Improved Thoracic Injury Risk Functions for the THOR-M-50 developed in a new simulation-based Approach

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ABSTRACT

To assess occupant safety in a crash test, criteria associating the measurements made with a crash test dummy to injury risk are necessary. To enable better protection of elderly car occupants the objective of this study was to develop improved thoracic injury criteria for the THOR average male dummy. The development of these criteria is usually based on matched dummy and Post Mortem Human Surrogate (PMHS) tests by relating the obtained PMHS injuries to dummy measurements. This approach is limited, since only a few tests in relevant loading conditions are available and any new test series requires high efforts to be performed due to their complexity and costs. To overcome these limitations and to extend the dataset for the development of THOR dummy chest injury risk functions a simulation-based approach was applied within the EC funded project SENIORS (Safety Enhanced Innovations For older Road Users - www.seniors-project.eu).

Within this study frontal impact sled simulations with an FE model representing a THOR average male dummy and matched simulations with a human body model (HBM) representing an elderly car occupant were carried out. The HBM used for this study was the THUMS TUC with modified rib cage, which was developed in SENIORS. The modifications included material and geometry changes aiming to represent an elderly car occupant.

The rib fracture risk was predicted with a deterministic approach whereby a rib was considered broken when the strain exceeded an age-dependent threshold. Furthermore, a probabilistic method was applied to predict the probability of sustaining a certain number of fractured ribs by comparing local strain values to the distribution of cortical rib ultimate strain. By relating the output from the HBM simulations to a multi-point dummy injury criterion, injury risk curves were calculated by statistical methods.

The wide range of loading conditions resulted in the desired range of injuries and THOR ATD output. The number of fractured ribs predicted by the HBM based on the deterministic prediction method was between 0 and 15. Furthermore, the probabilistic risk for the number of rib fractures equal or greater than two, three or four was calculated for each load case. The THOR rib deflection criterion R_{max} was between 18 and 56 mm, while the PC Score was in the range of 2.5 to 7.2.

Based on these outputs new risk curves for the predicted deterministic (AIS2+/3+) and probabilistic injury risk were calculated. The new curves show reasonable shapes and significance that provide trust in their application. The new risk curves are compared to risk curves obtained by traditional methods. The results were found similar to previous injury risk functions based on physical tests, which gives a high level of confidence in the chosen approach.

The simulation-based approach of matched ATD model vs. HBM simulation was successfully applied. R_{max} curves show a slightly better quality than the injury criterion PC Score.

INTRODUCTION

The THOR-M is the most advanced frontal impact dummy to be used for assessment of thoracic risk in upcoming test procedures. The dummy provides chest deflection measurement at multiple locations. To use the measurement for injury risk assessment and design of occupant restraint systems, criteria relating the measurements made with a crash test dummy to injury risk are needed. One objective of the EC funded project SENIORS (Safety Enhanced Innovations For older Road Users - www.seniors-project.eu) was to improve THOR dummy based thoracic injury metrics and risk functions to assess and enhance the protection of elderly car occupants in relevant loading conditions.

For the THOR different injury criteria and risk functions to assess the risk of thorax injury have been proposed previously (Crandall et al. 2013; Poplin et al. 2017; Davidsson et al. 2014). These criteria and risk functions are based on the approach of matched pair testing using ATD and Post Mortem Human Subject (PMHS) tests. Due to the matched test results the injury level from PMHS tests is related to different injury predictors or criteria derived from multi-point ATD deflection. In order to achieve the goal of improved thoracic injury criteria and risk functions, an extended dataset of PMHS and dummy test results was needed.

However, several limitations with this approach were identified. One the one hand, only a few matched PMHS and dummy tests are available that represent loading conditions of interest. Furthermore, the available tests were too severe in terms of loading and not representative of contemporary vehicles. They mainly consisted of fixed three-point belt loading, while only a few tests with distributed (airbag) or combined belt and airbag loading were available.

Some matching THOR dummy tests, including sled tests with combined belt airbag loading to improve thoracic injury criteria, were performed in the EC funded project THORAX (Davidsson et al. 2014). However, the dummy version used is now considered outdated. Thus, to work with this data set of load cases it would be necessary to repeat matched tests with the current ATD version. This led to another limitation, which is the availability of components for hardware testing, especially restraint components (belts, airbag) and vehicle seats. Based on this experience it would be necessary to perform a large number of new tests including PMHS and matching tests with the latest THOR dummy version to obtain a sufficient representative data set that would fulfil the requirements for improving chest injury criteria and risk functions. This was not possible within the limited time frame and resources of the project.

To overcome these limitations a new computer model simulation-based approach was proposed within the SENIORS project. The idea was to extend the data by performing matched frontal impact sled computer simulations with a model representing the latest THOR-M ATD version and matching simulations with a human body model (HBM) representing an elderly car occupant. This covers a wider range of loading conditions and generates an extended dataset of matched HBM and ATD test. More test conditions (restraint system, impact angle, velocity) could be included, especially addressing the less severe chest loading in modern vehicles.

Preliminary results were shown by Eggers et al. (2018c). Meanwhile the methods of this approach were refined and updated. The objective of this paper is to provide an updated detailed description of this simulation-based approach, the methods used, and to present the updated injury risk curves.

METHODS

The method of the simulation-based approach that was developed and applied within the EC funded project SENIORS is shown in Figure 1.

Simulation Matrix

The approach starts with the definition of the simulation matrix. This is crucial since the simulation space should cover the loading conditions which are identified to be relevant based on collision data analysis and representative of the loading condition in current and possibly also future vehicle occupant restraint systems. It should preferably be inhomogeneous in terms of chest loading to avoid a correlation of possible injury criteria to specific single loading conditions. It was decided to include only frontal and oblique (+/-30°) sled load cases in this study.

