BENEFIT OF ADAPTIVE OCCUPANT RESTRAINT SYSTEMS WITH FOCUS ON THE NEW US-NCAP RATING REQUIREMENTS

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ABSTRACT

Against the background of an always growing traffic volume on the roads and the thereby resulting aim to reduce the number of traffic fatalities continuously, the recent years saw a number of research projects and field studies.
As a result of this, legal tests and consumer requirements have been significantly tightened. Consequently, car manufacturers and suppliers are faced with completely new challenges as to the adaptation of occupant restraint systems. Here, so-called "smart" restraint systems gained more and more importance.

The US-NCAP requirements for the MY 2010, adopted by NHTSA in 2008, are a new milestone for the improvement of occupant protection. For the minimization of the total injury risk in frontal impacts, the protection criteria for head (HIC), neck (Nij), and thorax (chest deflection) are under special consideration.

With regard to the new requirements, it seems to be quite challenging to achieve a very good rating in frontal crash tests by standard restraint systems, especially when different dummy sizes and the legal requirements according to FMVSS 208 have to be considered.

The present study shall demonstrate which potential adaptive airbag and seat belt technologies can possess. Thus, the performance of different concepts of adaptive airbag techniques, knee bags, double pretensioning systems and adaptive force limiter are compared. Following, an evaluation of the different concepts as to their efficiency and benefits in terms of critical injury criteria will be made. Finally, a survey is given on how the consequent use of adaptive restraint systems can address the future requirements (law, ratings).

CHALLENGES OF THE NEW US-NCAP RATING

Based on the significant improvement of passive safety level in recent years, NHTSA has decided to change the existing front and side crash rating programs. These changes are effective for the 2011 model year. NHTSA will maintain the 35 mph (56 kph) full frontal barrier test for the frontal crash test program, but the 50%ile dummy on passenger side will be replaced by the 5%ile dummy. The assessment of the frontal impact star rating is extended by additional injury criteria for neck (N_{ij}, compression/tension force), chest deflection and femur forces. [1]

The current moving deformable barrier test at 38.5mph (63kph) is still used for the side impact crash configuration. In future this test includes new side impact test dummies (SID-2s and ES-2 dummy) and new assessment criteria (HIC36, rib deflection, abdomen and pelvic force). Additionally, a 20mph (32kph) oblique pole test with a 5% female ES-2 dummy will be applied for the assessment of new vehicles.

For rollover, NHTSA will continue to use the static stability factor (SSF) and the manoeuvrability assessment (tip-up or no tip) to rate the risk of vehicles to rollover. It is expected that the agency will update this rollover risk assessment, as soon as more real-world crash data of vehicles equipped with electronic stability control are available.

With the new US-NCAP rating, NHTSA will establish a new overall Vehicle Safety Score (VSS) that combines the front, side, and rollover star rating.

Furthermore, vehicles equipped with selected advanced technologies (crash avoidance technologies) will be noted: A text display will be used to inform about a standard vehicle (without advanced technologies) or an optional presence.

- Electronic Stability Control (ESC)
- Lane Departure Warning (LDW)
- Forward Collision Warning (FCW)

This article is focussed on the challenges resulting from the new requirements for the frontal crash test.

The assessment of the occupant protection in the frontal impact bases on injury probabilities of the considered body regions (head, neck, chest, and thigh) which correlate with a defined injury severity. For detecting the single probabilities selected injury / protection criteria on the basis of risk injury curves (generally AIS 3+, except femur axial forces: AIS 2+) are used. Here, the AIS3+ injury risk curves correspond to those taken for FMVSS 208. Figure 1 illustrates this exemplarily for the driver side (50%-ile dummy).

Injury Criteria	Risk Curve
Head (HIC_{15})	$P_{head}(AIS\,3+) = \Phi\left(\frac{\ln(HIC15) - 7.45231}{0.73998}\right)$ *where* Φ = cumulative normal distribution
Chest (deflection in mm)	$P_{chest\_defl}(AIS\,3+) = \frac{1}{1+e^{10.5456-1.568*(ChestDefl)^{0.4612}}}$
Femur (force in kN)	$P(AIS\ 2+) = \frac{1}{1+e^{5.795-0.5196\,Femur\_Force}}$
Neck (Nij and tension/compression in kN)	$P_{neck\_Nij}(AIS\,3+) = \frac{1}{1+e^{3.2269-1.9688Nij}}$ $P_{neck\_Tens}(AIS3+) = \frac{1}{1+e^{10.9745-2.375Neck\_Tension}}$ $P_{neck\_Comp}(AIS3+) = \frac{1}{1+e^{10.9745-2.375Neck\_Compression}}$ $P_{neck} = \max imum(P_{neck\_Nij}, P_{neck\_Tens}, P_{neck\_Comp})$

