POTENTIALS OF ADAPTIVE LOAD LIMITATION
PRESENTATION AND SYSTEM VALIDATION OF THE ADAPTIVE LOAD LIMITER

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ABSTRACT

The present state-of-the-art protection system on front seats features a belt system, incorporating a pretensioner, a load limiter, and an airbag. This protection system is not capable of changing its performance characteristics. The ability of an occupant protection system to adapt itself to dominant crash condition parameters, such as impact speed and type, occupant size and mass, offers a great improvement in occupant protection for a wider range of crash conditions, as well as occupants.

This paper presents first the third generation load limiter, the Adaptive Load Limiter, and conducts the system validation of this belt system using a dual stage airbag. For this purpose sled tests with 5%, 50% and 95% HIII Dummies are carried out.

As a result, a degressive characteristic of belt system load limitation improves chest deceleration of a mid size front occupant by 9%.

The resulting potential reduction of probability for an AIS+4 injury on head and chest for this occupant is 14% !

By depowering the load limitation characteristic the chest loading in terms of chest deflection on small female occupants can be reduced significantly by 15%. For small occupants the resulting potential reduction of probability for an AIS+4 injury on head and chest is 17% !

The high load limitation enables the avoidance of a bottoming out of larger and heavier occupants.

The adaptive load limiter is the first load limiter offering an improved chest loading distribution for the average male occupant through a degressive load limitation and a reduction of chest loading for small female occupants through a depowered load limitation. Additionally the adaptive load limiter satisfies the ECE-R16 Homologation requirement and thus enabling the deactivation of the airbag module for example when utilising child restraint systems.

1. ADAPTIVE LOAD LIMITER

For the case of wanting to have a Homologation of the belt system without airbag in accordance with the regulation ECE-R16, the adaptive load limiter requires a pre-set condition with the high load limitation level active. Thus the switching system utilising a gas generator has the function of altering the load path from the pre-set high load limitation level to the lower load limitation level. This should be able also within the car impact in order to offer the degressive load characteristic.

Next the function of the adaptive load limiter utilising a dual stage torsion bar is shown.

Figure 1 shows the pre-set condition of the adaptive load limiter. The webbing load is applied to the shaft and then transmitted to the torque tube via the locking elements. The two locking elements are restraint by the shaft ring.

Thus the torque tube connects the middle head of the dual stage torsion bar to the shaft. When the shaft rotates relative to the locked tread head the thicker section is plastically twisted and limit the webbing load at the high load level.

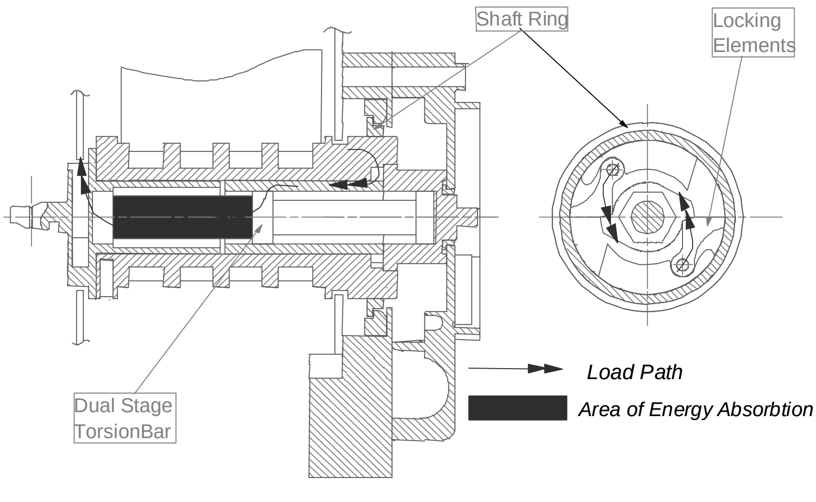

Figure 1: Adaptive Load Limiter on pre-set condition

The switching module has the function of releasing the locking elements, as shown in figure 2.

When the shaft ring is axially displaced the locking elements are not further restraint and can be pushed

outward of the shaft by the torque tube. When the torque tube is no longer restraint to the shaft the load path is altered as follow:
The webbing load is still applied to the shaft and passes the entire dual stage torsion bar which is connected to the shaft on its right head. The load level is now reduced due to the fact that the thinner section will initiate its plastic twisting at a lower load level then the thicker section. The new load path is illustrated in figure 2.

