THE EFFECT OF PRE-PRETENSIONING IN MULTIPLE IMPACT CRASHES

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ABSTRACT

German In-Depth Accident Study (GIDAS) data from 1999 to 2007 was compared to Hanover Medical School (MHH) data from 1973 to 1987 and it was found that the relative percentage of passenger cars sustaining more than one impact in a crash, so called multiple impact crashes, has increased by about one third within the last two decades. An analysis of 9316 GIDAS accidents from 1999 to 2007 showed a three-fold greater risk of severe injury and a four-fold greater risk of fatal injury for a multiple as opposed to a single impact crash.
This study analyses multiple impact crashes in general and in particular occupant protection by out-of-position mitigation between impacts.

It was found that in two thirds of all multiple impacts with severe injury outcome, the irreversible restraint systems, front airbags and pretensioners, were not activated in an initial front impact. The corresponding proportion for non-activation of side and curtain airbags in initial side impacts was approximately fifty percent.
To evaluate the risk of occupant out-of-position and the effect of one type of reversible system, a retractor pre-pretensioner, a finite element sled model including the human body model THUMS, was used.
In the simulation of initial front impacts with different changes of velocity, followed by a braking sequence, the pre-pretensioner leads to an obvious reduction in the forward chest displacement of the human model. Furthermore, depending on the pre-pretensioner force, the human model may be pulled back into its initial seating position.
The calculated time distribution between initial and subsequent impacts with a median of 0.6 to 0.8 seconds, was used for the evaluation of "pre-crash" measures.
The effectiveness of pre-pretensioning to position the occupant between impacts, ranges from 24% with 200N, to 93% with 400N pre-pretensioning force.

INTRODUCTION

Consumer rating crash test results, which usually have higher requirements than legal crash tests, have become a leading argument for the sales success of a vehicle model and therefore are an important orientation for vehicle manufacturers (OEMs) in the development and integration of safety innovations. However, there is a foreseen risk that the safety development might be more oriented toward rating tests rather than on the potential benefit for real traffic accidents [1].

Both crash tests required by legislation and consumer tests reproduce single impact crashes either in vehicle-to-vehicle or in vehicle-to-object constellations. Multiple impact scenarios have not yet been considered in these test modes. As a consequence, passive safety measures, especially irreversible systems, are generally optimised for occupant protection in only one impact.

The results from a MHH study [2] on multiple impact crashes, conducted in 1987 for the German Federal Highway Research Institute (BASt), showed that about 18% of the passenger cars were involved in multiple impact crashes. Studies based on the US National Automotive Sampling System / Crashworthiness Data System (NASS/CDS), the UK Co-operative Crash Injury Study (CCIS) and GIDAS data stated that the percentage of occupants involved in a multiple impact crash is around one quarter, whereas the percentage of severe (AIS3+) injuries in multiple impact crashes accounts for 30% to 42% [3], [4]. US data publishes that the risk of severe injury is more than two times higher in a multiple impact crash than in single impact crashes. Head and trunk were the body regions that showed a significantly higher risk of severe injury [4], [5]. UK and German accident data confirmed that head and thorax are the most often MAIS3+ injured body regions in multiple impact crashes [3].

In two multiple impact studies, the benefit of independent deployment of front and side airbags and the benefit assumed for maintaining airbag inflation for a longer time period [3], [6] was

discussed. Furthermore, an enlarged protection range of restraint components was proposed for out-of-position occupants after an initial impact [3].

The initial stage of this study provides statistics for multiple impact scenarios and injury outcomes for involved occupants. The activation probability of irreversible occupant restraint systems was used to determine the potential benefit of reversible restraint systems such as seat belt pre-pretensioners (pre-impact, seat belt, tensioner). Furthermore, the time distributions between impacts have been calculated to gain information about the time span for pre-crash measures before a subsequent impact.

Using the human body model, THUMS, the time to pull an occupant back in position after an initial front impact by pre-pretensioning, was derived. The effectiveness of pre-pretensioning at different force levels is shown for various first impact severities, by comparison of the time required to pull an occupant back to normal position and the time available between subsequent impacts.

METHODOLOGY

Definitions

Defining certain terms was necessary for the correct interpretation of results. Although the expression "crash" in "single impact crash" or "multiple impact crash" may seem to be on an accident level, a vehicle level has been expressed.
The term "impact" means that a vehicle sustains a change of velocity in a very short time interval while position remains practically unchanged. All coded impacts, independent on delta V, are considered in this study.