Figure 1. Injury criteria and probabilities for driver side (AM 50). [1]

From the product of the single probabilities the so-called combined injury probability P_{comb} is calculated for each the driver and passenger side.

$$P_{comb\ [Driv./Pass.]}=1-(1-P_{head})(1-P_{neck})(1-P_{chest})(1-P_{femure})$$

For the actual assessment a "relative risk score" factor (RRS) is taken being a quotient from combined injury probability and a statistical quantifying parameter[1]:

$$RRS_{[Driv./Pass.]} = P_{comb\ [Driv./Pass.]} / 0.15$$

[1] For the time being NHTSA has set this statistical quantifying parameter on 0.15, based on the statistical survey to assess the safety level of vehicles of MY 2008.

The probability and RRS values may then extract the "star rating" – separated into driver and passenger side - (See Figure 2).

	Frontal/ Side	
	probability	**RRS**
★★★★★	P < 0.10	RRS <0.667
★★★★	0.10 ≤ P 0.15	0.667 ≤ RRS <1.0
★★★	0.15 ≤ P < 0.20	1.0 ≤ RRS < 1.33
★★	0.20 ≤ P < 0.40	1.33 ≤ RRS < 2.667
★	P ≥ 0.40	RRS ≥ 2.667

Figure 2. Star rating based on combined probability and/or relative risk score (RRS). [7]

A total assessment is made by a so-called „Vehicle Safety Score" (VSS), uniting the weighted risk assessments from frontal crash test, side MDB pole test, as well as from the rollover assessment (See Appendix A).

The probability functions (See Figure 1) allow the conclusion that the following injury criteria for the rating according to US-NCAP New (frontal crash test) are to be considered especially critical:

Driver side:

- HIC 15
- chest deflection

Passenger side:

- HIC 15
- N_{ij}
- Chest deflection

For a conceivable scenario to achieve a „5 star rating" on the driver and passenger side (RRS < 0,667 the following target values should be reached:

Driver side:

- HIC 15 ≤ 200
- chest deflection ≤ 23 mm
- $N_{ij} \leq 0{,}3$[2]
- Femur Force ≤ 2,5 kN

[2] Due to the stored probability functions for the calculation of the single probabilities P_{neck_Nij}, P_{neck_Comp} und $P_{neck\_Tens,}$ the N_{ij} is normally the most critical load criterion.

Passenger side:

- HIC 15 ≤ 250
- chest deflection ≤ 19 mm
- $N_{ij} \leq 0,3$
- Femur Force ≤ 1,5 kN

Considering these target values on the one hand and the legal load cases according to FMVSS 208 on the other, it can be safely assumed that only very few vehicles from latest model years would have been able to reach a "5 star" rating in the frontal impact according to US-NCAP NEW.

HOW ADAPTIVITY SHOULD WORK

Basically, the adaptation of components of an occupant restraint system can be divided into two groups: active and passive adaptation.
An outstanding feature of active adaptation is the integration of a control mechanism into the system component.

Passive adaptivity is a special feature already inherent in the component that has not been added afterwards. Due to its viscous characteristics even the gas vent from an airbag, e.g., has to be considered an adaptive adaptation [2].

Further considerations, however, will focus on active adaptation because the efficiency factor here can increase to a much higher degree than for passive adaptations.

It is the goal of adaptive protection components to adjust the force application at the occupant to the initial and boundary conditions of the accident. This mainly involves the accident severity, type and sort of accident, the occupants' mass, size, position, and, possibly, even their age.

In simple terms we can say that adaptivity means the ability of the protection system to adapt its stiffness to selected accident and occupant parameter in order to increase the biomechanical quality of the complete protection system. Pre-studies reveal which parameters are especially relevant for an adaptation in a frontal impact. [3]

It is without any doubt that the accident severity comes in the first place of factors followed by mass and size of the occupant. Adjusting the level of a belt force limiter, for instance, allows to adapt the protection performance of a system very well as shown in [4].

Furthermore, adaptation mechanisms may also result in an increase of efficiency. Here, especially the first phase of interaction between restraint element and occupant is put into the focus of attention. Pressure-controlled venting holes of an airbag, being under series production for many years now, are a classical example to illustrate this [5].