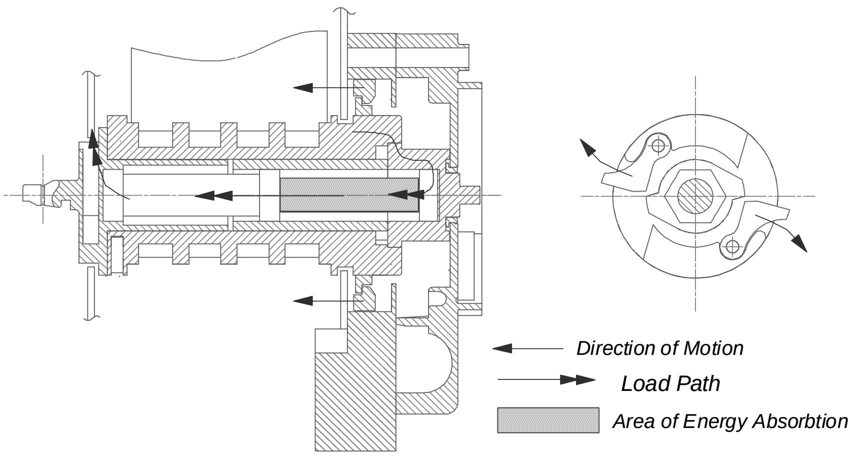

Figure 2: Adaptive Load Limiter after switching process

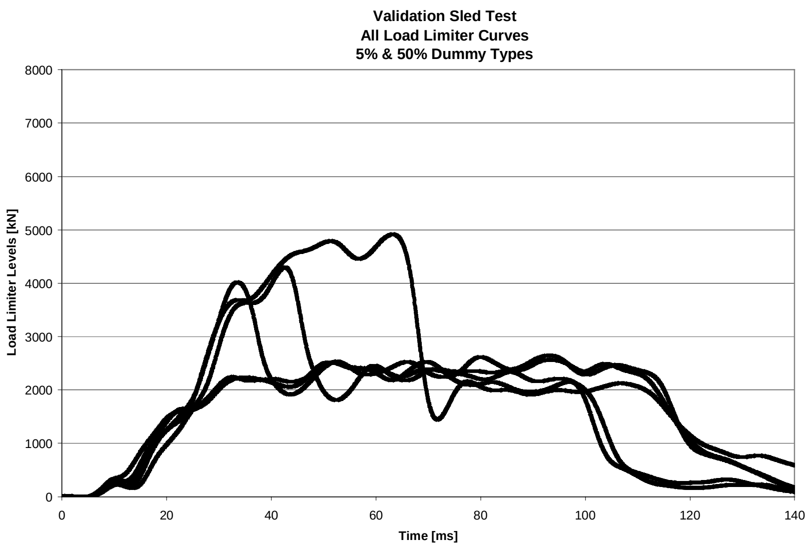

Figure 3: Adaptive Load Limiter output

2. SYSTEM VALIDATION

2.1. Definition of Set-up for system validation

The following definition of system components aims to achieve a "neutral" validation base. This means that as many standards are to be used as is possible. This enables to interpret the results gained later on at a non-customised level, and as such defining a basis for further examinations.
The approach is to use the defined component validation set-up and add the airbag module onto it, as shown in Figure 4.
The driver side will be used for the system validation as drivers are always involved in a crash accident thus representing a great potential are for improvement. Additionally the reduced available room for the occupant in conjunction with a smaller airbag than in the passenger side, represents a higher demand for the IOPS.
In accordance with Figure 4 the system validation set up is defined as follow:

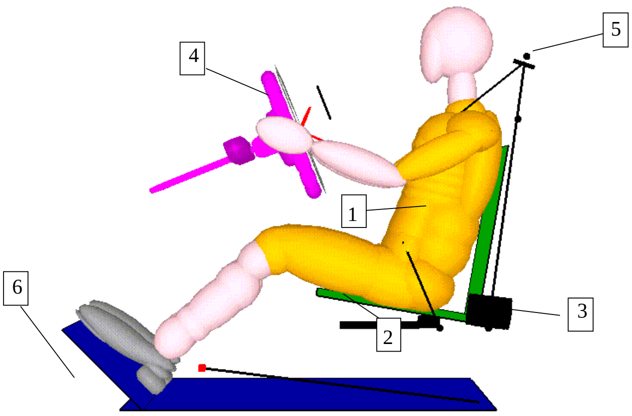

Figure 4: Illustrated overview of the set-up on the driver side with 50% HIII Dummy

1) Dummy Types
The three standard HIII Dummy types will be used for the system validation.