In a single impact crash, a vehicle sustains only one collision with a vehicle, an object, a person or an animal. A multiple impact crash is present if one vehicle sustains two or more collisions. It does not mean that two or more vehicles are involved in an accident.
The term "rollover crash" or "rollover" relates to vehicles that sustain a non-planar motion and reach a position at least 90º rotated over the longitudinal or lateral vehicle axis.
The expression "severe injury" is used for occupants with MAIS3+ injury outcome. This also includes fatalities. Nevertheless, fatalities will be presented separately.

The GIDAS Project

The GIDAS project is a joint venture of the FAT (German Automotive Research Organization) and the BASt (German Federal Highway Research Institute). The project was started July 1st, 1999 and is still running. Data from approximately 2000 accidents yearly was recorded at two sites; Hanover, Dresden and surroundings [7].
A statistically developed sampling plan defines the work shifts for the teams, which covers 12 hours per day. If an accident occurs with at least one injured person suspected, the GIDAS team is notified directly by the local police or rescue service via radio communication. GIDAS's investigation teams approach the crash scene with blue-lights [8]. This near immediate, on-the-scene investigation allows data collection of marks and traces available only for a short period of time after the accident. Sample criteria for the GIDAS database are that at least one accident participant has been injured and the accident occurs within the shifts and the specified regions.

Data Aggregation and Weighting

For specific research questions, filter criteria need to be applied to real world accident data. For this study, the GIDAS data from July 1999 to July 2007 was used with two general filters applied:

- Only cases with completed reconstruction
- Only passenger cars

After application of these filters the data set consisted of 9316 accidents, involving 13392 passenger cars with 15639 occupants, sustaining 18169 impacts. The data aggregation and statistical analysis were conducted with the software SPSS version 15. Furthermore, the software SAS 9.1 and the Enterprise Guide 4.1 were used for specific analyses.

The sampling plan for GIDAS was developed and stepwise improved to be representative of German national statistics. Nevertheless, studies have considered the application of weighting factors for specific research questions [9], [10]. Relative weighting factors were calculated to evaluate the generalisability of the analysed data.

Rollovers

The treatment of rollovers in previous multiple impact studies has been different. They were either included without separate examination [6], included with association of roof impact as rollover [4], or they were excluded from the data sets [5], [11]. One study presents more detailed rollover figures [3]. From both CCIS and GIDAS data, it was reported that rollovers mainly occur in multiple impact crashes [12]. This study considers rollovers in the statistical analysis. For the effectiveness assessment of pre-pretensioners, rollover crashes have not been considered, as the

coded GIDAS variables up until 2007 do not enable the calculation of time between impacts for these scenarios.

Delta V Groups

The change of velocity (delta V) is grouped in five ranges for the analysis. Besides an impact severity evaluation the ranges also consider an appropriate impact frequency distribution for further analysis.

The following delta V ranges have been defined:

- minor delta V (0 – 5 km/h)
- low delta V (6 – 15 km/h)
- moderate delta V (16 – 25 km/h)
- medium delta V (26 – 50 km/h)
- high delta V (>50 km/h)

Occupant Injury Outcome

The occupant injury analysis was conducted for belted occupants only. The exclusion of vehicles with only unbelted and "belt status unknown" occupant(s), resulted in a 19.6% reduction of single impact crashes and a 19.8% reduction of multiple impact crashes. Therefore this data-filtering step did not influence the relative proportion of single to multiple impact crashes.

Triggering of Irreversible Restraint Systems

It is not always obvious in a multiple impact crash which impact leads to the deployment of the irreversible restraint device.
To analyse the deployment threshold in a simplified system model, univariate logistic regression was applied to determine the probability of irreversible restraint activation depending on delta V. All single impact passenger cars equipped with the corresponding irreversible restraint system are classified by a status variable (0 = not activated) and (1 = activated). Pretensioner activation was coded accordingly to the airbag deployment status, because the airbag activation was easier to identify and therefore a more reliable variable. Deployment threshold differences between pretensioners and airbags are, therefore, not considered.
As the delta V is a vector and has both magnitude and direction, it is transformed into a longitudinal and lateral scalar component by usage of the change of momentum angle.

The probability of deployment is calculated with use of the logit $(\beta_0 + \beta_1 x)$ including two regression coefficients $\beta_{0,}\beta_1$ (Equation 1).

$$p(x) = \left(\frac{e^{(\beta_0+\beta_1 x)}}{1+e^{(\beta_0+\beta_1 x)}} \right) \qquad (1).$$

The application of a multivariate regression with predictors other than delta V may provide a more accurate estimate of the deployment threshold. However, the number of vehicles with activated restraint devices involved in multiple impact crashes is too small for the application of multivariate regression.

Reversible versus Irreversible Restraint System

Reversible restraint systems can operate far below the threshold of irreversible restraint systems. In general, the trigger level is more dependant on comfort than safety criteria.
To estimate the benefit of reversible restraint systems, like pre-pretensioners, multiple impact crashes were compared by triggering versus non-triggering of irreversible restraint systems at first impact.