Reducing the gas mass during the filling phase of the airbag by using a dual-staged gas inflator or redirecting the gas flow does not lead to an increase of efficiency of the protection system due to functional reasons. [6]

But those measures can restrict the aggressiveness of the airbag system and thus contribute to reduce the danger of the occupant to get injured by the airbag deployment in out-of-position situations.

ADAPTIVITY COMBINED WITH STANDARD AND ADVANCED RESTRAINT SYSTEMS

In parallel to the introduction of adaptive solutions, an enlargement of the system components by design can increase the protection potential purposefully.

In contrast to a „Standard Restraint Systems“, the „Advanced Restraint Systems", e.g., are characterized by a special airbag tailoring, knee airbags, digressive belt force limiters, and/or inflatable seat cushions (See Figure 3).

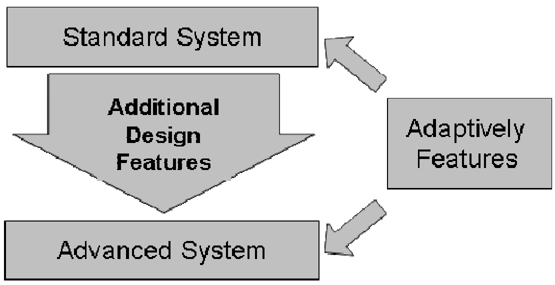

Figure 3. Adaptivity and its impact on standard and advanced restraint systems.

Depending on the restraint system performance and the boundary conditions (e.g. vehicle and module package, costs) it might be useful to prefer „advanced“ components instead of adaptive solutions or respectively to combine both features.

For example, the use of a knee airbag can reduce the chest deflection but increase the head loadings. Adaptivity in the airbag makes it possible to neutralize this effect and, moreover, to reduce the head loadings clearly.

The following chapters will show concrete examples illustrating this.

EFFICIENCY AND BENEFIT OF DIFFERENT ADAPTIVE CONCEPTS FOR FRONTAL CRASH CONFIGURATIONS

On the basis of the design of today's restraint systems for the different frontal crash configurations, the target conflict is even getting sharper as to safe fulfillment of legal requirements (FMVSS 208) and new US-NCAP rating .

It is especially an airbag design (stiffness, shape) focussed on unbelted load cases according to FMVSS 208 (0° and 30° impact) and on the requirements of phase 2b (30mph, 5%- und 50%-dummy) that will lead to worse rating results in the future. In the case of demanding crash pulses (high motorization) this dilemma will even get worse.

The results of this study are based on valid occupant crash simulation of driver and passenger side. As to its interior geometry, the selected vehicle obviously corresponds to a European middle-class car. The dummy models used are the 50%-ile male and the 5% -ile female dummy (See Figure 4).

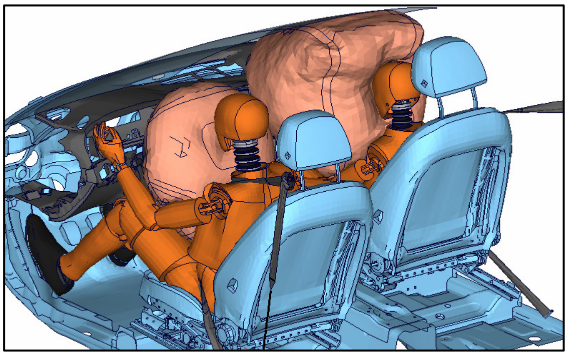

Figure 4. CAE model for driver and passenger side. [7]

The vehicle components and the dummies as well are exclusively modelled by the FE-method. In advance, the parameters of the airbag and seat belt model have been validated in their range of variations by component tests.

Basis for the choice of crash pulses for the simulation models were vehicles with extremely high front end stiffness (See Figure 5).

From previous studies we learned that especially these crash pulses require the highest performance from the protection system.

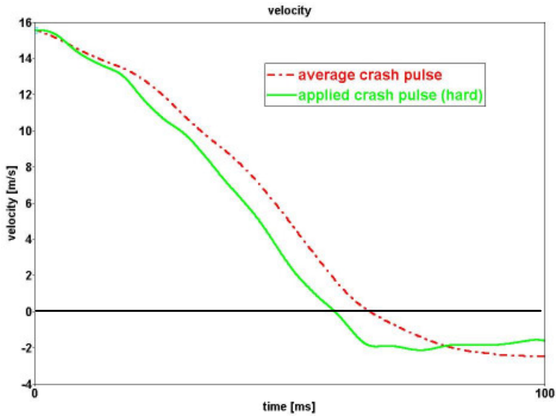

Figure 5. Comparison of US-NCAP crash pulses.