2) Seat and Seating Positions
Each Dummy will be seated in a nominal seating position. The reason for that is based upon the idea that each of the dummy should reach the pedals.
5% small female Dummy ➔ Foremost Position
50% male Dummy ➔ Mid-Position
95% large male Dummy ➔ Rearmost Position

3) Belt System
The adaptive Load Limiter as described in chapter 1 will be used.

4) Airbag Module and Steering wheel
A rigid steering wheel attachment will be used. The rigid steering wheel attachment has the disadvantage of generating higher loading to the occupant compared with a deformeable attachment, such as in a real vehicle. However the advantage of being easy to model and having no deviation throughout the test series makes this choice the most beneficial.
The geometry for the steering wheel is chosen in relation to the airbag being used. This is important as the steering wheel rim supports the airbag during deployment. The steering wheel is tilted 22° from the vertical as this will give a good approximation to a parallel position of the rim to the chest of the dummy in the most forward displacement, thus offering a good load distribution from the airbag to the upper body of the dummy.

5) Pillar Loop
A serial pillar loop from AUTOLIV GmbH will be used.

6) Vehicle Crash Pulse
For the system validation a "standard" pulse should be created. This is for the purpose of being customer vice neutral.
The approach for this is based upon the following idea:
The deformation of the vehicle with 100% overlap to a rigid barrier (US-NCAP) is split into three time zones:
1. Time zone: Deformation of softer frontal section of vehicle structure.
2. Time Zone: Deformation of harder frontal section of vehicle structure including engine block.
3. Time Zone: Local Collapsing of stiffer frontal section of vehicle before intrusion into vehicle interior.
Based upon this definition the pulse on Figure 5 is defined for the system validation.

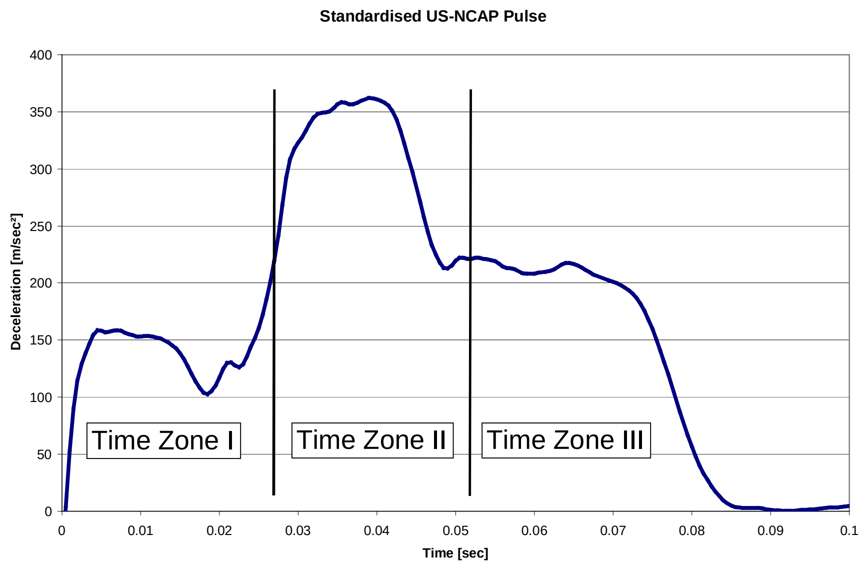

Figure 5: Standardised US-NCAP Pulse for System Validation

The deceleration level of each of the three time zones are to be regarded as an average approach. These levels could be of course point of discussion, and this pulse is only meant to present a neutral, customer independent, pulse for the system validation of IOPS.