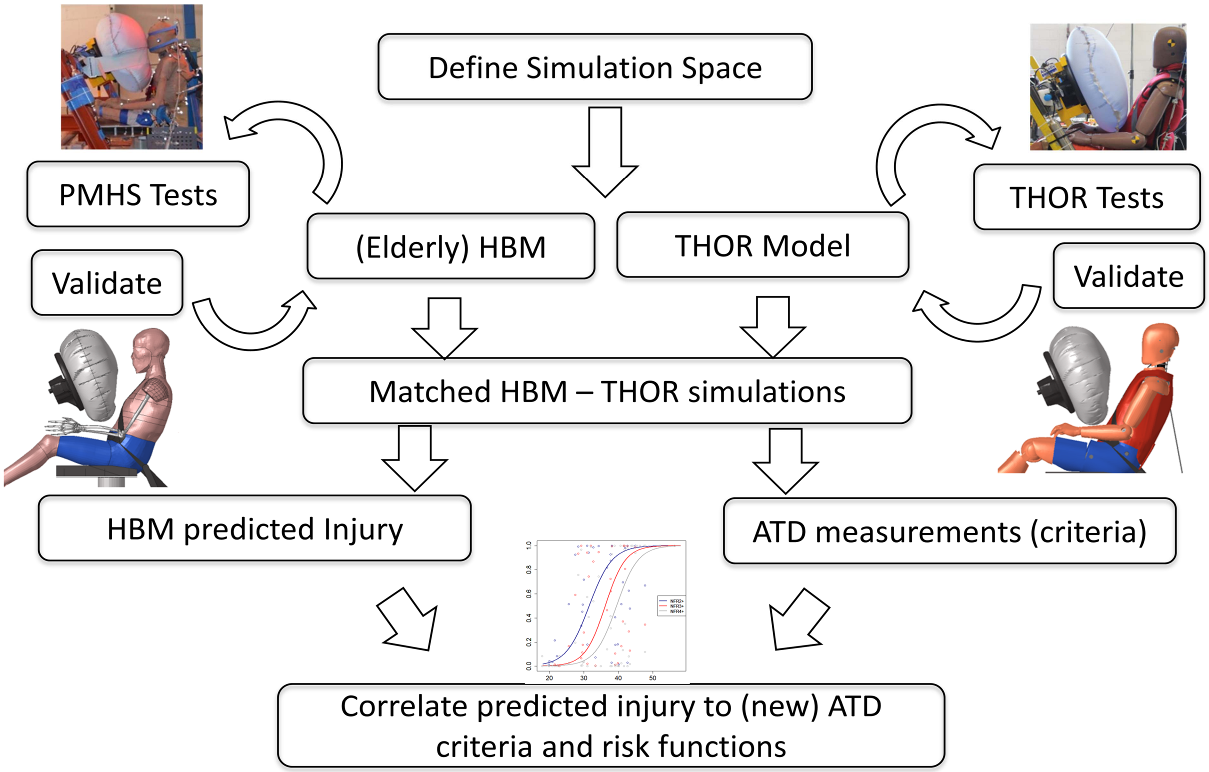

Figure 1. SENIORS simulation-based approach for improved occupant thoracic injury criteria and risk functions

Appendix 1 shows the simulation matrix consisting of 58 load cases that was used for this study. The variation of some key parameters in this simulation matrix is listed below:

- Impact velocities between 25 km/h and 56 km/h
- Impact directions: frontal (0°), near-side (+30°) and far-side (-30°)
- Different belt load limiter levels (no load limiter, 2 kN to 6 kN)
- Without pretensioner / with single and multiple pretensioning
- Without airbag / with airbag
- Different 3-point belt routing (variation of upper D-ring and buckle position)
- Load cases with alternative restraints (four-point belt system, split buckle)
- Different seat friction coefficients (standard/high)

In order to be able to reproduce these tests and simulations in the future (e.g. with another or new occupant model), for most load cases generic components were used. The main part of the simulation matrix is based on a simple generic test setup, which was developed within the SENIORS project (Eggers et al., 2017) using a three-point belt system (L01 to L16). For some load cases a generic load limiter and a pre-inflated driver airbag were used. The basis of this set-up including seat pan and generic bag was used for further load cases (A17 to A45) with advanced restraint systems like four-point belts, split buckle and multiple pretensioning. Details of theses alternative belt systems are described by Mroz et al. (2018). Furthermore some load cases were based on the 'Gold Standard' test set-up (Shaw et al. 2009, Crandall et al. (2015a, 2015b)) including a generic load limiter and oblique conditions (A01 to A08).

The gold standard test conditions were also used for biofidelity evaluation of the HBM simulations. Results can be found in the SENIORS report D2.5a (Eggers et al., 2018b). To assess the validation of the THOR dummy model and the components of sled environment, THOR dummy tests of some of these load cases were performed. Detailed descriptions of the loading configurations and validation results are provided in D2.5a. (Eggers et al., 2018b). Based on the results the validation status of the HBM, dummy and sled models were found to be sufficiently validated to be used in this simulation-based study.

Occupant models and output definition

THOR dummy model

THOR dummy simulations were done with the LS-DYNA version 1.3.2 of the Humanetics THOR adult average male model. This FE-model represents the US NCAP Version of THOR-M SBL-A with THOR-LX legs.

The output from the dummy model simulations that is used for injury criteria and risk curve development are the four resultant IR-Tracc measurements. From the measurements two candidate injury criteria that are currently discussed to be used for vehicle safety assessment tests (PC Score according to Poplin et al. (2017) and R_{max}) were calculated.

Human body model

For this study, a modified version of the THUMS TUC v3.01 was used. Age-related modifications focused on representing the rib cage of a 65+ year-old car occupant. Therefore, the rib cage was geometrically morphed and the corresponding properties were adapted to account for age-related changes to the biomechanical characteristics of the thorax. Age- related material properties were taken from literature. Thereby, the cortical bone thickness decreases with age and was consequently set to 0.63 mm while the Young's modulus of the costal cartilage was increased to 69.38 MPa (calcification). Details of the age-related rib cage morphing and adjustments to the material properties are described in the SENIORS deliverable D2.4 (Eggers et al., 2018b). Figure 2 (left) shows the rib cage of the original THUMS model while Figure 2 (right) shows the 65+ year-old morphed rib cage that was used for this study.

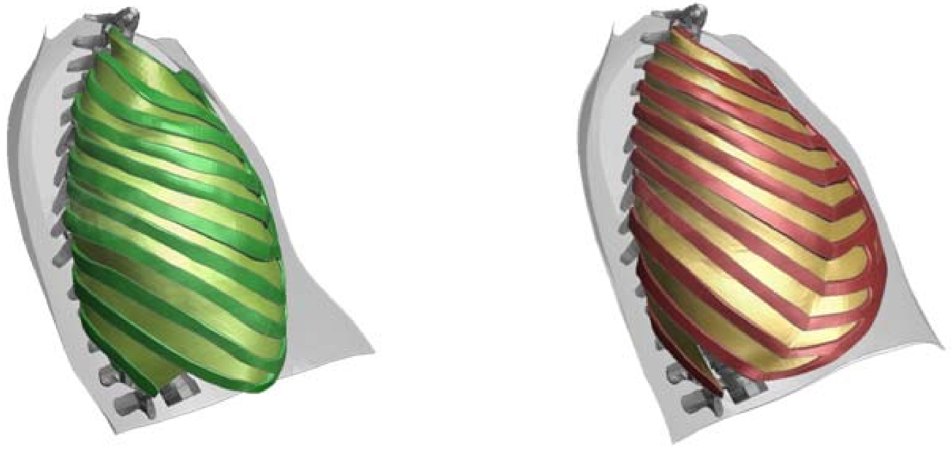

Figure 2. Chest of original THUMS TUC 3.0.1(left) and THUMS TUC 65+ years-old morphed chest (right)

While reviewing the results of the SENIORS project, some questionable interactions of the rib cage and seat-belt with a presumably too stiff pelvic region were observed. For verification, the pelvic region was compared against abdominal impact response corridors defined by Hardy et al. (2001). The abdominal impact response of the original model in the free-back rigid bar tests, as well as for the seatbelt loading test was overall too stiff, while a model with adjusted pelvic soft tissue material properties (bulk modulus reduced by a factor of 10^3) showed good conformity with these biofidelity targets (Figures 3 and 4).