The evaluation of the simulation results does not only include the classical occupant load values (see above) but also the kinematics of the dummies themselves (e.g. the risk for „submarining“) and the double forces/moments in the lumbar region. Only thus, a holistic analysis of the effects of single components in the occupant protection system can be made.

Furthermore, all changes and/or adaptive measures at the protection system are evaluated for several crash configurations. The influence on the configurations of FMVSS 208 is considered as well. The measure for the evaluation is a shortfall of 20% under the legally allowed limits for the dummy loads.

Thus, the statements or recommendations, that can be made, become broader, but the focus, however remains to be the new US-NCAP.

DRIVER SIDE

First step of the analysis is to study the single changes at the protection system separately. So it becomes possible to evaluate the respective potential apart from the others and to quantify its use for an advanced and/or adaptive protection system.

The use of an adaptive seat belt force limiter in the retractor, which is able to switch from a high level to a lower one at a defined moment, is analyzed first.

According to the US-NCAP NEW assessment the injury probability reduces by approximately 10% (see Figure 6).

Without this adaptive seat belt force limiter a safe fulfillment of FMVSS208 would not be possible in the vehicle under evaluation (load case: 5%-ile dummy). Thus, the adaptive belt becomes a confirmed part for all further variants.

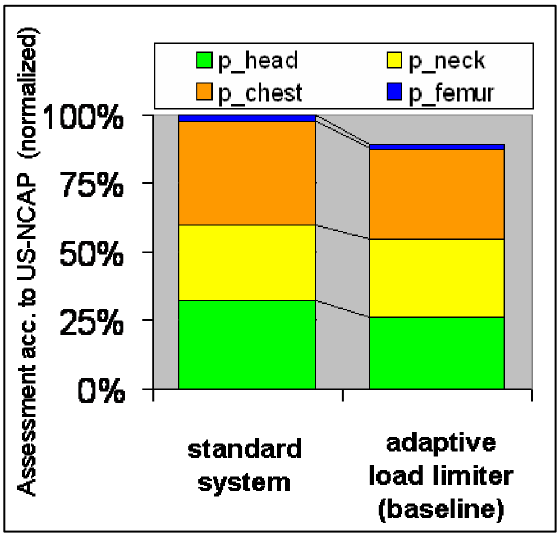

Figure 6. Adaptive belt load limiter compared to standard system.

The application of a knee bag reduces the injury risk by further 25% (see Figure 7).

The knee bag induces a reinforced support of the occupant in the pelvis area. This is accompanied by a reduction of the belt force in this area leading to positive effects on the chest deflection.

The modified kinematics of the occupant caused by the knee bag also results in reduced head loads of the dummy.

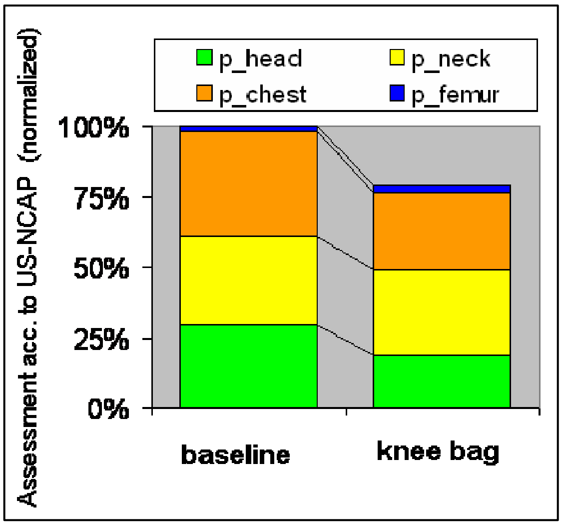

Figure 7. Kneebag compared to baseline.

Optimizing the airbag shape allows to evidently increase the protective effects in the US-NCAP NEW. The airbag tailoring is trimmed so that the head restraint becomes better and the force application on the thorax is restricted to bio-mechanically acceptable values (see Figure 8).