2.2. Parameters for the system Validation

The complete parameter list to be used for the system validation is as follow:

A) System Input
1) Load measured at the Belt System
2) Load measured at the Shoulder

B) Reactions Loads and displacements:
3) Load measured at the Anchor Plate
4) Webbing Payout
5) Chest displacement

C) Dummy Responses:
C1) Head
6) Head resultant acceleration
C2) Neck
7) Neck Shear
8) Neck Flexion
9) Neck Extension
C3) Chest
10) Chest resultant acceleration
11) Chest deflection
12) Chest displacement
C4) Pelvis
13) Pelvic resultant acceleration

2.3. Restraint System Characteristics

The available airbag used here is being presently developed for the application with a constant load limiter and not for the application with the adaptive load limiter.

Adaptive Load Limiter:

The same hardware as was used on the component validation will be used for the system validation, too.

Thus the same load limiter levels will be used for the system validation, too. Only the time to switch from high level into low level may be varied in order to determine an optimum degressive setting.

Dual Stage Airbag:

The available prototype airbag module will be triggered in accordance to the projected time to fire, being:

"Low Setting": For US-NCAP
First Stage: 9ms
Second Stage: 19ms

"High Setting": For FMVSS208
First Stage: 9ms
Second Stage: 29ms

This driver airbag module has the following technical data:

Airbag volume: 64 Litre
Airbag Venting: 1x 40mm diameter
Airbag Stages: First Stage 50%
Second Stage 50%

The characteristics of the two airbag settings, 9/19ms and 9/29ms can be seen in Figure 6.

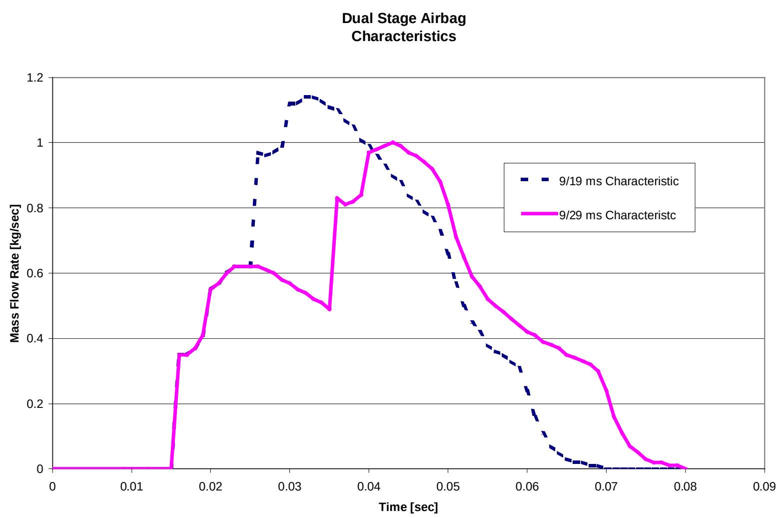

Figure 6: Airbag Characteristic

2.4. Test and Simulation Matrix

The system validation will carry out a comparison between optimum settings and bench mark settings, being here the present state of the art. This is to gather evidence of the potential improvements of IOPS.

The question is related to what crash situations the system validation should concentrate on.
A good approach would be to carry out the system validation on those crash situations where IOPS has shown its greatest potential improvements, in accordance with the simulations carried out in the previous chapter.

Crash Type	***Crash Situation***
A	Improvement of the US-NCAP rating for the 50% male Dummy on a hard pulse
B	Depowering of the restraint load for the 5% small female Dummy on a hard pulse
C	Avoidance of a bottoming out of the 95% large male Dummy

Table 1: Overview of crash situations with highest potential improvements

For each of the chosen crash situations, the optimum setting and the bench mark setting will be compared to each other by simulation and test series.

Crash Type	**5% small female Dummy**	**50% male Dummy**	**95% large male Dummy**
Type A	-/-	2x: Optimum Setting 2x: Bench Mark	-/-
Type B	2x: Optimum Setting 2x: Bench Mark	-/-	-/-
Type C	-/-	-/-	2x: Optimum Setting 2x: Bench Mark

Table 2: Overview of System Validation Test Matrix

The general shape of the load limiter characteristics for the “Optimum Setting” and the “Bench Mark Setting” as gained from the simulations as already published (Clute 1999) carried out for the hard pulse, i.e. US-NCAP, are shown in Figure 7.

