instead of the complete one.

Table 2.
Accident data for car-to-car crashes for a specific subject car A (incomplete 2x2 table)

Driver of opponent car	Driver of subject car		
	Not Injured	Injured	
Not Injured	$N_{1,1} = ?$	$N_{1,2} = 97$	$N_{1,+} = ?$
Injured	$N_{2,1} = 90$	$N_{2,2} = 85$	$N_{2,+} = 175$
	$N_{+,1} = ?$	$N_{+,2} = 182$	$N = ?$

Based on a table like Table 2 the following relative injury risk indicators or ratios R are in use (cf. Hautzinger (2001) for a review of existing rating methods):

- Folksam (Sweden): $$R = \frac{N_{+,2}}{N_{2,+}}$$
- Helsinki University: $$R = \frac{N_{+,2}}{N_{+,2} + N_{2,+}}$$
- Department of Transport (UK): $$R = \frac{N_{+,2}}{N_{1,2} + N_{2,1} + N_{2,2}}$$
- Monash University (Australia), Newstead Method: $$R = \frac{N_{2,2}}{N_{2,+}}$$

The Insurance Institute for Highway Safety (IIHS) uses the following different ratio:

$$\frac{\text{no. of fatally injured drivers of subject car}}{\text{no. of vehicle years for subject car model}}.$$

Every contingency table is of course a sampling version of a theoretical table in which the entries are the probabilities of the corresponding events (cf. Table 3). For example the value $P_{1,2}$ in Table 3 corresponds to the probability of an accident in which the subject car driver is injured and the driver of the opponent car is not injured.

From the complete Table 1 we can easily obtain all injury probabilities by computing relative injury frequencies, i.e. $P_{r,s}=N_{r,s}/N$, r,s =1,2.

Table 3.
Injury probabilities in car-to-car crashes for a specific subject car A

Driver of opponent car	Driver of subject car		
	Not Injured	Injured	
Not Injured	$P_{1,1}$	$P_{1,2}$	$P_{1,+}$
Injured	$P_{2,1}$	$P_{2,2}$	$P_{2,+}$
	$P_{+,1}$	$P_{+,2}$	$P = 1.0$

The probability $P_{+,2}$, i.e. the probability that in a crash the subject car driver suffers an injury, may serve as a rather reasonable starting point for constructing a crashworthiness coefficient. In case that we have a complete accident table at hand, we can obtain this value as follows:

$$P_{+,2} = \frac{N_{+,2}}{N} = \frac{\text{no. of accidents with subject car driver injured}}{\text{total no. of accidents with subject car involved}}$$

This value depends only on the injury distribution of the subject car drivers. The injury distribution of the drivers of the opponent cars does not enter in this quantity. This is highly desirable, because then we do not have any influence of the aggressivity of the subject car to the crashworthiness coefficient. Aggressivity of the subject car namely certainly has an influence on the injury distribution of the opponent car drivers. By exactly the same argument one may regard the value

$$P_{2,+} = \frac{N_{2,+}}{N} = \frac{\text{no. of accidents with opponent car driver injured}}{\text{total no. of accidents with subject car involved}}$$

as a quantity, which measures aggressivity. Thus it may look like we are done. But we are not! In real accident data examples, we have to live with the above mentioned incomplete tables, which do not allow the computation of $P_{+,2}$ and $P_{2,+}$ as described above.

Several existing crashworthiness rating procedures try to pose assumptions on the underlying accident material, which allows at least a reconstruction of the missing accident frequencies in the incomplete tables. Let us first see what type of assumptions these are and how the reconstruction under these assumptions works. Then – in a second step – we will have a look whether we can check these assumptions on data or not and – if we can – what the results are.