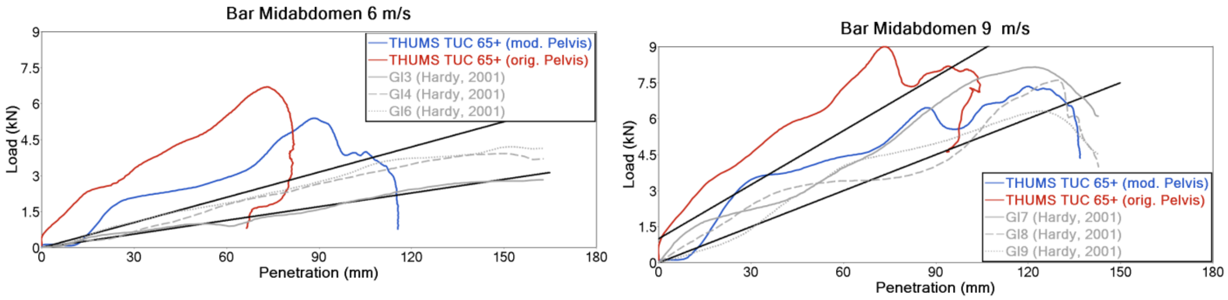

Figure 3. Abdominal impact response to free-back rigid bar tests with v = 6 m/s (left) and v = 9 m/s (right) for the original pelvic material (red) and with adjusted material properties (blue)

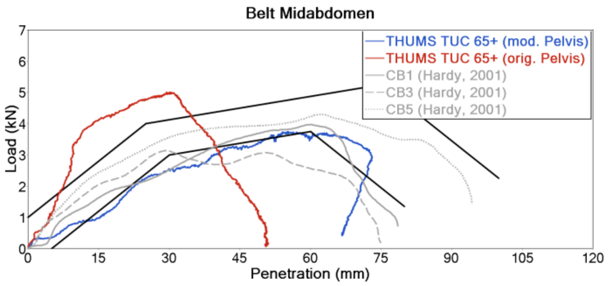

Figure 4. Abdominal impact response to seat belt loading for the morphed THUMS TUC with original pelvic material (red) and with adjusted material properties (blue)

Since adjusting the pelvic soft tissue material showed good conformity with the biofidelity targets, these changes were adopted for this study.

Rib fracture injury risk assessment based on HBM simulations

To assess the thoracic injury risk, deterministic and probabilistic approaches were used. For both approaches the peak strain of the cortical bone in each rib was obtained by using a post-processing script, which calculates the extrapolated surface strains with the first principal strain at the outermost and innermost integration point of the strain tensor:

$$\varepsilon_{\text{extrapolated surface}} := \left| \varepsilon_{\text{IP,outer}} + \frac{1 - d_{\text{NIP}}}{2 \cdot d_{\text{NIP}}} \cdot \mathrm{diff}\left(\varepsilon_{\text{IP,inner}}, \varepsilon_{\text{IP,outer}}\right) \right|_{\max} \qquad \text{(Equation 1)}$$

The distance from the outermost integration point to the actual surface is dependent on the number of integration points. Within this study, the cortical bone of each rib was modelled with five integration points; therefore, d_{NIP} is equal to 0.9062. For the deterministic approach the peak strain in each rib was compared to the assumed ultimate failure strain threshold of a 65 year old occupant based on Kemper at al. (2007). Thereby each individual rib, which peak strain exceeded 1.9%, was considered to have fractured. For each load case the number of fractured ribs was counted and then translated to the AIS thoracic injury coding using the 2008 update of the 2005 version of the Abbreviated Injury Scale (AAAM, 2008). Consequently, load cases with three or more fractured ribs were classified as an AIS3+ rib cage injury, while two or more fractured ribs resulted in an AIS2+ rib cage injury.

Additionally, a probabilistic approach suggested by Forman et al. (2012) was used to determine the severity of each load case. Thereby, with the peak strain in each rib and using a statistical distribution, the risk of fractures to the whole rib cage can be predicted. The method provides a risk percentage value for exactly two, three or four broken ribs as well as risk percentage values for at least two, three or four broken ribs.

Matching occupant positioning and belt fitting to the ATD and HBM Model

The results of the HBM and ATD simulations are later matched. Therefore, high effort went into positioning the models in matching postures and to obtain a comparable belt path and distance to the airbag. To position the occupant models the focus was to align the H-point and the chest surface in the mid-sternum area between the HBM and the THOR ATD model (see Figure 5). Since there are no directly comparable landmarks on the chest of the occupant models, the chin-to-belt distance was chosen as a reference measure to define a comparable belt path. Additionally, the distance between the belt and the sternum notch was used as an additional measurement to check the matching positions of the belt.

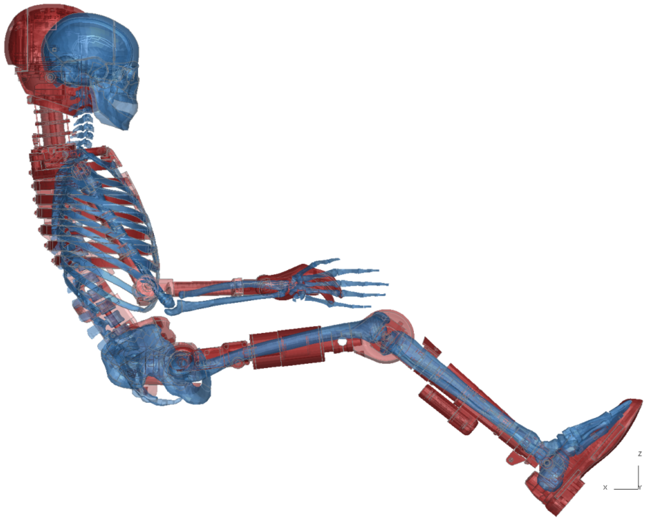

Figure 5. Comparison of the matching seating position of THUMS TUC (blue) and THOR-M-50 model (red).

Statistical methods for new risk curves

Two approaches were used to update injury risk curves establishing a relationship between rib fracture risk and multi-point measurement based THOR dummy chest injury criteria. Details of the statistical models are provided in SENIORS Deliverable 2.5a (Eggers et al., 2018a). A short summary is provided below.

Deterministic models

A Weibull model, commonly used for survival analysis, has been applied to the matching simulation data to determine the relationship between the probability of thorax injury in terms of AIS2+/3+ chest injury risk (based on number of fractured ribs) from HBM rib strain output and the injury prediction based on R_{max} and PC Score (Poplin et al., 2017) from the THOR simulations.

Probabilistic model using linear regression model

To determine the relationship between the probability of a certain injury severity, here expressed as the risk to sustain a certain number of fractured ribs NFR (Forman et al., 2012), and an injury predictor provided by the THOR dummy simulations (R_{max} and PC Score), a probabilistic approach using a linear regression model was used.

In more detail a dose response relationship (logit, Generalized Linear Model) between the PC Score and the response in terms of “x” fractured ribs was assumed for which reason a logit transformation was applied to the given probabilities. Assuming a generalized linear model, a linear relationship shall exist between the logit transformed values and the dose parameter (PC Score values). The coefficients are computed by means of a linear regression. Finally, the intercept and the slope of the linear regression model were used for the inverse logit transformation to calculate the estimators for the probabilities, see also SENIORS D2.5a (Eggers et al., 2018a).

RESULTS

In total 58 matching sled simulations as defined according to the simulation matrix (Appendix 1) have been performed with the THOR ATD model and the THUMS elderly human model respectively.