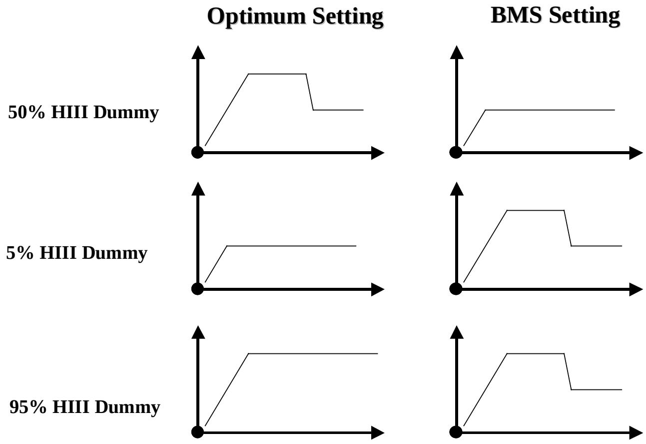

Figure 7: Overview of Load Limitation Performance for the System Validation on hard pulse

The simulation is carry out as follow:

1. Determine the optimum setting for the crash Type A, which will be bench mark setting for remaining two crash types, B and C.
2. Carry out simulation with remaining crash types and determine differences in dummy responses for both Optimum and Bench Mark Settings

Crash Type		**LLA**	**AB1**	**AB2**
Type A 50% Dummy	Optimum Setting Bench-Mark-Setting	55ms 9ms	9ms 9ms	19ms 19ms
Type B 5% Dummy	Optimum Setting Bench-Mark-Setting	9ms 55ms	9ms 9ms	19ms 19ms
Type C 95% Dummy	Optimum Setting Bench-Mark-Setting	No Fire 55ms	9ms 9ms	29ms 19ms

Table 3: Overview of System Validation Matrix

In the table 3 there are the following used abbreviations:

LLA Time to switch the adaptive load limiter to low load level
AB1 Time to fire the airbag first stage
AB2 Time to fire the airbag second stage

3. Analysis of Results

After having conducted the system validation, the test results from the two settings are to be compared with each other in order to determine the improvements of IOPS for each of the three dummy types.

A) Degressive load limitation for the 50% Dummy: Type A

Body Region	**Criteria**	**Bench Mark Setting** Constant Load Limitation		**Optimum Setting** Degressive Load Limitation		**Average Percentage Improvement**
		Test #1	**Test#2**	**Test #1**	**Test#2**	
Head	Head max	55,4 g	56,1 g	53,9 g	54,7 g	**2,6 %**
	HIC36	485	514	473	526	**0 %**
Neck	Neck Fx	0,69 kN	0,66 kN	0,57 kN	0,63 kN	**11 %**
	Neck Fz	2,1 kN	2,0 kN	1,71 kN	1,80 kN	**14 %**
	Neck M	35,1 Nm	34,2 Nm	41,3 Nm	46,7 Nm	**- 26 %**
Chest	Chest 3ms	47,7 g	47,1 g	42,5 g	43,6 g	**9 %**
	Chest Deflection	43,5 mm	42,5 mm	-/-	48,3 mm	**- 12 %**

Table 4: Upper body responses of sled test results – 50% HIII Dummy

Besides the neck moment and the chest deflection, all dummy responses have been improved with the optimum setting.
The maximum peak loading for the chest deceleration show the improvement being in the range of 9%. For a more detailed analysis of the effect of the degressive load limitation the chest acceleration is plotted over time and compared between the optimum and the bench mark setting, as shown in Figure 8.