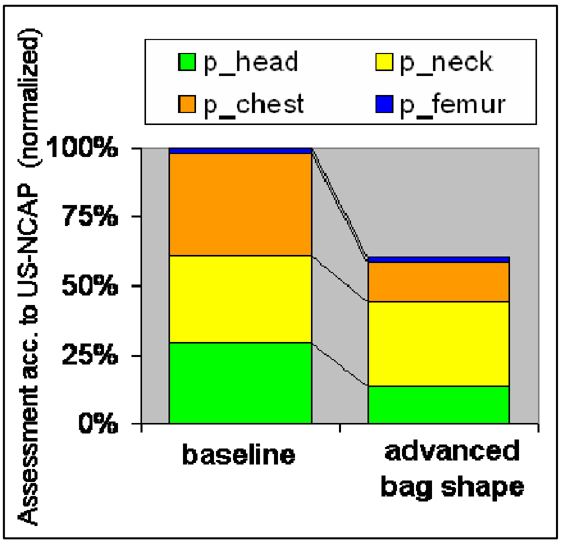

Figure 8. Advanced airbag shape compared to baseline.

The use of an adaptive airbag component, such as well as the adaptive seat belt, shows a high potential for an improvement of the protective effects in connection with the 5%-ile dummy.

Under the boundary conditions of the US-NCAP NEW, i.e. with the 50%-ile dummy, the efficiency of the analyzed airbag adaptivity is rather low.

A double belt pretensioning in the retractor and in the belt bracket or in the buckle results in a reduction of the total injury risk by approximately 10%.

As already mentioned in the beginning, the baseline crash pulse corresponds to an extremely stiff vehicle front end structure. Therefore the vehicle response was also used as a parameter within the CAE study to see which impact an average US-NCAP crash pulse has on the load values.

In comparison to the other selected modifications particularly head, neck and femur injury probabilities could be reduced significantly (See Figure 9, No. 6: average crash pulse).

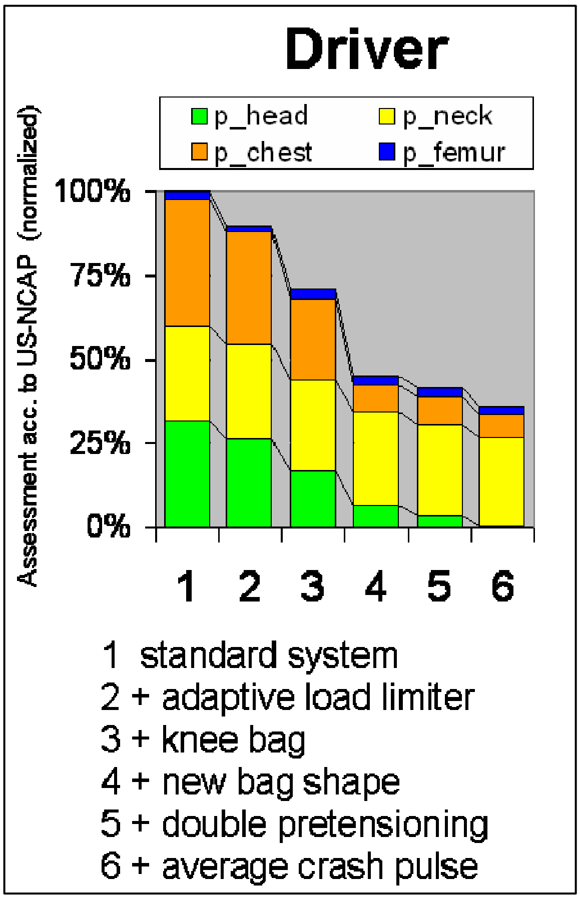

Figure 9. Overview: Benefit for driver side.

Figure 9 demonstrates clearly to which regions of the body the injury risk can be addressed by adaptive and advanced measures. The total of all measures leads to a reduction of more than 60%.

This outstanding result almost completely traces back to improvements in the head and chest area.

In contrast, the probability for injuries in the neck and lower leg regions is hardly addressed by the analyzed modifications under the given boundary conditions.

PASSENGER SIDE

The basic design for the passenger side was in that case a standard restraint system with 3D airbag shape and constant belt force limiting (without knee airbag).

As for the driver side, the influence of the restraint performance of the complete system is reported separately for each modification. This allows to derive the potential of an adaptive and advanced protection system for the passenger side.

In a first step, based on the standard system an adaptive airbag system reduces the head injury probability (HIC15) for the 5%-ile female dummy significantly. Hence, clear benefits for the total assessment according to US-NCAP can be achieved (See Figure 10).
The second modification in form of a dual-stage belt load limiters, which goes down to a lower force limit (e.g. to 2kN) at a very early stage, is made.

This modification leads also to a positive effect on the US-NCAP rating (particularly chest deflection), though the chest load values are mainly dominated by the airbag. As already described for the driver side, an adaptive belt load limiting is a basic prerequisite for the safe fulfillment of legal requirements with equally good results in the ratings. The biggest benefit here is drawn from the reduction of the chest acceleration.