Distribution of dummy and HBM output

IR-Tracc outputs (resultant multi-point deflections) and belt loads from THOR simulations are provided in Appendix 2. Chest injury predictors determined from IR-Tracc output (R_{max} and PC Score) are also provided.

The table in Appendix 3 shows the corresponding HBM output for each load case. The injury output from the HBM simulations includes the probabilistic risk to sustain exactly or more than two, three or four fractured ribs based on the method proposed by Forman et al. (2012), the number of fractured ribs determined by the deterministic approach and the corresponding AIS2+ and AIS3+ chest injury level.

The objective was to cover a wide range of injury severities and loading conditions. The output shows that this resulted in a wide distribution of IR-Tracc deflection peak values as well as the injury predictors indicating a broad distribution of chest loading severity, which was the intention of the extend loading condition matrix. The belt loads in THOR simulations ranged between 1 and 6 kN. R_{max} values were in the range between 18 and 56 mm. The PC Score (Poplin et al. 2017) values ranged between 2.5 and 7.2.

Also the distribution of the number of fractured ribs showed a good variation in a range between zero and 15 fractured ribs (see

Figure 6). The probabilistic injury risk prediction also showed a good distribution having a zero injury risk for several load cases through to load cases with 100% risk.

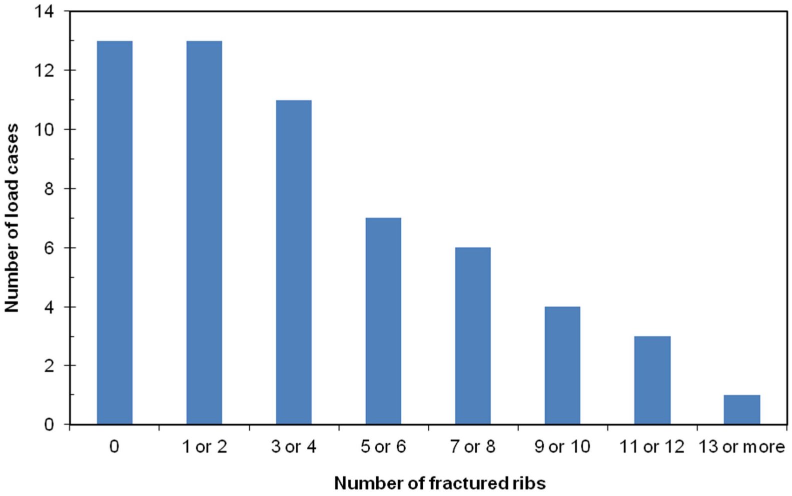

Figure 6. Frequency distribution for the number of fractured ribs in the 58 load cases (determined in HBM simulation based on extrapolated rib surface strain exceeding 1.9%)

New injury risk curves

The matched simulation outputs of the THOR (injury predictors) and HBM (injury in terms predicted rib injury) were used to develop new THOR dummy chest injury risk functions.

Deterministic Injury Risk Functions

The following plots show the injury risk functions relating a rib injury severity in terms of AIS2+ or AIS3+ based on deterministic rib fracture prediction from HBM simulation, and injury criteria from THOR dummy simulations (R_{max} and PC Score, respectively). The new injury risk functions are shown in Figure 7 to Figure 10. Table 1 shows the p-values of the generated injury risk function models.

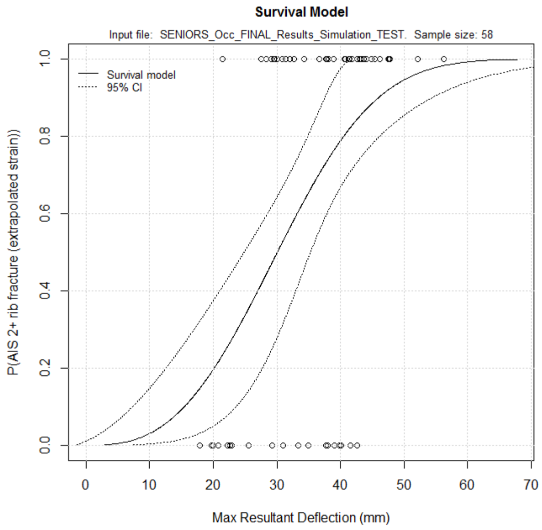

Figure 7. AIS2+ rib injury vs. R_{max}

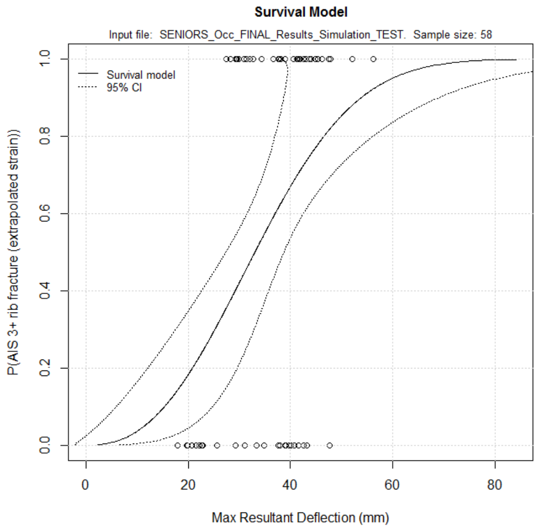

Figure 8. AIS3+ rib injury vs. R_{max}

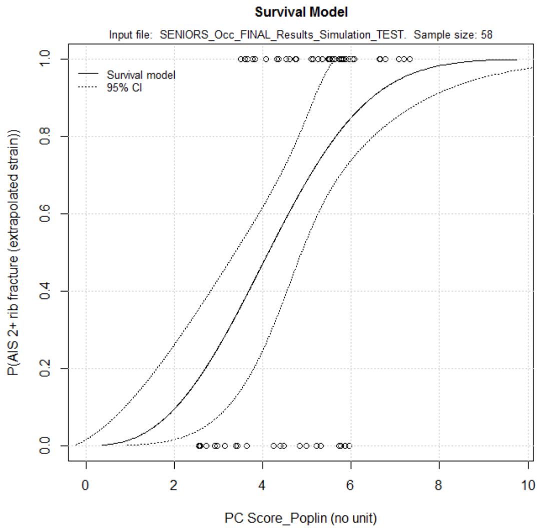

Figure 9. AIS2+ rib injury vs. PC Score

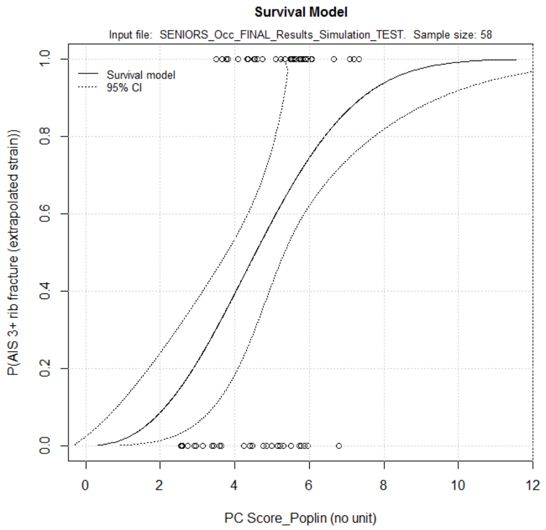

Figure 10. AIS3+ rib injury vs. PC Score

Table 1. P-values received processing the survival model based on deterministic HBM injury output

	AIS2+	AIS3+
R_{max}	5.35E-04	7.84E-03
PC Score	1.54E-03	7.70E-03

The p-values indicate that all risk curves are statistically significant. For the AIS2+ risk the curves that are based on the injury criterion R_{max} shows better results in terms of p-values compared to the risk curves based on PC Score. Regarding AIS3+ injury risk curves based on R_{max} and PC Score show very similar results in terms of statistical significance. In general, the p-values were slightly better for R_{max} injury risk functions at a given AIS than for PC Score.