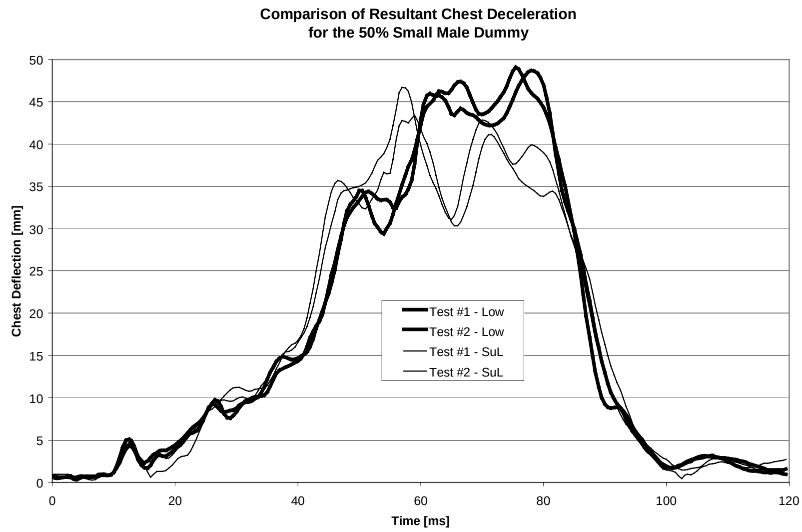

Figure 8: Comparison of Chest deceleration between Optimum and Bench Mark Setting

Figure 8 clearly shows the effect of the degressive load limitation in creating a stiffer restraining of the occupant in the initial phase of the impact. The increase of the chest deceleration between 40ms and 60ms is clearly visible, which subsequently leads to a reduced overall chest deceleration. More clearly is the high duration at a high deceleration level at the low load limitation, which is replaced by two peaks, thus reducing the 3ms values significantly by 9% !

The arising question is what is the effect of the degressive load limitation on the chest deflection Figure 9 shows this effect

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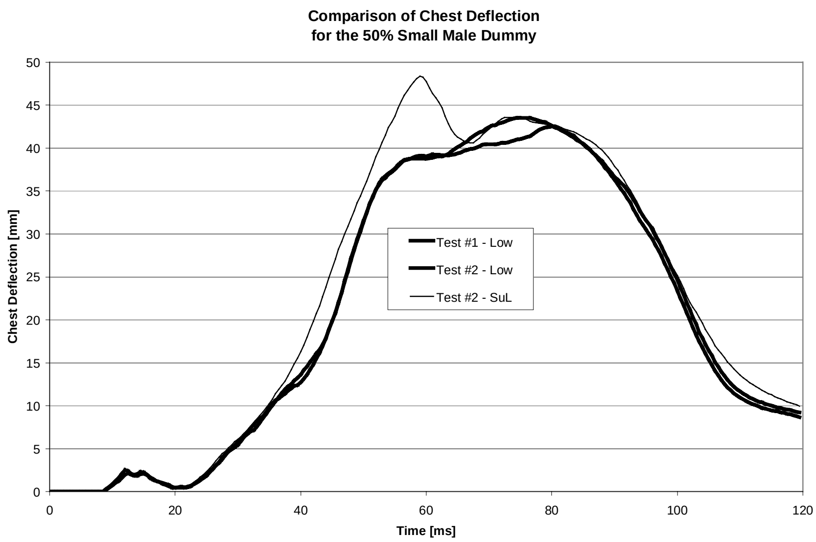

Figure 9: Effect of the degressive load limitation on Chest Deflection

Figure 9 explains the results in Table 4 by showing that the degressive load limitation increases the chest deflection during the phase of increased occupant restraint.

Figure 10 illustrates the improvement of the US-NCAP rating. Here again it can be observed that the degressive load limitation targets the improvement of the chest deceleration without having noticeable influences on the head loading.