The analysed crash scenarios were:

- Front - Front
- Front - Side
- Front - Multiple
- Side - Front
- Side - Side
- Side - Multiple

The term "Multiple" in the above scenarios expresses a combination of subsequent impacts in three or more impact crashes.
To consider the importance of the injury outcome, only MAIS2+ and MAIS3+ crashes respectively, were selected.

Time between Impacts

The time between impacts was not a variable in the GIDAS database status July 2007. Therefore these times had to be computed from existing variables.
For vehicles with constant velocity between impacts, the time was calculated by the distance between impacts and the vehicle velocity. Where the vehicle was braked, skidded or accelerated between two consecutive impacts, a mean acceleration was also considered.
For 2076 passenger cars that sustained a multiple impact crash, the times between the impacts and the overall scenario time were calculated.

As the span of time between impacts can have only positive values and there was a higher frequency of shorter time spans but only a few very long time spans, a gamma distribution was applied to describe the calculated time distributions.

The gamma distribution function is valid for $t > \theta$, where θ is the threshold parameter, σ is the scale parameter ($\sigma > 0$) and α is the shape parameter ($\alpha > 0$) (Equation 2).

$$p(t) = \frac{1}{\Gamma(\alpha)\sigma}\left(\frac{t-\theta}{\sigma}\right)^{\alpha-1} \exp\left(-\left(\frac{t-\theta}{\sigma}\right)\right) \qquad (2).$$

The displayed cumulative percentage curves for the scenario time and the times between impacts are generated by the estimated quantiles of the gamma distribution.

The scenario time is defined as the time span from the first to the last impact and summarizes the time between impacts. The impacts themselves were not considered having temporal length. It is to be noted that rollovers were not considered in the scenario time calculation.

THUMS Simulation Model

The human body model THUMS (Total Human Model for Safety, adult male 50%ile version 2.21-040407) was used in a generic sled model to simulate the forward displacement of the occupant due to an initial frontal impact and to estimate the time to pull the occupant back to a normal seating position by a pre-pretensioner.
Different frontal impact levels were defined to represent previously defined delta V ranges where the mean delta V was below the 50% deployment probability of irreversible front restraint devices. This implies that both pretensioner and frontal airbags were not activated in the simulation model. The initial impact time was considered with a temporal length of 150 milliseconds. After the initial impact, a constant negative acceleration according to the distribution of the coded deceleration between subsequent impacts in GIDAS, was applied to the sled model with the aim of reflecting braking and skidding of the vehicle, respectively.
The pre-pretensioner was activated at the beginning of the initial front impact. Simulations without pre-pretensioner activation were used as references. The pre-pretensioner force was measured from the shoulder to the b-pillar loop. Forward displacement of the chest is measured at the 8th thoracic vertebra in a purely horizontal longitudinal direction. The measurement position corresponds to a HIII 50%ile, chest x-accelerometer position. The pull back time defines the time from end of the first impact (150ms) until the occupant's chest has reached the original position in the longitudinal x-direction. The initial occupant seating position corresponds to ECE-R94 (EU 96/79) [13] for a 50%ile occupant size. The second impact was not simulated. Muscle activation was not utilized for the THUMS model.

Effectiveness of Pre-Pretensioning

Passenger cars sustaining an initial front impact below the 50% probability of irreversible front restraint activation (N) can be split in two groups by comparison of the time between impacts (t_{BI}) and the time to pull the occupant to the normal seat position (t_{IP}) (Equation 3).

$$N = N_{t_{BI} \geq t_{IP}} + N_{t_{BI} < t_{IP}} \qquad (3).$$

The effectiveness (E) of pre-pretensioning was calculated by the proportion of vehicles exposed to an interval between impacts equal to or greater than the time required to pull the occupant back into the normal seating position (Equation 4).

$$E = \frac{N_{t_{BI} \geq t_{IP}}}{N} \qquad (4).$$

RESULTS

Data Weighting

When the data set was split into groups by injury outcome according to the police record, the relative weighting factors for the GIDAS data were:

- Slightly injured: 1.10
- Severely injured: 0.85
- Fatally injured: 0.72

A factor equal to 1.00 represents a percentage in GIDAS that corresponds to the national statistics, a factor below one expresses over-representation, and a factor above one expresses under-representation.

As the main analysis results are presented as a relative comparison between single and multiple impacts or focus on MAIS3+ injured persons only, the bias of the dataset towards severe and fatal injuries was assessed to be of lesser importance. Therefore the data set was not weighted in this study, but the given weighting factors could be applied for evaluation beyond this study.