The combination of adaptive belt force limiting and adaptive airbag system is therefore primarily necessary to address the target conflict between 208 load case (56kph, 50%AM belted) and US-NCAP requirements (5%AF).

The combined adaptivity in the belt and airbag system allows a reduction of the HIC15 by 30% and of chest deflection by approximately 10% in the present parameter variation compared to the standard system (See Figure 10).

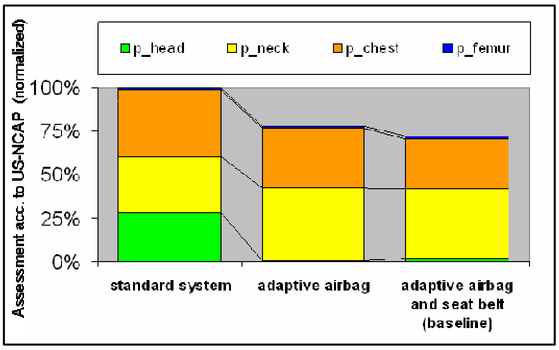

Figure 10. Adaptive airbag and belt load limiter compared to standard system.

The adaptive components as part of a new basic system are also used in all other parameter variations.

As already stated for the driver side, the use of a knee bag leads to an improved pelvis restraint. Thus, especially the chest deflection can be reduced by approximately 40%.

In combination with the adaptive belt load limitation and an adaptive airbag system, the reduction of the head loads turns out to be surprisingly high (HIC15 by about 70%). At the same time, it has to be accepted that the knee bag causes a significant increase of the axial femur force when the loads are on a low level.

As to the FMVSS 208 load cases, this modification also effects benefits for the chest acceleration (primarily 5%-ile dummy).

All in all, the injury probability can be reduced by approximately 12 % when a knee bag is used (See Figure 11).

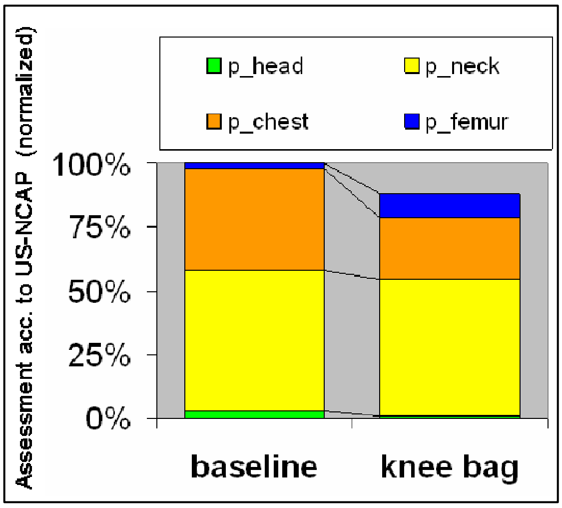

Figure 11. Knee bag compared to baseline.

The modifications studied by now showed clear reductions for the head and chest loads. Benefits for the neck loads (N_{ij}), however, could not been proved yet.

The next step will therefore be an optimization of the airbag shape as this seems to dominate the neck loadings of the 5%-ile dummy.

Due to the positive influence of the knee bag on the head and chest loads it will further be part of the considerations.

First a modification of the standard 3D shape is made for the region of the head and chest contact. This already allows a significant reduction of the neck injury risk. But at the same time head and chest loads change for the worse. Nevertheless, the total injury risk declines by 15% when all load criteria are considered. (See Figure 12, advanced airbag shape).

This is why the second step analyzes the Takata patented *Twinbag* [8]. Using a two-chamber airbag shape the „coupling" of head and thorax and the resulting force application in this area can be improved systematically. This variant allows to reduce the chest deflection again by more than 50% compared to the basic variant (adaptivity in belt/airbag + knee airbag).

Furthermore, in comparison to the baseline the neck injury probability (N_{ij}) can be reduced by approximately 30%.

The use of the *Twinbag* results in a reduction of the combined injury risk by more than 30% (See Figure 12, *Twinbag*).

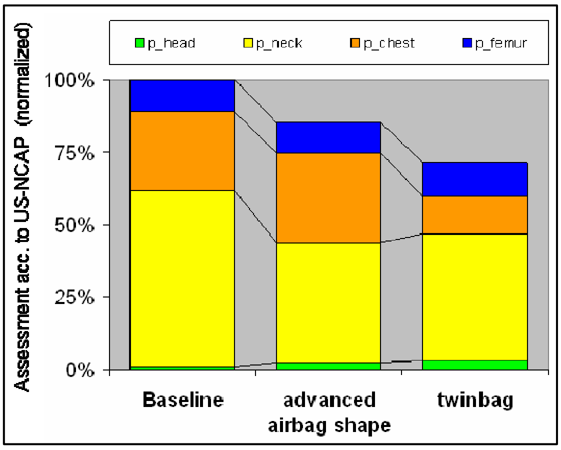

Figure 12. Advanced airbag shape and Twinbag compared to baseline (all modifications with knee bag).