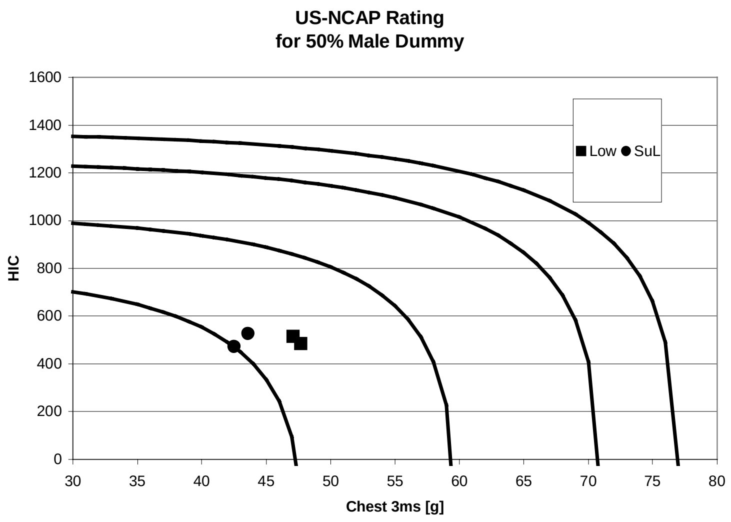

Figure 10: US-NCAP rating for the 50% Dummy

B) Depowering for 5% Dummy: Type B

Body Region	**Criteria**	**Bench Mark Setting** Degressive Load Limitation **Test #1**	**Test#2**	**Optimum Setting** Constant Load Limitation **Test #1**	**Test#2**	**Average Percentage Improvement**
Head	Head max	68,1 g	70,0 g	65,7 g	59,3 g	**9 %**
	HIC36	545	591	628	542	**-3%**
Neck	Neck Fx	0,52 kN	0,46 kN	0,63 kN	0,71 kN	**- 36 %**
	Neck Fz	1,54 kN	1,77 kN	1,41 kN	1,30 kN	**18 %**
	Neck M	33,8 Nm	27,3 Nm	30,8 Nm	39,8 Nm	**- 15 %**
Chest	Chest 3ms	55,3 g	55,8 g	50,8 g	50,2 g	**9%**
	Chest Deflection	41,8 mm	43,4 mm	37,5 mm	34,9 mm	**15%**

Table 5: Upper body responses of sled test results – 5% HIII Dummy

The assumption that the degressive load limitation represent a too stiff restraining of the 5% small female occupant is shown in Table 5. Gain the variation of the load limitation has predominary influence on the chest responses of the dummy. Here both the chest deflection and the chest deceleration are improved by the low load limitation.

The time history of chest deflection is shown in Figure 11. It is clearly visible that the degressive load limitation increases the chest deflection significantly and that the low load limitation improves the chest deflection.

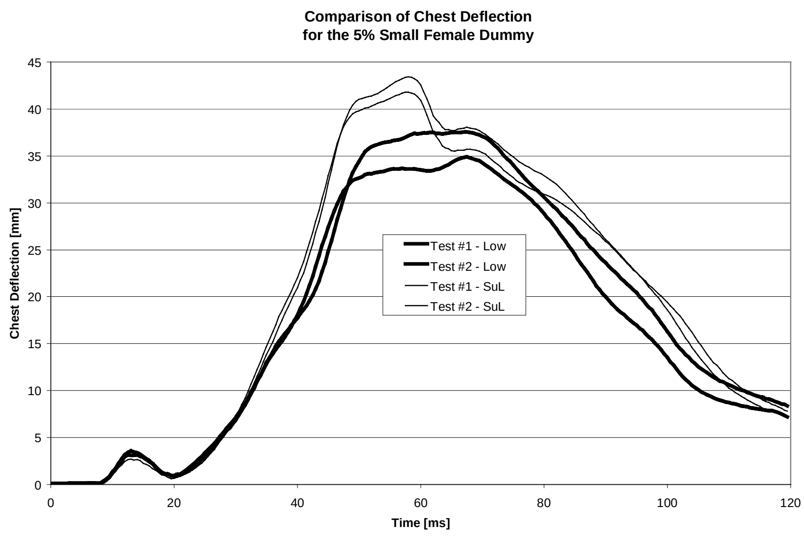

Figure 11: Time history for the chest deflection

C) High powered for 95% Dummy: Crash C

Body Region	**Criteria**	**Bench Mark Setting** Degressive Load Limitation		**Optimum Setting** High Load Limitation		**Avarage Percentage Improvement**
		Test #1	**Test#2**	**Test #1**	**Test#2**	
Head	Head max	54,8 g	55,4 g	60,3 g	64,2 g	**- 13 %**
	HIC36	453	484	657	745	**- 50 %**
Neck	Neck Fx	1,01 kN	1,14 kN	1,00 kN	0,90 kN	**11 %**
	Neck Fz	1,75 kN	1,89 kN	1,97 kN	2,17 kN	**- 13 %**
	Neck M	61,7 Nm	86,1 Nm	51,8 Nm	45,1 Nm	**34 %**
Chest	Chest 3ms	42,7 g	43,2 g	48,7 g	50,0 g	**- 15 %**
	Chest Deflection	-/-	-/-	-/-	-/-	-/-

Table 6: Upper body responses of sled test results – 50% HIII Dummy

Here the assumption that a high load limitation is required in order to avoid the bottoming out of the 95% seams not valid based upon the results in Table 6.
The overall loading at the bench mark setting is lower than those at the optimum setting. Indication for a bottoming out would have been peak loading on head and/or chest acceleration.