The most common way out of the dilemma described above, i.e. that we can observe incomplete accident tables only, is the assumption of independence between the two injury outcomes for the subject car and for the opponent car drivers. This assumption means that the two injury outcomes do not influence each other. Such an assumption seems to be rather questionable, because we expect, for example, under the assumption that the subject car driver is injured, a higher probability for the opponent car driver to also be injured as when the subject car driver is not injured. Especially this seems to hold true if the subject car is a vehicle with a high mass. Beside these reservations let us stay for a moment with the assumption of independence for the two injury events and let us see why it really would help. By definition the independence says that the following crucial identity holds:

$$\frac{N_{r,s}}{N} = P_{r,s} = P_{r,+} * P_{+,s} = \frac{N_{r,+} * N_{+,s}}{N^2}$$

In other words: We can reconstruct the complete 2x2 table under the independence assumption! For example we obtain:

$$\frac{N_{2,2}}{N} = P_{2,2} = P_{2,+} * P_{+,2} = \frac{N_{2,+} * N_{+,2}}{N^2}$$
$$\Rightarrow N = \frac{N_{2,+} * N_{+,2}}{N_{2,2}}$$

Once having the total number of accidents, we can reconstruct the whole table as follows:

Table 4.
Accident data for car-to-car crashes for a specific subject car A (reconstructed 2x2 table)

Driver of opponent car	Driver of subject car		
	Not Injured	Injured	
Not Injured	$N_{1,1} = N - N_{+,2} - N_{2,1}$	$N_{1,2}$	$N_{1,+} = N - N_{2,+}$
Injured	$N_{2,1}$	$N_{2,2}$	$N_{2,+}$
	$N_{+,1} = N - N_{+,2}$	$N_{+,2}$	$N = N_{2,+} * N_{+,2} / N_{2,2}$

This reconstructed 2x2 table immediately leads to

$$P_{+,2} = \frac{N_{+,2}}{N} = \frac{N_{2,2}}{N_{2,+}}$$

and

$$P_{2,+} = \frac{N_{2,+}}{N} = \frac{N_{2,2}}{N_{+,2}}.$$

As has been stated above, Folksam Research uses the following ratio as the basis for their crashworthiness rating

$$\frac{N_{+,2}}{N_{2,+}} = \frac{P_{+,2}}{P_{2,+}}.$$

This is exactly the ratio of the two total numbers of injured drivers in the subject and in the opponent car. In summary we have seen that the assumption of independence for the injury outcome in the subject and in the opponent car enables us to overcome the dilemma of observed incomplete accident data.

The important question now is whether we can check on data this assumption of independence and, if we can, what the result is. Unfortunately, the answer is in the negative, if we restrict ourselves to 2x2 tables. To see this observe that, regardless what the values of the three frequencies $N_{1,1}$, $N_{1,2}$ and $N_{2,1}$ are, we always can replace the missing accident frequency (both drivers not injured) within the table in such a way that the data appears clearly in favour of independence. In the opposite direction, we can replace the missing value in such a way that the data looks as far away as desired from being independent.

The situation is completely different when we not only have the information whether the drivers are injured or not, but when we additionally have information on the injury severity. As a measure for the injury outcome, the Abbreviated Injury

Scale (AIS) scale has become an international standard. Injuries of eight body regions are classified on a scale from 0 (no injury) to 6 (maximum injury):

- head
- face
- neck
- thorax
- abdomen
- spine
- upper extremities
- lower extremities

Table 5.
Description of AIS-code

AIS Code	Description
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Maximum

In most accidents, persons suffer either no injury at all or more than one. The highest AIS-value (MAIS, Maximum AIS) gives an indication of a person's overall injury outcome, cf. Association for the Advancement of Automotive Medicine (1998).

The following Table 6 refers to the same accidents as Table 1, but now the injuries have been classified according to MAIS.

Table 6.
Accident data for car-to-car crashes for a specific subject car A
(injuries classified according to MAIS)

Driver of opponent car	Driver of subject car				
	MAIS 0	MAIS 1	MAIS 2-3	MAIS 4-6	
MAIS 0	79	88	8	1	176
MAIS 1	77	53	10	1	141
MAIS 2-3	12	11	7	2	32
MAIS 4-6	1	1	0	0	2
	169	153	25	4	351

As has been argued above, the value 79 in the left upper corner of Table 6 does not coincide with the number of all accidents with both drivers not injured. This value and therefore the value 351, the number of all accidents, should not be included in our investigation. We have to delete both values from the table and have to base our investigations again on the following incomplete contingency table.