Probabilistic Injury Risk Functions

The relationship between the probability of a certain number of fractured ribs (NFR) predicted by HBM simulation, and injury criteria (R_{max} and PC Score) using the output from the THOR dummy simulations, was determined by processing a probabilistic model using a generalized linear regression model. The resulting injury risk functions are shown in Figure 11 and Figure 12. Table 2 shows the observed p-values of the generated injury risk function models. It can be observed that all curves are statistically significant (<5%).

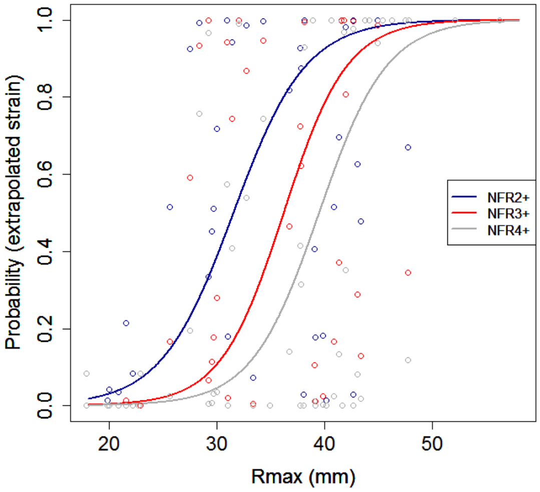

Figure 11. Probability of sustaining two or more (2+), three or more (3+) or four or more (4+) fractured ribs vs. R_{max}

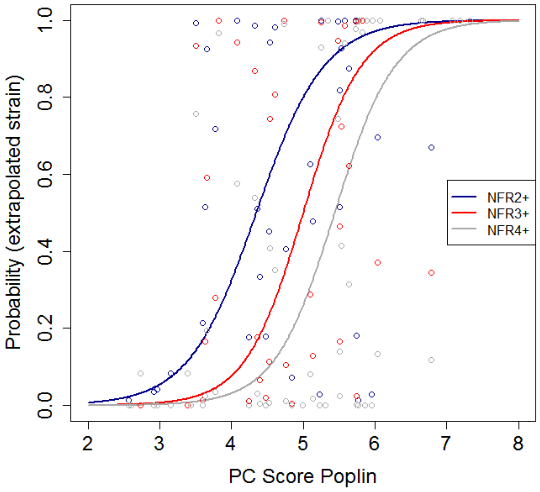

Figure 12. Probability of sustaining two or more (2+), three or more (3+) or four or more (4+) fractured ribs vs. PC Score

Table 2. P-values received processing the probabilistic model using a linear regression model

	NFR2+	NFR3+	NFR4+
Rmax	4,26E-06	8.79E-07	2.24E-06
PC Score	1.46E-05	1.89E-06	2.35E-06

Overall, the injury risk functions presented here show reasonable shapes and excellent p-values of the regression models. In addition, it can be generally confirmed that a higher injury criterion (R_{max} or PC Score) corresponds with a higher probability of injury which was a prerequisite of the applied statistical model.

DISCUSSION AND LIMITATIONS

The main purpose of the simulation-based approach was to address one major limitation of the traditional experimental testing based approach, which is the limited size of the data set that is not sufficiently representing relevant loading conditions. The new dataset is more representative for occupant loading in modern vehicles, including a broader range of chest ATD loading patterns in terms of peak and differential deflections.

New risk curves relating the injury criteria to AIS thorax injury and to a probabilistic risk for a certain number of rib fractures were developed. The results regarding new risk curves look very promising. Compared to the preliminary curves provided before (Eggers et al., 2018a) the curves show improvement in terms of statistical significance. This might be related to improvements to the HBM used for this study giving more consistent injury output.

The deterministic risk curves developed in this simulation based approach can be directly compared to risk curves developed by the traditional approach using PMHS and ATD tests. The AIS3+ risk curves shown by Poplin et al.

(2017) are very similar in terms of shape, which gives confidence in this new approach. A more detailed comparison shows differences in the level predicted injury risk, which should be further investigated. For example the PC Score based AIS3+ risk is slightly higher based on the risk curves developed by the simulation based approach. This is similar for the R_{max} based risk. In a next step it would also be possible to combine the data from test and simulation to develop curves based on a further extended data set.

The risk curves that were developed based on the probabilistic approach cannot be directly compared to previously published curves that were based on PMHS test. However, a comparison of curves obtained by the deterministic approach within this study is possible. Comparing for example the deterministic AIS3+ risk based on R_{max} to the probabilistic NRF3+ shows a slightly higher risk. For the PC Score a respective comparison of the risk curves indicates much lower risk values based on the probabilistic method compared to the deterministic AIS3+ risk. The probabilistic approach by Forman et al. (2012) might need some further discussion and improvement itself to be used for this kind of applications. Furthermore, some limitation related to the applied statistics to generate the risk curves should be considered.

The application of the logistic regression model in the probabilistic approach has some limitations. By default, the logistic model is used for binary outcome variables. However, considering the theoretical backgrounds (e.g. considering a rather linear relationship between the PC Score and the NFR), it was assumed that the logistic model could also be applied to the given injury probabilities. Further, the results are based on a small number of simulated probabilities and show high variations; therefore, the linear relationship between the log odds and the injury criteria cannot be shown clearly. This shows that the ability of the injury criteria (e.g., PC Score) in describing the injury outcome is limited. Therefore it is recommended establishing further work and validation on this method.

The comparison of risk curves based on R_{max} and PC Score do not show a clear advantage of the PC Score for improved differentiation of injury risk. This would suggest applying R_{max} for further restraint system evaluation based on statistical significance. However, a further improved multi-component version of the PC Score taking into account for example more principal components, taking full advantage of the extended data set, might lead to different findings.

A further limitation that was already mentioned in previous publications related to this work (Eggers et al., 2018a) is related to the validity and quality of the occupant models. The HBM as well as the ATD model are constantly being improved. Some improvements regarding robustness and biofidelity of the HBM injury have been taking into account for this study. However, further improvements might be necessary, which consequently could lead to more reliable results.

Another limitation resulting from the use of only one HBM in this simulation based approach is related to the missing human biomechanical variation, e.g. in terms of anthropometry. In PMHS test this human variation is introduced by the use of several test subjects for each load case. However, the number of subjects per test condition is usually very limited and thus far away for being statistically representative of the population. A possible solution to address this variation in a simulation based approach could be the use of several HBMs for each loading condition, with variations representing for example an elderly occupant by varying the anthropometry and/or material properties.