On the other hand it is possible that the bench mark setting is close to a bottoming out situation. For this analysis it is essential to look at the distance between the head/chest to the steering wheel at the maximum forward displacement of the dummy. Using the validated simulation model the distance between the head and the steering wheel can be evaluated. Table 7 shows that the bench mark setting is at the border line to a bottoming out, while the optimum setting leads to a 35mm remaining head steering wheel distance.
This explains that the dummy loading for the bench mark are reduced, because a greater displacement of the dummy has been used for the energy absorption !

Setting Condition	**Head / Steering wheel distance**
Optimum Setting	35 mm
Bench Mark Setting	0 mm

Table 7: Head distance to steering wheel

Additional the high speed videos can be analysed, too. Figure 12 compares the frames from two tests at maximum occupant displacement in order to evaluate the distances between the head/chest to the steering wheel. Because the airbag disable to measurement to the actual steering wheel to rigid attachment of the steering module is chosen as reference instead.

Figure 12: High Speed Video analysis for the 95 % large male Dummy

During the degressive load limitation an increased friction on the pillar loop was observed. This increased friction has lead to an load increased at the shoulder, as seen in Figure 113, leading to a higher energy absorption. In the event of a correct load limiation level at the shoulder the bottoming out situation would become even more probable. A difference of 25mm head distance is calculated, which correlates well with the 35mm from Table 8.

4. Reduction of injury probability

First the results from the conducted sled tests will need to be correlated to a reduction in injury probability.

For this initial approach the 50% will be analysed only, as it first represents the average driving occupant and secondly the more detailed injury risk curves data are available.

50% male Dummy:

Since the improvement of the chest deceleration comes together with an increase of chest deflection, a combined injury assessment for both, chest deceleration and chest deflection, should be used, too. The CTI, Combined Thoracic Index, will be used herein. The CTI is defined as

$$CTI = [(A_{max} / A_{Int}) + (D_{max} / D_{Int})]$$, where

A_{max} is the maximum chest deceleration measured, A_{Int} is the X-Axis intercept value (specific for each Dummy) for chest deceleration. D_{max} is the maximum chest deflection measured and D_{Int} is the Y-Axis intercept value for the chest deflection (NHTSA 2000).

The Intercept values are (NHTSA 2000):

	50% Dummy	**5% Dummy**
D_{Int}	103 mm	84 mm
A_{Int}	90	90

Table 8: NHTSA Intercept Values for CTI

Table 9 lists the sled test mean values and the risk of injury AIS +4 for each of the chosen criteria.

	50% Dummy			**5% Dummy**		
	BMS	Optimum	% Improv	BMS	Optimum	%Improv
US-NCAP						
Head AIS +4	3,7%	3,7%	**0%**	3%	3,24%	**-6,2%**
Chest AIS+4	9,5%	7,1%	**24,8%**	6,9%	4,9%	**28%**
Head/Chest AIS+4	12,8%	10,5%	**18%**	9,7%	8%	**17,4%**
NPRM						
Head AIS +4	1,4%	1,4%	**0%**	1,8%	1,9%	**-5,5%**
Chest AIS+4	20,6%	19,1%	**7,3%**	30%	16,3%	**21%**
Chest Deflection	4,5%	5,7%	**-26,7%**	12,9%	10%	**22,5%**
CTI	4,3%	4,3%	**0%**	13,9%	5,6%	**59,7%**

Table 9: Overview of reduction of injury probability

The chest deceleration risk of injury regarding the NPRM is higher than the injury risk for the chest deflection, thus proving the requirement of improving the chest deceleration, while keeping the CTI unchanged. This means that even when IOPS increases the chest deflection when reducing the chest deceleration, the overall combined chest loading stays constant, but a better distribution of both affected risk of injury is improved, too.

5% small female Dummy:

As can be seen the most critical injury probability is related to the chest deflection and the CTI. Both criteria can be significantly reduced by 22.5% and 59,7% respectively.

5. Summary

The system validation test series for a severe crash type proved the functionality of the adaptive load limitation and the significant improvement of occupant protection for the three standard dummy types.

6. References:

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