Table 7.
Accident data for car-to-car crashes for a specific subject car A
(injuries classified according to MAIS)

Driver of opponent car	Driver of subject car				
	MAIS 0	MAIS 1	MAIS 2-3	MAIS 4-6	
MAIS 0	?	88	8	1	?
MAIS 1	77	53	10	1	141
MAIS 2-3	12	11	7	2	32
MAIS 4-6	1	1	0	0	2
	?	153	25	4	?

If the hypothesis holds, that the injury outcomes for both drivers are independent, then we must obtain more or less the same probability for the driver of the opponent car to be injured with MAIS=1, regardless of the MAIS level of the subject car driver. From Table 7 we obtain, given that the subject car driver has an injury with an MAIS of 1, a probability for the driver of the opponent car to have no injury (i.e. MAIS = 0) from approximately 88/153 = 57.5 %. Given that the subject car driver suffers an injury with MAIS equal to 2 or 3, we obtain a probability for the opponent car driver to be not injured of approximately 8/25 = 32.0 %. Both probabilities differ significantly. Indeed, if we perform a Chi-Square test of independence on the data of Table 7 we obtain a highly significant rejection of the hypothesis of independence. This means that we don't have any indication for the assumed independence of the two injury outcomes of the drivers in the subject car and in the opponent car. The method suggested above in order to overcome the dilemma that we only observe an incomplete contingency table, is not valid!

Thus we have to conclude that on the basis of incomplete 2x2 accident contingency tables we hardly can obtain any reliable result.

But, if we have some information on injury severity available, for example as in Table 7, which is also an incomplete, but now higher order table, then we can compute slightly different conditional probabilities than above. For example, we can compute the probability for the subject car driver of being severely injured, e.g. injured with an MAIS of at least 2, given that the subject car driver suffers an injury in a crash at all. From Table 7 we obtain, for example, the following value for this probability: 29/182 = 15.9 %.

A suggestion could be to use this conditional probability as the basis for a measure of crashworthiness of the subject car.

Conversely we can compute a similar value for the opponent car driver. In the example of Table 7 we obtain a probability of 34/175 = 19.4 % for the opponent car driver of being severely injured (i.e. MAIS>=2), given that the opponent car driver suffers an injury at all.

Both values have the appealing feature that they don't depend on the injury outcome of the other party. For example the probability for the subject car driver of being severely injured, given that he or she is injured at all, depends only on the injury distribution in the subject car and *not* on the injury distribution in the opponent car. More specifically this value depends only on the distribution of the injury severity, given that the driver suffers an injury at all. Thus, it is impossible to decrease this value for the subject car by increasing the number of (severely) injured drivers in the opponent car, i.e. by increasing the aggressivity of the subject car. On the other hand, the corresponding probability for the opponent car driver population does not depend on the injury distribution in the subject car. Thus, this probability for the opponent car driver to be severely injured, given that he or she is injured at all, may be used as a basis for a measure of aggressivity. However, one has to be careful with these conditional frequencies or probabilities, too. If the manufacturer, for example, changes the make of the vehicle in a way that accidents with severe injuries are more or less unchanged, but a significant proportion of minor injuries (MAIS = 1) can be avoided, then the number of accidents with severe injuries (i.e. the numerator of the suggested crashworthiness coefficient) will not noticeably change. But the number of accidents in which the driver suffers an injury at all (MAIS >=1) (i.e. the denominator of the suggested crashworthiness coefficient) will be reduced. Thus, we end up with a higher crashworthiness coefficient which does not reflect the underlying situation! Therefore one should also think of another denominator. A quantity, which comes into question, is the number of tow-away crashes with a specific subject car involved in the accident. A reasonable crashworthiness coefficient therefore could be:

$$\frac{\text{no. of crashes with severely injured driver}}{\text{no. of tow-away crashes}}$$

But in principle, one can think of the same objections as before. Think, for example, of a change in the make of a car that reduces the number of tow-away crashes but not the number of injured drivers in crashes.