CONCLUSIONS AND RECOMMENDATIONS

A simulation-based approach was used to develop multi-point deflection chest injury risk functions for the frontal impact dummy THOR applicable to low-to-moderate severity collisions. This application range of the new risk curves is especially relevant for elderly car occupant protection. This approach allowed to extend matched-pair data, to include lower severity and more representative loading. It also allowed the use of restraint systems being more representative of those fitted to modern cars, which apply lower forces to the thorax than the older-style restraints used in most of the physical PMHS and ATD test data in the literature.

An advantage of the simulation-based approach is the possibility to easily re-evaluate the results and thus consider modification or updates to the ATD. The changes to the ATD hardware and certifications requirements could be easily integrated into the ATD simulation model, which could be used to repeat the whole ATD simulation part of the simulation matrix. In an experimental testing based approach, the effort required to generate the data to update injury risk functions for new dummy updates would be significantly higher.

Previous studies by Eggers et al. (2018a) suggested a repetition of the HBM simulations with an improved human body model, since the validity of the applied simulations and the rib fracture prediction approach was questioned. Within this study the pelvic region of the HBM was updated, which improved the biofidelity of the lower abdomen and furthermore improved the risk curves in terms of statistical significance. However, further improvement to the HBM and strain based injury prediction approach are recommended.

Regarding the work on improved multi-point criteria, it is recommended to develop and evaluate a higher order version of the PC Score to take further advantage of the extended data set. The currently applied version of PC Score (Poplin et al., 2017) uses only the first principal component to relate the four primary deflection parameters (UP_{tot}, LOW_{tot}, UP_{dif}, LOW_{dif}) to calculate the PC Score. The reason is that based on the data used by Poplin et al. (2017) they found sufficient explanation of the variance in the deflection patterns by using only the first component. However, with the extended dataset covering a broad range of loading conditions the influence of the second or even third component to the explained variance should be considered as it is assumed that these components will show a higher importance. This could provide an improved new version of PC Score, which might be able to better assess the injury protection effect of load distributing advanced restraint systems. This work could also require adding even more relevant load cases to the simulation matrix. Using a simulation-based approach allows doing this with significantly less effort and in a more reliable way compared to the traditional experimental approach.

The whole approach including occupant simulation models and the load cases including models of the generic sled environment in a simulation version as well as hardware version for validation test of added load case are well described and documented within SENIORS project reports and publications. Based on these findings it will be possible to continue the work taking into account the proposed steps to improve the results and extent the dataset.

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APPENDIX 1

	Load Case	Velocity (km/h)	Angle (deg)	Pulse	Belt Type	Load limiter setting	Airbag	D-Ring	Seat Friction
L01	SENIORS Generic set-up	25	0	SENIORS 25km/h	3p, no PT	No	No	D1	Standard
L02	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	No	No	D1	Standard
L03	SENIORS Generic set-up	25	0	SENIORS 25km/h	3p, no PT	medium	No	D1	Standard
L04	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	medium	No	D1	Standard
L05	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	medium	No	D2	Standard
L06	SENIORS Generic set-up	25	0	SENIORS 25km/h	3p, no PT	medium	No	D2	Standard
L07	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	medium	Yes	D3	Standard
L08	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	low	Yes	D3	Standard
L09	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	medium	No	D3	Standard
L10	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	low	No	D3	Standard
L11	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	medium	Yes	D1	Standard
L12	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	medium	Yes	D2	Standard
L13	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	medium	No	D3	High
L14	SENIORS Generic set-up	35	0	SENIORS 35km/h	3p, no PT	medium	Yes	D3	High
L15	SENIORS Generic set-up	45	0	SENIORS 45km/h (scaled)	3p, no PT	low	Yes	D3	Standard
L16	SENIORS Generic set-up	45	0	SENIORS 45km/h (scaled)	3p, no PT	medium	Yes	D3	Standard
A01	Gold Standard 1	25	0	SENIORS 25km/h	3p, no PT	No LL	No	GS	Standard
A02	Gold Standard 1	40	0	GS 40km/h	3p, no PT	No LL	No	GS	Standard
A03	Gold Standard 2	30	0	GS 30km/h	3p, no PT	2,7	No	GS	Standard
A04	Gold Standard 2	45	0	SENIORS 45km/h (scaled)	3p, no PT	2,7	No	GS	Standard
A05	GS3 30deg farside	25	30	SENIORS 25km/h	3p, no PT	2,7	No	GS	Standard
A06	GS3 30deg farside	30	30	GS 30km/h	3p, no PT	2,7	No	GS	Standard
A07	GS3 30deg farside	35	30	SENIORS 35km/h	3p, no PT	2,7	No	GS	Standard
A08	GS3 30deg farside	45	30	SENIORS 45km/h (scaled)	3p, no PT	2,7	No	GS	Standard
A09	SENIORS alt restr	25	0	SENIORS 25km/h	3-point, double PT	4,0	Yes	D2	Standard
A10	SENIORS alt restr	35	0	SENIORS 35km/h	3-point, double PT	4,0	Yes	D2	Standard
A11	SENIORS alt restr	45	0	SENIORS 45km/h (scaled)	3-point, double PT	4,0	Yes	D2	Standard
A12	SENIORS alt restr	56	0	SENIORS 56km/h	3-point, double PT	4,0	Yes	D2	Standard
A13	SENIORS alt restr	25	0	SENIORS 25km/h	3p 2-retr, double PT	2,0	Yes	D2	Standard
A14	SENIORS alt restr	35	0	SENIORS 35km/h	3p 2-retr, double PT	2,0	Yes	D2	Standard
A15	SENIORS alt restr	45	0	SENIORS 45km/h (scaled)	3p 2-retr, double PT	5,0-2,0	Yes	D2	Standard
A16	SENIORS alt restr	56	0	SENIORS 56km/h	3p 2-retr, double PT	5,0-2,0	Yes	D2	Standard
A17	SENIORS alt restr	25	0	SENIORS 25km/h	Criss-cross 2-retr, triple PT	1,0+1,0	Yes	D2	Standard
A18	SENIORS alt restr	35	0	SENIORS 35km/h	Criss-cross 2-retr, triple PT	1,0+1,0	Yes	D2	Standard
A19	SENIORS alt restr	45	0	SENIORS 45km/h (scaled)	Criss-cross 2-retr, triple PT	2,0+2,0	Yes	D2	Standard
A20	SENIORS alt restr	56	0	SENIORS 56km/h	Criss-cross 2-retr, triple PT	2,0+2,0	Yes	D2	Standard
A21	SENIORS alt restr	25	0	SENIORS 25km/h	split buckle, triple PT	6,0	Yes	D2	Standard
A22	SENIORS alt restr	35	0	SENIORS 35km/h	split buckle, triple PT	6,0	Yes	D2	Standard
A23	SENIORS alt restr	45	0	SENIORS 45km/h (scaled)	split buckle, triple PT	6,0	Yes	D2	Standard
A24	SENIORS alt restr	56	0	SENIORS 56km/h	split buckle, triple PT	6,0	Yes	D2	Standard
A25	SENIORS alt restr	25	30 nearside	SENIORS 25km/h	3-point, double PT	4,0	Yes	D2	Standard
A26	SENIORS alt restr	35	30 nearside	SENIORS 35km/h	3-point, double PT	4,0	Yes	D2	Standard
A27	SENIORS alt restr	45	30 nearside	SENIORS 45km/h (scaled)	3-point, double PT	4,0	Yes	D2	Standard
A28	SENIORS alt restr	25	30 nearside	SENIORS 25km/h	3p 2-retr, double PT	2,0	Yes	D2	Standard
A29	SENIORS alt restr	35	30 nearside	SENIORS 35km/h	3p 2-retr, double PT	2,0	Yes	D2	Standard
A30	SENIORS alt restr	45	30 nearside	SENIORS 45km/h (scaled)	3p 2-retr, double PT	5,0-2,0	Yes	D2	Standard
A31	SENIORS alt restr	25	30 nearside	SENIORS 25km/h	Criss-cross 2-retr, triple PT	1,0+1,0	Yes	D2	Standard
A32	SENIORS alt restr	35	30 nearside	SENIORS 35km/h	Criss-cross 2-retr, triple PT	1,0+1,0	Yes	D2	Standard
A33	SENIORS alt restr	45	30 nearside	SENIORS 45km/h (scaled)	Criss-cross 2-retr, triple PT	2,0+2,0	Yes	D2	Standard
A34	SENIORS alt restr	25	30 nearside	SENIORS 25km/h	split buckle, triple PT	6,0	Yes	D2	Standard
A35	SENIORS alt restr	35	30 nearside	SENIORS 35km/h	split buckle, triple PT	6,0	Yes	D2	Standard
A36	SENIORS alt restr	45	30 nearside	SENIORS 45km/h (scaled)	split buckle, triple PT	6,0	Yes	D2	Standard
A37	SENIORS alt restr	25	30 farside	SENIORS 25km/h	3-point, double PT	4,0	Yes	D2	Standard
A40	SENIORS alt restr	25	30 farside	SENIORS 25km/h	3p 2-retr, double PT	2,0	Yes	D2	Standard
A41	SENIORS alt restr	35	30 farside	SENIORS 35km/h	3p 2-retr, double PT	2,0	Yes	D2	Standard
A43	SENIORS alt restr	25	30 farside	SENIORS 25km/h	Criss-cross 2-retr, triple PT	1,0+1,0	Yes	D2	Standard
A44	SENIORS alt restr	35	30 farside	SENIORS 35km/h	Criss-cross 2-retr, triple PT	1,0+1,0	Yes	D2	Standard
A45	SENIORS alt restr	45	30 farside	SENIORS 45km/h (scaled)	Criss-cross 2-retr, triple PT	2,0+2,0	Yes	D2	Standard