Multiple Impacts Crashes

Twenty-four percent of all passenger cars in the GIDAS data sample sustained a multiple impact crash.
Two-impact crashes accounted for 16%, three-impact crashes for 5% and four-impact crashes for 2% of all passenger cars. Less than 1% of all

passenger cars were exposed to more than four impacts in one crash (Table 1).

Table 1.
Frequency of impacts GIDAS 1999-2007

GIDAS Data (1999 - 2007)	Passenger Cars		
Crash Type	Freq.	Percent	
		All Impacts	Multiple Impacts
Single Impact	10184	76.0%	
Multiple Impacts	3208	24.0%	100.0%
2 Collisions	2151	16.1%	67.1%
3 Collisions	699	5.2%	21.8%
4 Collisions	250	1.9%	7.8%
5+ Collisions	108	0.7%	3.3%
Total	13392	100.0%	

If all vehicles that sustained a rollover were excluded from the sample, the relative percentage of multiple impact crashes was reduced from 24.0% to 20.5% (Figure 1).

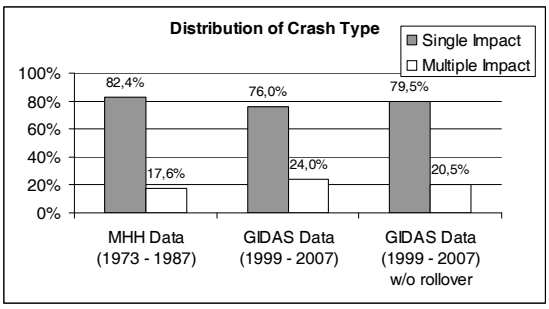

Figure 1. Distribution of crash type.

Rollovers were sustained by 4.4% of all passenger cars, of which 4.0% were involved in a multiple impact crash and 0.4% involved in a single impact crash.

Pre-Crash Velocity

Multiple impact crashes are often associated with high-speed crashes, as it is more likely to sustain a subsequent impact if the kinetic energy is high after the first impact.

The median (50% percentile) pre-crash velocity in two impact crashes was nearly twice as high as the median for single impact crashes.

Approximately 50% of all vehicle crashes with three or more impacts had a pre-crash velocity higher than 100 km/h (Figure 2).

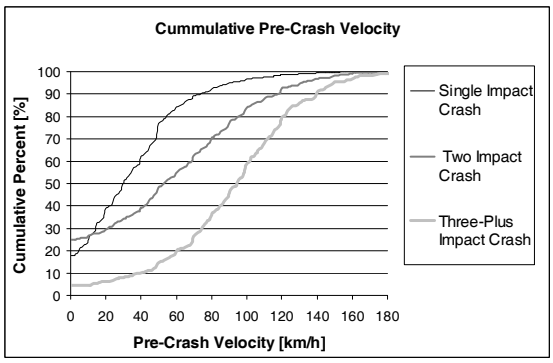

Figure 2. Cumulative pre-crash velocity distribution for single, two, and three-plus-impact crashes.

MAIS3+ and Fatality Risk

In Table 2 single impact crashes are denoted "SIC" and multiple impact crashes "MIC". Injury risk is calculated as the quotient of occupants with MAIS3+ and fatal injury, respectively, and all exposed occupants. The abbreviation "CI [+/-]" shows the confidence interval for the injury risk.

Table 2.
Injury risk in single and multiple impact crashes

all	SIC	CI [+/-]	MIC	CI [+/-]	Ratio
MAIS 3+ Risk	1.5%	0.2%	4.7%	0.7%	3.1
Fatality Risk	0.5%	0.1%	2.2%	0.5%	4.7
Rollover only	SIC	CI [+/-]	MIC	CI [+/-]	Ratio
MAIS 3+ Risk	5.2%		7.6%	2.0%	1.5
Fatality Risk			3.0%	1.3%	
w/o Rollover	SIC	CI [+/-]	MIC	CI [+/-]	Ratio
MAIS 3+ Risk	1.5%	0.2%	4.1%	0.7%	2.8
Fatality Risk	0.5%	0.1%	2.0%	0.5%	4.3

The risk of a serious injury was approximately three times higher in a multiple impact crash compared to a single impact crash. For fatal injury the risk was approximately five times higher.

With the exclusion of rollovers, which occur mainly as multiple impact crashes, the ratios for severe and fatal injury risk between single and multiple impact crashes were slightly lowered.

The significance of the difference in MAIS3+ and fatal injury risks for single and multiple impact crashes without rollover is shown in Figure 3.