Concerning an aggressivity coefficient, one ideally wants the following behaviour. The higher the aggressivity of a car, the larger the coefficient should be. Since the proposed aggressivity coefficient is the probability for the opponent car driver to be severely injured, given that he or she is injured at all, we have to ensure that the opponent car distribution is nearly the same for all subject cars we are interested in. If it is the case that a specific subject car has a completely different opponent car distribution (for example a strong bias towards larger and heavier vehicles) than another subject car, then we would expect that the above suggested indicator for aggressivity for the first subject car is smaller than for the other subject car mainly because its average opponent vehicle is heavier and therefore more safe for the opponent car passengers. Thus, it would be an interesting question, whether opponent vehicle distributions for different subject cars are similar or not. We will address this question in the following section.

4. MAIN FACTORS WHICH INFLUENCE RATING RESULTS

In the preceding section we have seen that an ideal measure of crashworthiness does not exist. It is necessary to have a close look at the underlying database and to see which measure of safety to what extent really can be computed. If this is done, the next bulk of questions arises. The main question is: Are crashworthiness coefficients for different subject cars comparable? A proper answer to this question is difficult. If all vehicles are driven by the same driver population, on more or less the same roads with comparable mileage and, very importantly, all vehicle have comparable weight and engine power, then the answer to the above question could be a careful YES.

The first question we have to answer is: Are there differences in driver populations, usage of the car and so on? If there are differences, we further have to investigate the consequences of these differences to rating procedures.

To investigate these problems we have chosen three different subject cars A, B and C. All following figures are obtained from accident data of the GIDAS project.

The plots given in Figures 1, 3 and 4 are so-called Boxplots. The grey-shadowed boxes contain the central 50 per cent of the observations. E.g. Below and above the box we find 25 per cent of the observations. The upper end of the bar gives the largest non-outlier observation and the lower end of the bar corresponds to the smallest non-outlier within the observations. The horizontal line within the box represents the median of the corresponding data set.

From Figure 1 we see that the distribution of the driver age in subject car C is very different to the distribution of the age of the driver in the two other subject cars A and B.

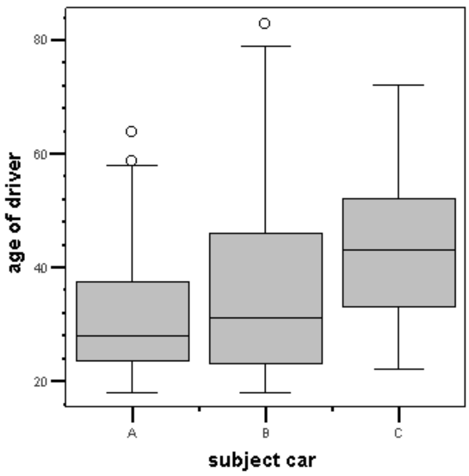

Figure 1. Boxplots of driver age for three different subject cars.

The higher average age of the drivers in subject car C is expected to lead to a higher crashworthiness coefficient because of the poorer biomechanic behaviour of older people, only.

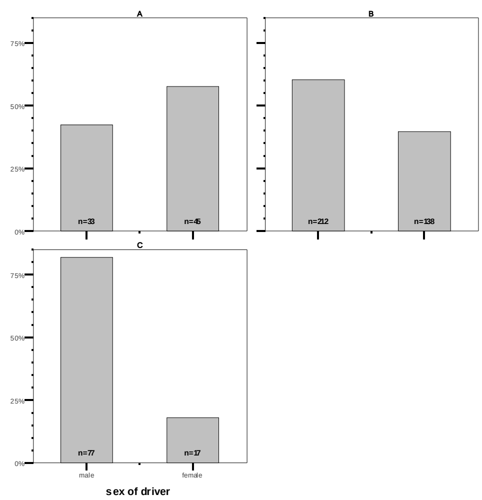

Figure 2. Distribution of driver sex for three different subject cars.