The modification in the belt using double pretensioning (retractor and anchor or buckle), analyzed hereinafter, leads to a significant improvement of chest acceleration and chest deflection values, but it has a negative effect on head and neck loadings resulting in a clearly worse rating in the US-NCAP.

Analogous to the driver side, finally the influence of a (average) crash pulse on the evaluation according US-NCAP NEW is studied. On the passenger side, too, this variant results in an improvement of the head and chest loadings, those, however, not being that clear referring to the total rating of the 50%-ile dummy on the driver side (See Figure 13, No. 5: average crash pulse).

Finally, the study should find out whether disregarding an optimized airbag shape may allow for doing without an adaptive airbag system. Here, the *Twinbag* formidably shows its benefit on the combined injury probability using a hard crash pulse and the modifications explained above (adaptive belt limiter + knee airbag).

With reference to the combined injury probability this variant shows an improvement of approximately 55% even without the use of airbag adaptivity when directly compared to the standard system. This mainly traces back to considerable reductions in HIC15 and chest deflection (See Figure 13, No. 6: *Twinbag* w/o airbag adaptivity).

In contrast to the driver side, the injury risk for the neck (N_{ij}) also sinks by 15% to 20% when the system is supported by the analyzed modifications at the airbag shape (advanced airbag or *Twinbag*).

Figure 13 gives an overview on the studied modifications and their potential with reference to the injury risks according to US-NCAP NEW rating.

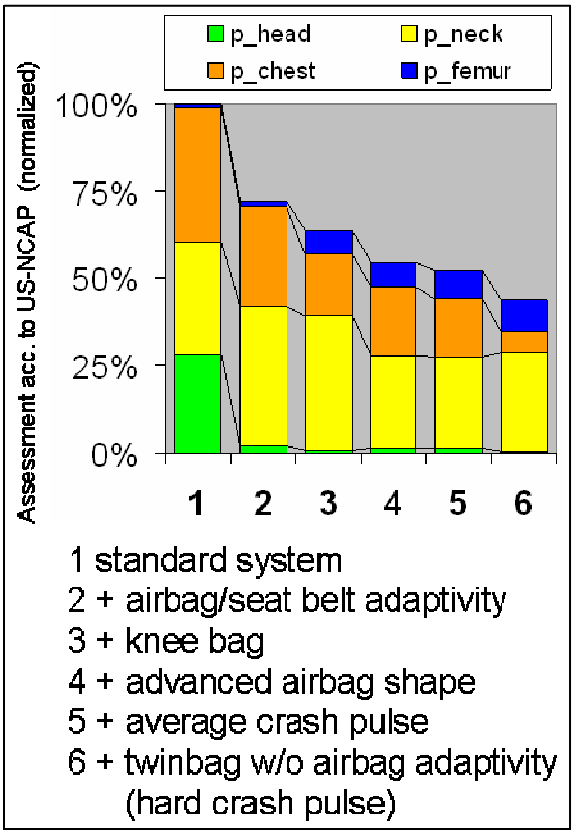

Figure 13. Overview: Benefit for passenger side.

CONCLUSIONS

According to the new US-NCAP requirements, the assessment of the frontal impact star rating is extended by additional injury criteria for neck (N_{ij}, compression/tension force), chest deflection and femur forces. With conventional airbag and seatbelt technologies, it seems to be very difficult to achieve a 5-star rating; on top of that if the tuning of the restraint system is based on a hard crash pulse.

Facing the legal requirements according to FMVSS 208 – unbelted and belted load cases (particularly Phase 2a and 2b) and the new US-NCAP rating scheme, HIC15, chest a3ms und chest deflection can be addressed sufficiently using an adaptive seat belt and airbag system on driver and passenger side.

On the driver side and on the passenger side as well a significant reduction of the injury risk could be evidenced for the 5%-ile and 50%i-le dummy load cases, particularly with regard to the head and thorax loadings. Combined with a knee bag and/or measures at the airbag shape the use of adaptivity for the restraint system can be obviously extended.