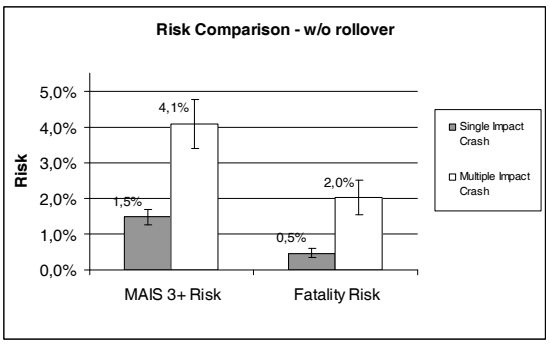

Figure 3. Risk comparisons with confidence intervals for single and multiple impact crashes without rollover.

The MAIS3+ injury risk was calculated for specific two-impact scenarios (Table 3). For three or more impact scenarios the number of MAIS3+ injured occupants per scenario was too small to derive a risk of severe injury with confidence intervals.

The comparison to single impact crashes (Table 4) shows, that the MAIS3+ injury risk in a multiple impact crash is generally higher than in a single impact crash.

Table 3.
MAIS3+ risks in multiple impact crashes

Scenario	MAIS3+ risk	Confidence interval
Front – Front	3.2%	+/- 2.1%
Front – Side	5.5%	+/- 2.5%
Side – Front	4.8%	+/- 2.4%
Side – Side	3.9%	+/- 1.9%

Table 4.
MAIS3+ risk in single impact crashes and rollovers

Scenario	MAIS3+ risk	Confidence interval
Single Front	1.6%	+/- 0.3%
Single Side	1.8%	+/- 0.5%
Single Rear	0.1%	-

The MAIS3+ injury risk in a front-side and side-front collision was about three times higher and for front–front and side–side about two times higher compared to a single front or single side impact. An MAIS3+ injury outcome was rarely found in single rear impacts.

Triggering of Irreversible Restraint Systems

The probability of irreversible front and side restraint systems activation in single impact crashes was derived from the GIDAS data.

The logistic regression for front restraint device deployment probability in a front impact was based on 2089 vehicles equipped with driver airbag, from which 735 were activated.
For side protection systems the deployment probabilities for side airbag only and side airbag plus curtain airbag were determined by logistic regression.
One hundred and seventy vehicles exposed to a side impact were equipped with a side airbag. In 52 vehicles the side airbag was activated. In 8 of 36 vehicles exposed to a side impact, both side and curtain airbag were deployed.

The probability of front airbag deployment depending on the longitudinal delta V during a front impact is shown in Figure 4.

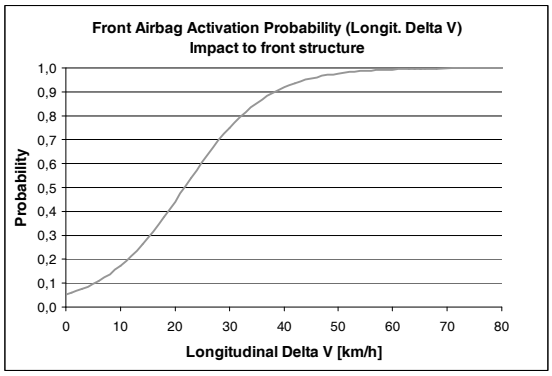

Figure 4. Front airbag deployment probability by longitudinal delta V.

Regression coefficients and percentages were calculated for front airbag, side airbag only and side plus curtain airbag deployment probability (Table 5, 6 and 7).

Table 5.
Front airbag deployment probability

Front Airbag Deployment Probability Regression Coefficients				
β_0		β_1		
-2.897		0.133		
Probability	25%	50%	75%	95%
Long. delta V	13 km/h	22 km/h	30 km/h	44 km/h

Table 6.
Side Airbag only deployment probability

Side airbag only deployment probability Regression coefficients				
β_0		β_1		
-1.640		0.074		
Probability	25%	50%	75%	95%
Lat. delta V	7 km/h	22 km/h	37 km/h	N/A

N/A = Not applicable, no data available

Table 7.
Side plus curtain airbag deployment probability

Side plus curtain airbag deployment probability Regression Coefficients				
β_0		β_1		
-2.481		0.161		
Probability	25%	50%	75%	95%
Lat. delta V	8 km/h	15 km/h	22 km/h	N/A

N/A = Not applicable, no data available

The 50% deployment probability of a front airbag and side airbag only are presented by a longitudinal and lateral delta V of 22 km/h, respectively. For the combination side and curtain airbag the 50% activation probability was present at a lateral delta V of 15 km/h.

Scenarios for Reversible Restraint System Evaluation

In about two thirds of multiple impact crashes with MAIS2+ or MAIS3+ injury outcome the irreversible (front) restraints were not triggered in an initial front impact. If the first impact was a side impact, the proportion of non-activated, irreversible side protection systems corresponds to approximately 50% (Table 8 and 9).