An even more striking result is obtained for the sex-distribution of the drivers in cars A, B and C. From Figure 2 it is clearly seen that, concerning car model C, many more male drivers are involved in accidents than for the other two car models. This in turn would lead to a decrease of the crashworthiness rating for model C with respect to the two other makes and models since female drivers on average are expected to suffer more severe injuries than male drivers in comparable accidents.

Concerning seat belt usage, we obtain from the GIDAS accident material the following Table 8.

Table 8.
Percentage of unbelted drivers in crashes for three different subject cars

	A	B	C
Percentage of not belted drivers in crashes	1 %	4 %	5 %

At first glance one may be tempted to ignore the “slight differences” in seat belt usage reported in Table 8. If one recalls that the accidents with the most severe injury outcomes occur if the corresponding driver is not belted, then a 25 % higher rate of unbelted drivers in subject car C with respect to subject car B may lead to a considerably biased crashworthiness result. Concerning subject car A the situation is even more striking.

Thus, it is a must that the possibly different driver populations for the investigated subject cars are taken into account. One really has to try to eliminate the influence of a varying driver population from rating results. We discuss this problem in more detail in the next section.

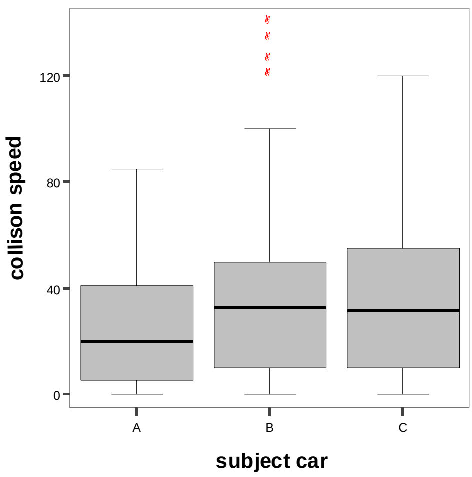

Figure 3. Boxplots of collision speed for three different subject cars.

Finally let us have a look on two further essential influence factors, namely the collision speed and delta-v. From Figures 3 and 4 we see that both the distribution of the collision speed as well as the distribution of delta-v differs over the three investigated subject cars. Sometimes an increase in average collision speed coincides with an increase in delta-v (subject cars A and B) and sometimes not (Subject cars A and C). Even a similar collision speed is no indication for a similar delta-v (subject cars B and C). More specifically it has been obtained that there is no empirical evidence that the two influence factors, collision speed and delta-v, are correlated at all.

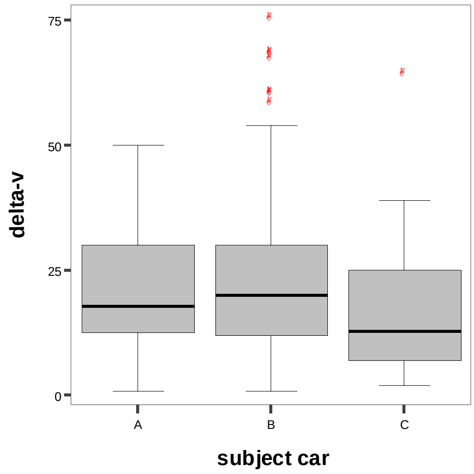

Figure 4. Boxplots of delta-v for three different subject cars.

Since injury outcomes in real world accidents depend heavily on delta-v and on collision speed (cf. next section), one must not avoid considering the distribution of collision speed and of delta-v for the different subject cars very carefully. Differences in these quantities can't be neglected and the influences have to be removed from the crashworthiness rating.

Finally one may argue that another important influence factor on crashworthiness ratings, namely the mass of the vehicle, is a safety feature of the underlying car and the effect should not be removed. Even if one follows this argument, one should answer the question whether the crashworthiness of different subject cars differs only because of the different size or mass of the two vehicles. In other words one should be interested to see crashworthiness ratings behind a sometimes dominating mass effect.