APPENDIX 2

	UL Res	UR Res	LL Res	LR Res	PC Score	Rmax	DcTHOR	Dmax	shoulder (B3)	diagonal belt at buckle (B4)	lap (B6)
L01	38,9	13,2	33,6	20,1	5,89	38,9	34,00	36,2	3,88	7,82	4,53
L02	46,2	18,3	38,5	24,0	7,08	46,2	46,16	42,8	5,37	10,28	6,22
L03	29,2	14,4	27,4	16,4	4,40	29,2	14,04	23,6	2,51	5,83	4,47
L04	34,3	20,4	31,9	19,3	5,48	34,3	17,04	29,0	3,09	7,48	6,15
L05	37,7	26,0	37,5	15,6	5,53	37,7	37,70	34,7	3,39	8,01	6,26
L06	32,7	22,8	33,3	15,9	4,84	33,3	28,01	29,7	2,94	6,69	4,94
L07	27,7	42,6	39,6	16,7	5,95	42,6	38,74	40,4	3,47	8,93	7,00
L08	24,7	38,0	32,8	15,3	5,22	38,0	29,99	35,5	2,56	7,06	6,52
L09	24,7	41,6	38,2	15,4	5,86	41,6	39,70	39,1	3,50	8,77	6,64
L10	20,0	34,9	31,9	12,0	4,99	34,9	28,15	32,4	2,62	7,15	6,43
L11	37,8	21,3	34,6	21,7	5,64	37,8	26,10	34,1	3,15	7,48	6,06
L12	39,8	32,9	39,8	19,0	5,74	39,8	40,42	37,2	3,37	8,01	6,37
L13	23,4	37,7	35,3	14,5	5,30	37,7	32,70	35,1	3,44	7,22	3,97
L14	36,7	40,1	38,2	15,8	5,77	40,1	39,30	38,1	3,42	7,27	3,99
L15	35,4	41,3	38,6	19,4	6,04	41,3	38,74	38,9	2,76	7,82	7,88
L16	33,7	47,7	44,9	20,4	6,78	47,7	49,32	45,6	3,53	9,46	7,59
A01	36,7	12,9	35,4	24,7	5,50	36,7	27,30	34,7	4,39	3,19	0,51
A02	39,0	13,0	40,6	25,5	5,96	40,6	35,81	37,2	6,04	4,48	0,53
A03	31,0	11,3	24,0	16,3	4,48	31,0	13,96	26,7	2,80	3,32	0,60
A04	32,7	14,0	21,4	13,0	4,33	32,7	16,90	26,7	2,81	3,55	1,12
A05	29,7	9,8	26,8	19,8	4,35	29,7	16,96	26,1	2,80	3,33	0,71
A06	29,5	9,3	27,9	20,4	4,53	29,5	14,70	25,5	2,80	3,46	0,54
A07	31,4	11,4	27,3	18,6	4,54	31,4	18,51	27,0	2,81	3,60	0,82
A08	32,0	14,5	28,8	22,7	4,73	32,0	15,39	27,3	2,82	4,47	1,19
A09	37,4	26,7	38,1	15,1	5,25	38,1	33,65	36,1	3,92	2,97	2,54
A10	41,5	29,4	41,4	14,0	5,77	41,5	39,91	40,6	4,21	3,28	3,49
A11	43,7	30,6	43,3	13,2	6,06	43,7	44,97	43,0	4,26	4,02	5,65
A12	48,0	37,7	56,2	16,4	7,32	56,2	66,49	55,3	4,35	5,83	9,80
A13	21,9	20,1	22,7	12,5	3,43	22,7	16,44	20,7	2,03	1,96	2,93
A14	25,6	21,9	24,2	12,7	3,64	25,6	19,12	24,2	2,05	2,22	3,91
A15	37,6	31,0	40,8	12,4	5,50	40,8	41,74	39,1	4,26	3,98	5,81
A16	40,5	31,8	42,6	15,4	5,73	42,6	45,33	41,0	4,30	4,38	10,70
A17	17,1	19,8	15,5	15,4	2,56	19,8	12,27	13,7	1,05	1,20	2,97
A18	17,1	19,8	15,5	15,6	2,57	19,8	12,38	13,7	1,05	1,19	4,22
A19	21,2	21,5	22,2	21,6	3,15	22,2	18,94	19,1	2,11	1,85	5,41
A20	27,9	28,3	21,5	23,1	3,51	28,3	23,51	27,9	2,14	2,31	11,12
A21	31,2	39,1	21,2	18,4	4,25	39,1	20,00	31,6	4,52	3,62	3,20
A22	34,6	43,3	29,7	17,0	5,14	43,3	27,07	38,5	5,22	3,91	3,62
A23	36,4	43,0	27,8	16,2	5,09	43,0	26,04	38,7	5,35	3,84	6,57
A24	42,3	44,9	31,8	19,9	5,58	44,9	35,11	42,1	5,44	3,85	11,08
A25	38,8	28,9	41,8	19,3	5,82	41,8	38,85	39,2	3,70	4,02	2,48
A26	45,4	33,0	44,6	19,3	6,65	45,4	45,96	42,7	4,24	4,76	3,14
A27	47,3	35,0	47,5	22,7	7,19	47,5	50,46	45,7	4,30	5,29	4,94
A28	21,2	20,1	30,0	15,9	3,78	30,0	18,55	27,0	2,03	2,75	2,94
A29	23,8	20,8	30,9	17,2	4,08	30,9	20,25	27,3	2,07	3,06	2,95
A30	39,6	34,6	44,1	18,8	6,66	44,1	44,80	41,9	4,23	4,87	4,16
A31	16,5	17,9	17,2	13,0	2,60	17,9	11,68	12,4	1,02	1,23	2,93
A32	18,5	18,0	20,8	15,4	2,92	20,8	12,03	12,5	1,04	1,49	2,92
A33	20,7	19,6	29,2	27,3	3,82	29,2	19,83	24,5	2,19	2,66	4,30
A34	31,4	41,9	23,1	18,7	4,60	41,9	19,36	32,5	4,74	5,22	3,18
A35	36,5	47,8	26,5	21,7	5,34	47,8	22,88	37,8	5,45	5,77	3,24
A36	39,5	52,1	28,7	25,1	5,78	52,1	26,66	41,3	5,51	6,01	4,40
A37	28,7	26,7	39,0	18,1	4,75	39,0	31,95	36,1	3,78	2,61	2,65
A40	18,2	20,1	22,9	13,9	3,39	22,9	15,33	20,5	2,02	1,62	2,97
A41	20,7	20,8	21,5	18,9	3,60	21,5	15,35	19,4	2,04	1,85	5,86
A43	16,6	17,9	14,8	17,8	2,73	17,9	11,92	12,6	1,06	1,19	2,94
A44	16,7	17,9	18,9	20,0	2,97	20,0	12,19	13,1	1,06	1,20	5,69
A45	19,6	20,6	26,2	27,5	3,65	27,5	19,59	22,4	2,08	1,58	7,38