Table 8.
Percentage of "no trigger" for irreversible restraint systems in first impact, MAIS2+

Vehicles with at least one AIS2+ injured occupant			
Initial impact: Front		Initial impact: Side	
Front – Front	64%	Side – Front	39%
Front – Side	65%	Side – Side	59%
Front – Multiple	100%	Side – Multiple	89%
All subsequent impacts			
Front – x	67%	Side – x	50%

Table 9.
Percentage of "no trigger" for irreversible restraint systems in first impact, MAIS3+

Vehicles with at least one AIS3+ injured occupant			
Initial impact: Front		Initial impact: Side	
Front – Front	83%	Side – Front	21%
Front – Side	53%	Side – Side	60%
Front – Multiple	100%	Side – Multiple	86%
All subsequent impacts			
Front – x	71%	Side – x	48%

Evaluation of Vehicle Acceleration before and after Initial Front Impact

To enable the simulation of representative impact scenarios below the threshold of irreversible restraint systems the acceleration situation of vehicles before and after the first impact was investigated.
The results showed that approximately 30% of all vehicles braked or skidded before an initial front impact (neg. Acc.), whereas this proportion increased to over 80% after initial front impact.
Less than 10% of the passenger cars had a constant velocity (no Acc.) between initial front and subsequent impact (Figure 5).

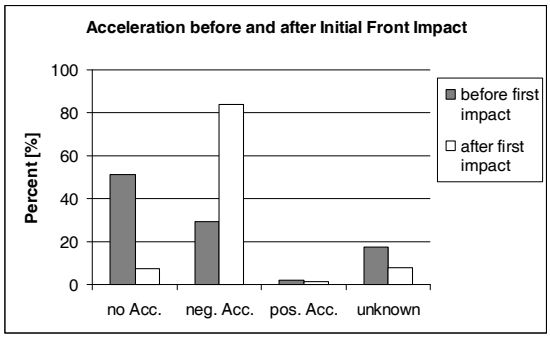

Figure 5. Vehicle acceleration status before and after initial front impact.

The quantile plot shows the cumulative distribution of mean deceleration in [m/s^2] for the vehicles that braked or skidded after the initial front impact (Figure 6)

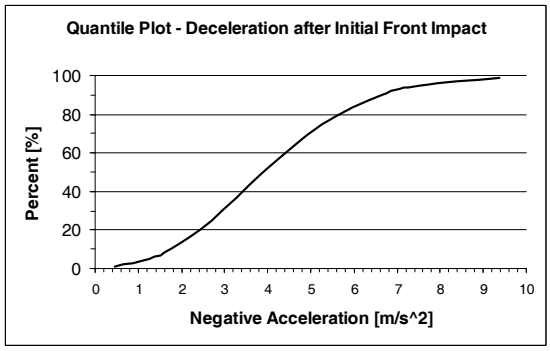

Figure 6. Quantile plot for mean deceleration of vehicles after initial front impact.

Roughly 95% of all passenger cars that sustained an initial front impact had a mean deceleration of less than 7m/s^2.

THUMS Simulation of Occupant Pre-Pretensioning after Initial Front Impact

The simulation scenarios were defined according to the results from real traffic accidents. Only those delta V ranges were considered for which the mean delta V of the category was below the 50%

deployment probability of irreversible restraint systems. All initial front impacts were simulated with duration of 150 milliseconds.
The corresponding (constant) deceleration during the impact was calculated based on the given mean delta V per range and the impact period (Table 10). The minor delta V impact was equivalent to a braking sequence.

Table 10.
Simulation of initial front impact

Delta V range	Mean Acceleration	Mean Delta V
Minor (1-5 km/h)	0.7g / 150ms	~4 km/h
Low (6-15 km/h)	2.0g / 150ms	~10 km/h
Moderate (16-25 km/h)	4.0g / 150ms	~20 km/h

After the first impact, a constant negative acceleration of 0.7g was applied to the sled model according to previous results (Figure 5 and 6).

When no pre-pretensioning was applied, the THUMS simulation results showed a maximum longitudinal chest displacement of 9 cm for the minor delta V impact, 11 cm for the low delta V impact and 15 cm for the moderate delta V impact (Table 11).

For example, with the application of a pre-pretensioning force of 200N (400N), the forward displacement of the chest of the THUMS model was reduced from 9 cm to 3 cm (0 cm) for the minor delta V impact.

The pre-pretensioning force necessary to pull back the occupant to its original position was dependent on the delta V. For low delta V a force of 300 N is required, while a force of 200 N was needed for moderate delta V.