5. RELATIONSHIP BETWEEN ACCIDENT SEVERITY AND INJURY OUTCOME

In accident research and passive safety analysis, one has to distinguish between the severity of an accident (the cause) and its influence on the passengers (the effect). To achieve comparable performance ratings, legislative and consumer crash tests keep the accident severity constant (e. g. FMVSS 208, NCAP). Since, in real life, a wider range of accidents occurs, there is the need for variables that measure accident severity. These variables are often used for parameter analyses and a statistical justification of the mentioned test procedures, cf. Appel et al. (2002).

There are different variables that may be used to measure accident severity. Some of them are given in the following listing:

- Collision speed / impact velocity: Most important measure for collisions between vehicles and unprotected road users (pedestrians), also used for side impacts.

- Delta-v: The change of velocity (centre of gravity) that is caused by the impact. Important measure for frontal, rear and side collisions (vehicle – vehicle)

- EES: Equivalent energy speed. The EES-value is derived from a car's deformation and corresponds to its energy consumption. It is also used to describe the severity of frontal, rear and side collisions. For research institutes without crash test experience and without computer simulation capabilities, the EES is difficult to determine.

- There are several other variables (e. g. SPUL (Spezifische Unfall-Leistung), VDI (Vehicle Deformation Index) and CDC (Collision Deformation Classification)) that are often hard to determine, of a too complex structure or of lacking comprehensibility, cf. Appel et al. (2002).

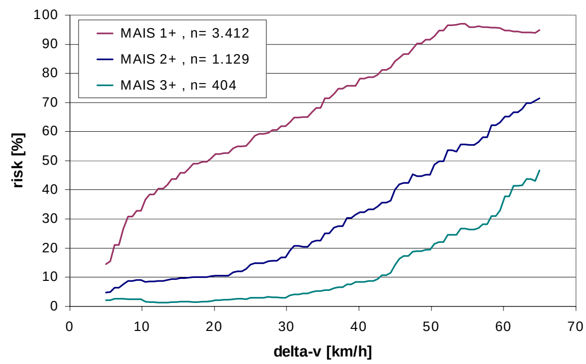

Figure 5. Risk of a specific injury severity as a function of delta-v.

As a measure for the injury outcome, we use, as before, the Abbreviated Injury Scale (AIS).

Figure 5 shows the risk functions of MAIS 1+ (MAIS1..MAIS6), MAIS 2+ and MAIS 3+ versus delta-v for car-passengers sitting in the front during a frontal collision.

Figure 6 displays similar risk functions for belted and unbelted passengers. It is clearly seen that one has to separate in crashworthiness investigations between belted and unbelted passengers. Additionally recall from Section 4 that the percentage of unbelted drivers substantially vary over different subject cars.

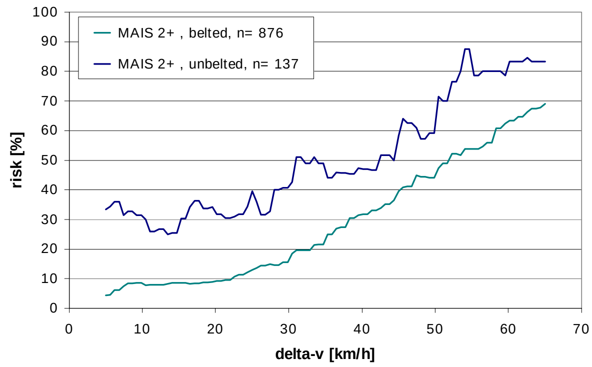

Figure 6. Risk of a specific injury severity for belted and unbelted front passengers.

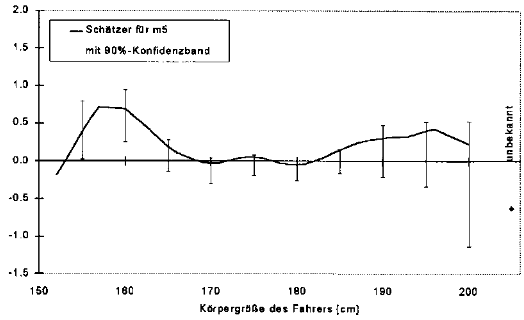

Figure 7. Influence of the height of the driver on the injury outcome.