In principle, the airbag stiffness/damping is adapted to the unbelted load case with a 50%-ile dummy according to FMVSS 208. On the driver side an adaptive (airbag) system is primarily not needed to improve the rating according to US-NCAP. Provided an occupant classification system (OCS), here an adaptive parameter might be required to address the 5%-ile dummy load cases according to FMVSS 208. Due to the requirements for the 50%-ile dummy (unbelted) the usually applied extension of the venting area in the airbag is normally not to realize.

When the moments of activation of the adaptive airbag and belt system differ, the load cases for the 5%-ile and 50%-ile dummy can be addressed separately.

On the passenger side especially the injury probability for head and thorax is clearly reduced by the use of an adaptive airbag and airbag system. Here, benefits fort he neck loads can be proven having a positive effect on the total rating.

The combination of adaptive and advanced technologies (adaptive airbag / seat belt, knee bag, airbag shape) leads to a reduction of the combined probability of about 50%.
Using a knee bag or a double pretensioning belt system (retractor and buckle ore anchor), pelvis forward movement and dummy kinematics can be controlled sufficiently.

An optimized / advanced airbag shape can help to control load paths on head and thorax and to reduce chest deflection and neck loads (N_{ij}).

In the end, the analyzed parameter variations show that adaptivity with regard to legal and consumer requirements are an important part in the adaptation of the restraint system.

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APPENDIX A

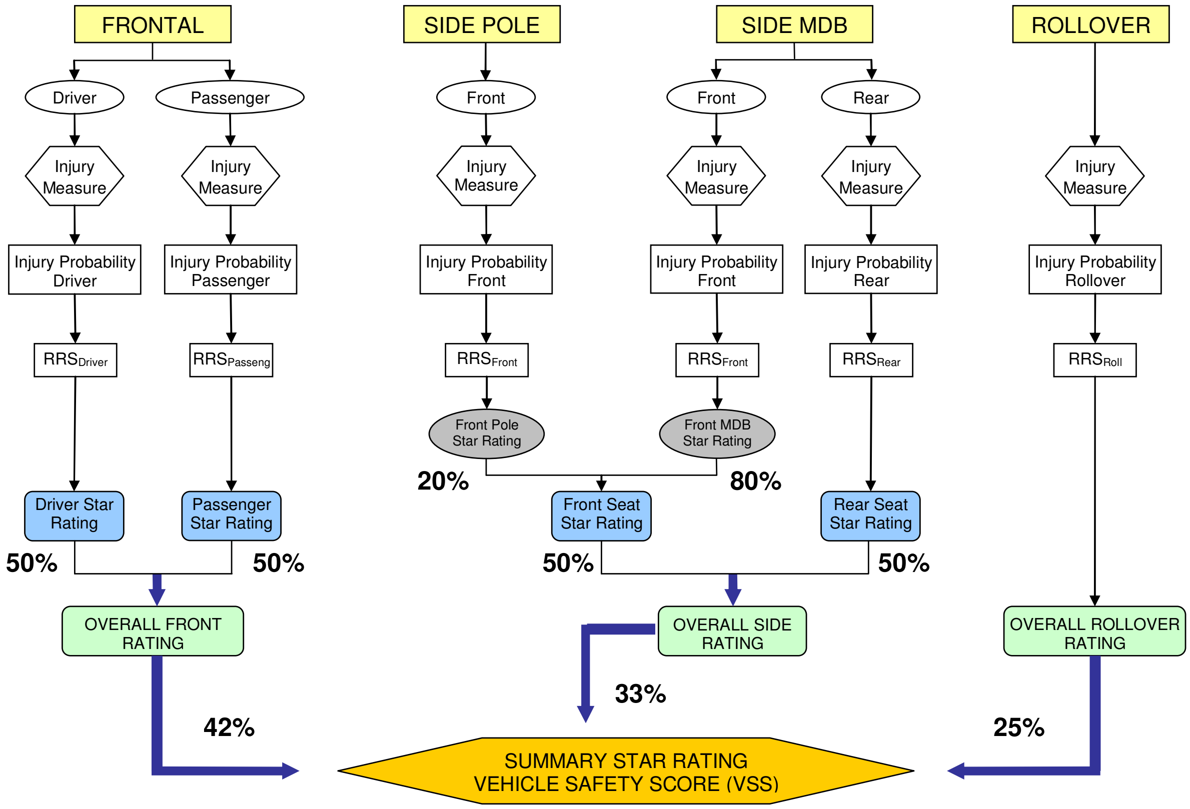

Figure A1. Overall vehicle rating acc. to US-NCAP New based on weighted Relative Risk Scores (RSS).