Table 11.
THUMS simulation results for chest displacement (CD) and occupant in position time (IPT)

THUMS Simulation Results						
PPT Force [N]	Minor delta V		Low delta V		Moderate delta V	
	0.7g 150ms		2.0g 150ms		4.0g 150ms	
	CD [cm]	IPT [s]	CD [cm]	IPT [s]	CD [cm]	IPT [s]
w/o	9	N/A	11	N/A	15	N/A
200	3	N/P	9	N/P	14	0.37
300	0	0	8	0.36	13	0.27
400	0	0	7	0.26	12	0.21

N/A = Not applicable
N/P = Chest not fully pulled back by the pre-pretensioning force

Effectiveness of Pre-Pretensioning

For the effectiveness of pre-pretensioning the time elapsed between the impacts in the GIDAS data sample was calculated. The estimated quantiles of a gamma distribution were used to describe the cumulative percentage distribution of the time between the first and second impacts for minor, low and moderate delta V impacts (Figure 7).

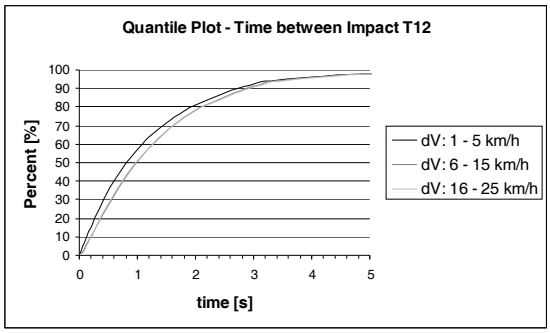

Figure 7. Quantile plot for gamma distribution of time between impacts with minor, low and moderate delta V at the first impact

Additionally, the gamma distribution parameters for the minor, low and moderate delta V first impacts are shown (Table 12).

It is noted that the distribution characteristic for low and moderate delta V were nearly identical and therefore only shown in one table.

Table 12.
Gamma distribution parameters for time between impacts

Time between Impacts Minor delta V		
Parameter	Symbol	Estimate
Threshold	Theta	0.00
Scale	Sigma	1.22
Shape	Alpha	0.96
Time between Impacts Low and Moderate delta V		
Parameter	Symbol	Estimate
Threshold	Theta	0.00
Scale	Sigma	1.07
Shape	Alpha	1.22

The distribution of the delta V ranges below the 50% activation probability of front restraint systems was considered for the calculation of the pre-pretensioner effectiveness (Table 13).

Table 13.
Distribution of delta V ranges below the 50% activation probability of front restraints

Time between Impacts - Gamma Distribution		
Delta V range	Percent	Cum. Percent
Minor (1-5 km/h)	39.5%	39.5%
Low (6-15 km/h)	30.2%	69.7%
Moderate (16-25 km/h)	30.3%	100.0%

The following results for the effectiveness of pre-pretensioning after an initial front impact were derived:

- 200N: 24% effectiveness
- 300N: 90% effectiveness
- 400N: 93% effectiveness.

Thus with, for example, a pre-pretensioner force level of 300N in 90/100 vehicles that sustained an initial frontal impact the occupants were pulled back in position before a subsequent impact.

DISCUSSION

The comparison of the multiple impact crash frequency between this study and the BASt report from 1987 lacks information for the sampling criteria for the BASt report. Nevertheless, it was stated that older MHH data was more biased towards severe and fatal accidents than the current analysed GIDAS data, collected along with the TU Dresden [14]. As the risk of severe or fatal injury is much higher in a multiple than a single impact crash it is obvious, that the older MHH data is more likely to over-represent multiple impact crashes. Therefore it can be stated that the relative percentage of multiple impact crashes has increased by about one third in the last two decades.

The calculations for the deployment probability of irreversible occupant protection systems are based on a univariate regression model depending on delta V alone. This is a gross simplification of complex occupant restraint system algorithms, but considered acceptable for plain statistical usage. One may assume an identical deployment probability for side airbag only and side plus curtain airbag. It can be noted that the vehicles equipped with both side and curtain airbags were generally newer and, moreover, that the number of these vehicles was limited in the sample.

We propose an approach towards a benefit analysis method for pre-pretensioner in multiple impact crashes. The method is based on a system model including the human body model THUMS, where both the vehicle interior and the occupant model have been validated mainly for higher impact velocities than used in this study. Also, muscle activation was not considered in the model, which is seen by the large head displacements in Figure 8. Therefore, the displacement of the chest was used instead of head displacement as a more reliable measurement. In comparison to volunteer experiments, differences might also be expected.