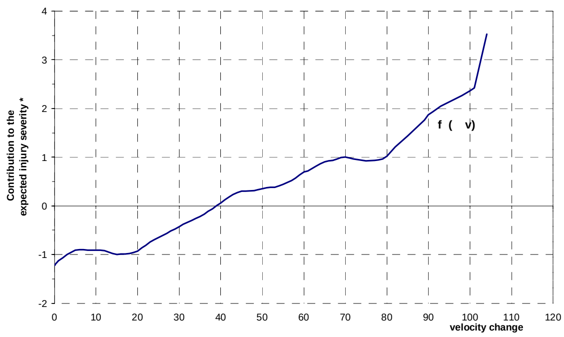

Figure 8. Influence of delta-v on the injury outcome.

Using a non-linear method due to Achmus (2000) (see also Achmus and Zobel (1997)) we can display the measured influence of the height of the driver, the influence of delta-v and the influence of the seat belt usage on the injury outcome (cf. Figures 7-9). Especially the influence of the height of the driver it is observed as highly non-linear and one should therefore apply more sophisticated and complex estimation techniques beyond linear methods. Achmus used an estimation procedure, which is completely non-parametric, i.e. the procedure she applied does not postulate any parametric form of the influence function like linear, quadratic or whatever.

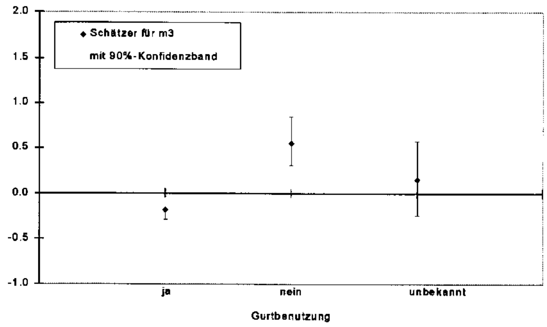

Figure 9. Influence of the seat belt usage on the injury outcome.

We have observed strong indicators suggesting the presence of relevant influence factors which have to be controlled and their influence on pure crashworthiness coefficients removed. This is not an easy task. One possible way is described as follows: In a first step select all relevant influence factors $A_1,\ldots,A_K$ and compute from the underlying database the multivariate and non-linear influence function f on the injury severity, i.e.

$$f(A_1,\ldots,A_K).$$

Usually it is very difficult to estimate functions f of several variables $A_1,\ldots,A_K$ with completely unknown form. Even for extremely large data sets functions f of dimension K larger then 3 to 5 are more or less impossible to estimate (so-called curse of dimensionality). Achmus (2000) considered a possibility of estimating K functions of dimension one instead of one function of dimension K, i.e. to simplify by posing the following assumption on the influence function f

$$f(A_1,\ldots,A_K) = f_1(A_1) + \ldots + f_K(A_K).$$

This model assumption covers the case of a linear influence of the dependent variable which, in our case, is the injury severity.

6. CONCLUSIONS

- The specific structure of real world accident data makes it rather difficult to establish a reasonable and interpretable measure of crashworthiness.

- The essential and frequently used assumption of independence of the injury outcome of the drivers of the subject and the opponent vehicle is not tenable.

- A measure of crashworthiness depends heavily on external and impossible to control influence factors like age, sex and belt usage of the driver, delta-v and collision speed and so on. Since it is desirable to measure the isolated influence of the make and model on crashworthiness, other influence factors, which cause bias into the crashworthiness measure, have to be removed.
  A complete exclusion of the influence of all existing factors seems to be impossible.

- Not all influence factors effect measures of crashworthiness in a simple linear way. This paper shows that non-linear influences do occur. Thus, crashworthiness ratings must take non-linearity into account.

- Any measure of crashworthiness for a specific subject car should not be influenced by possible injuries of the opponent car's occupants. If this influence is present, aggressivity and crashworthiness of a subject car cannot be separated.

- Common crashworthiness ratings do not consider the influence of active of primary safety components. However, primary safety features of a vehicle clearly bias the passive safety results and are of not minor importance to vehicle safety.

7. ACKNOWLEDGMENTS

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