APPENDIX 3

	Probabilistic Risk (%)			Probabilistic Risk (%)			Belt Loads	
	NFR 2+ 65+	NFR 3+ 65+	NFR 4+ 65+	NFR peak strain > 1,9% (65+)	AIS3+ (yes/no)	AIS2+ (yes/no)	Shoulder Belt Force (B3) / kN	Lap belt force (B6) / kN
L01	100,0%	100,0%	100,0%	8	1	1	4,3	3,2
L02	100,0%	100,0%	100,0%	11	1	1	5,8	4,9
L03	33,3%	6,7%	0,4%	1	0	0	2,5	3,1
L04	99,6%	94,6%	74,3%	6	1	1	3,1	4,6
L05	92,8%	72,5%	41,4%	5	1	1	3,3	4,6
L06	7,2%	0,5%	0,0%	0	0	0	2,9	3,1
L07	2,8%	0,0%	0,0%	0	0	0	3,5	4,8
L08	2,8%	0,0%	0,0%	0	0	0	2,5	4,8
L09	0,0%	0,0%	0,0%	1	0	0	3,5	4,9
L10	0,0%	0,0%	0,0%	1	0	0	2,5	4,8
L11	87,4%	62,2%	31,5%	5	1	1	3,1	4,7
L12	18,1%	2,5%	0,2%	1	0	0	3,3	4,5
L13	0,0%	0,0%	0,0%	0	0	0	3,5	3,5
L14	1,4%	0,0%	0,0%	0	0	0	3,5	3,4
L15	69,6%	37,2%	13,3%	3	1	1	2,5	6,0
L16	67,0%	34,5%	11,9%	2	0	1	3,7	6,1
A01	81,9%	46,4%	13,9%	4	1	1	5,2	0,7
A02	100,0%	100,0%	100,0%	9	1	1	6,9	0,7
A03	18,0%	2,0%	0,1%	1	0	0	2,8	0,5
A04	98,5%	86,8%	53,9%	4	1	1	2,8	1,7
A05	51,0%	17,7%	3,2%	3	1	1	2,8	0,8
A06	45,1%	11,4%	0,7%	3	1	1	2,8	0,7
A07	94,3%	74,4%	40,8%	4	1	1	2,8	1,1
A08	100,0%	99,9%	99,0%	9	1	1	2,8	1,6
A09	100,0%	99,4%	93,0%	7	1	1	4,0	2,6
A10	100,0%	100,0%	99,6%	8	1	1	4,2	3,7
A11	100,0%	100,0%	100,0%	9	1	1	4,3	4,9
A12	100,0%	100,0%	100,0%	15	1	1	4,4	10,1
A13	0,0%	0,0%	0,0%	0	0	0	2,4	3,6
A14	51,5%	16,6%	2,5%	0	0	0	2,4	3,6
A15	51,5%	16,6%	2,5%	2	0	1	4,2	5,2
A16	100,0%	99,7%	97,8%	11	1	1	4,3	10,5
A17	0,0%	0,0%	0,0%	0	0	0	1,8	3,5
A18	1,4%	0,0%	0,0%	0	0	0	1,8	3,5
A19	8,3%	0,0%	0,0%	0	0	0	2,1	4,6
A20	99,3%	93,4%	75,7%	5	1	1	2,1	10,4
A21	17,8%	1,2%	0,0%	1	0	0	5,1	3,5
A22	47,7%	12,9%	1,7%	2	0	1	5,3	3,5
A23	62,6%	28,9%	8,2%	3	1	1	5,4	5,6
A24	99,8%	98,6%	94,1%	11	1	1	5,4	11,1
A25	100,0%	100,0%	96,8%	6	1	1	3,8	2,6
A26	100,0%	100,0%	100,0%	7	1	1	4,3	3,1
A27	100,0%	100,0%	100,0%	10	1	1	4,4	4,3
A28	71,8%	27,9%	3,6%	3	1	1	2,4	3,5
A29	100,0%	94,3%	57,5%	4	1	1	2,4	3,5
A30	100,0%	100,0%	100,0%	7	1	1	4,2	4,4
A31	0,0%	0,0%	0,0%	0	0	0	1,8	3,5
A32	3,5%	0,0%	0,0%	1	0	0	1,8	3,5
A33	100,0%	100,0%	96,7%	5	1	1	2,1	3,7
A34	98,1%	80,7%	35,2%	4	1	1	5,0	3,5
A35	100,0%	100,0%	100,0%	5	1	1	5,4	3,5
A36	100,0%	100,0%	100,0%	8	1	1	5,5	4,2
A37	40,7%	10,5%	1,1%	2	0	1	3,9	2,9
A40	0,0%	0,0%	8,3%	0	0	0	2,4	3,6
A41	21,4%	1,4%	0,0%	2	0	1	2,4	5,5
A43	0,0%	0,0%	8,3%	0	0	0	1,8	3,6
A44	4,2%	0,0%	0,0%	1	0	0	1,8	4,6
A45	92,6%	59,1%	19,5%	3	1	1	2,1	6,4