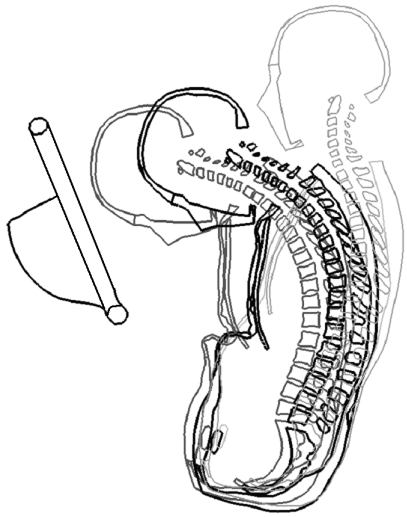

Figure 8. THUMS displacements for initial position (light grey), without pre-pretensioning (grey) and with pre-pretensioning 400N (black).

The pullback force was seen to depend on the delta-V due to the rebound of the occupant upper body and head. A lower force to reposition the occupant was thus required for the moderate delta V case (with large rebound) compared to the low delta V case (with small rebound). Volunteer tests with the moderate delta V level do not seem to be feasible as they are likely to induce harm.

The effectiveness of a pre-pretensioner to pull back the occupant into the normal seating position after an initial side impact has not been discussed. It might be assumed that the possibilities of the pre-pretensioner are smaller due to the reduced lateral restraint function of a seat belt. But this is part of further investigations.
Several reversible occupant restraint solutions have already been presented discussing an enhanced lateral fixation of the occupant, e.g. 3+2-point belt, or active seat side bolsters [15], [16].

The calculation of the overall scenario time can be used for further evaluation of the occupant protection benefit in multiple impact crashes with curtain airbags that have longer stand up capabilities, e.g. when activated in an initial impact.

The quantiles for gamma distribution of the scenario time show that 90% of all multiple impact crashes with a side and curtain airbag deployment in the first impact have an overall scenario time of less than 4 seconds. Ninety five percent of these crashes do not exceed 5 seconds (Figure 9). Multiple impact crashes including rollovers were not considered.

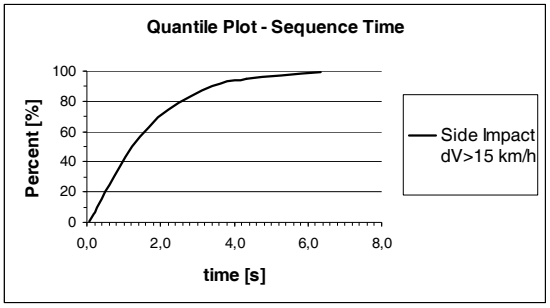

Figure 9. Quantile plot for gamma distribution of overall scenario time after curtain airbag activation.

The gamma distribution parameters which describe the distribution uniquely, are presented in Table 14.

Table 14.
Gamma distribution parameters for overall scenario time after curtain airbag activation

Scenario Time - Gamma Distribution		
Parameter	Symbol	Estimate
Threshold	Theta	0.03
Scale	Sigma	1.19
Shape	Alpha	1.32

The potential protection benefit by a curtain airbag with a stand up time of about five seconds is obvious and it represents available technology, although it has been developed mainly for rollover protection.

In general, the pre-pretensioner shows a very high potential to reduce out-of-position in frontal impacts, especially those with a small delta V, and additionally pull occupants back into previous the seating position. One boundary condition is a smart activation and force level algorithm, ensuring that no additional harm is induced by pre-pretensioning.

CONCLUSIONS

The comparison of MHH data 1973-1987 and GIDAS data 1999-2007 reveals that the relative percentage of passenger cars sustaining a multiple impact crash has increased in the last two decades by about one third.

The risk of sustaining a severe injury is three times higher in a multiple impact crash than in a single impact crash and for fatal injury the risk is four times higher, even if rollover crashes are excluded.

With use of the 50% probability deployment thresholds in about two thirds of all multiple impact vehicles with at least one MAI3+ injured occupant, the front airbag is not activated in the first impact. When the first impact is a side impact, the percentage of non-deployed side and curtain airbag is about 50%. This reveals an obvious potential for a reversible occupant restraint system like a pre-pretensioner to retain or retract the occupant in position.

To assess the occupant forward displacement during an initial frontal impact, a finite element sled model including the human body model THUMS and standard interior safety systems was used. No muscle activation was applied.
The activation of a pre-pretensioner with different force levels demonstrates a major benefit firstly in reducing occupant out-of-position, especially in impacts with a small delta V, and secondly in getting the occupant back into the original seating position.

With a pre-pretensioning force of 200N the occupants in 24% of the vehicles, sustaining a front impact without front airbag activation (50% probability), are in position before a subsequent impact. With a pre-pretensioning force of 300N this percentage is increased to 90%. With 400N pre-pretensioning force, an effectiveness of 93% is achieved.

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