A SIMULATION STUDY ON THE EFFECT OF AEB ON INJURIES ON 50% OCCUPANTS

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Paper Number 17-0281

ABSTRACT

The paper presents a simulation study on the effects of varied crash speed (due to pre-crash deployment of Automated Braking System) on the injuries sustained by vehicle occupants in a subsequent crash. The methodology used for the study, has been previously outlined (1), showing the effects of altered pre-crash conditions due to emergency braking. The present study focuses on exploring the adaptability potentials of existing state-of-the-art restraint systems to protect occupants even better under different collision conditions created by deployment of AEB.
In the simulation study, a generic passenger vehicle (d-class) is exposed to a reference 56 km/h USNCAP Full Width Frontal test preceded by emergency braking of about 0.8g derived from vehicle testing. In order to investigate the effect of collision speed on the efficiency of occupant protection, a crash pulse scaling method was developed and accordingly applied. This allowed to investigate the case at every random crash speed below 56 km/h.
All simulations are performed in MADYMO (a multibody, numerical solver) and use 3 different 50%-ile occupant models: Active Human Model (AHM), Hybrid III and THOR.
The results show significant capacities of a DOE optimized safety system in reducing AIS 2+ injury risk for the varied collision speed, especially in the range of 25-40 km/h delta V.
The introduction of adaptability of restraint system settings to the varied collision speeds (different than specified by test protocols) resulted in significant improvement of occupant protection. It is thus anticipated that introduction of further system adaptations to the other crash condition parameters will have similar or even more pronounced beneficial effect. Further studies will be focused on adapting restraint systems to varied occupants parameters (size, BMI, age), occupant out of position and also collision conditions e.g. crash angle or crash severity based on predictive detection and classification of collision participants.

1. INTRODUCTION

Road vehicles are increasingly equipped with active safety systems that aid the driver in preventing collisions e.g. autonomous emergency braking (AEB) or lane keeping assistance (LKA). These systems use sensing technologies like radar, LIDAR and cameras and are designed and introduced as safety systems that help avoid crashes or mitigate injuries when crashes are unavoidable.
Previous investigations on the effect of autonomous braking and/or evasive steering on the occupant’s position have shown, that the occupant being out of position may result in an altered injury mechanism during the crash (2)(3). Furthermore, countermeasures like predictive pre-pretensioning (3) are effective in reducing the occupant’s out-of-position situation provided that the timing of the pre-tensioning of the belt is optimally chosen.
With the introduction of active safety systems the possibility to estimate the conditions of an imminent collision has arisen. In case of an upcoming collision that cannot be avoided, the information about the expected crash conditions (e.g. direction, delta-v) or about the travelling occupants (e.g. size, BMI, age, initial position) creates possibilities to pre-set and control occupant restraint systems to ensure maximum protection for the specific collision that is about to happen.
Current state-of-the-art occupant safety systems are very mature in supplying maximum protection for the crash conditions as defined by legal or consumer test protocols. However, the level of protection of occupants secured by the same restraint safety systems is not monitored for non-standardised collision conditions e.g. for cases where after deployment of an autonomous braking system the collision speed is reduced and the occupant’s initial positions are altered by pre-crash braking loading.
Creation of occupant safety systems that intelligently adapt to the variety in state, anthropometry and age of occupants and changing conditions of road collisions is the next challenge in the development of occupant safety systems. A recent study on Occupant Classification and Adaptation (4) presented a balanced operation of Motorized Seat Belt, belt load limits and airbag firing times and showed the significance of using occupant state information to improve their protection during the crash.

This paper builds on the earlier presented methodology (1) that enables engineers to study various accidents and implement adequate adaptability to the existing restraint systems to further optimize them for varying collision conditions.
The methodology is demonstrated in the example case study of a frontal collision preceded by the activation of AEB.

2. METHODOLOGY

The Integrated Safety System is a vehicle safety system in which active safety systems and passive safety systems continuously exchange information regarding occupant state and vehicle state to provide the maximum protection to the occupants. Integrated Safety is a relatively new domain in the automotive safety landscape and design processes are starting to be adapted to account for a further integration of passive and active safety system design. The proposed methodology (1) of building such systems is illustrated in Figure 1.

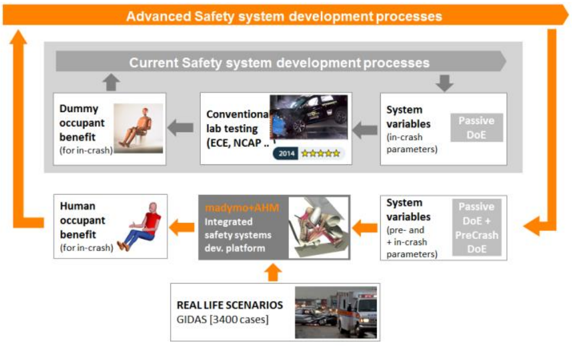

Figure 1. Integrated Safety Methodology: Development & test loops for proving the benefit for human occupants for real life accidents.

The process described in the inner box (grey) illustrates the current approach to safety system development in which the in-crash system variables (e.g. DAB or PAB parameters, pre-tensioner and load-limiter settings etc.) are tested under laboratory conditions and the efficiency of the system settings is then measured on Anthropometric Test Devices.
The development process (outer orange) for the presented methodology proposes to include all system variables relevant in a complete pre- and in-crash event (e.g. pre-crash occupant state control settings,), test them under computer simulated real-life crash conditions based on accidentology databases, and finally measure the effect of the safety system on a human model that accommodates predictive and biofidelically valid behaviour for both pre- and in-crash phases being a complete collision event.
The development process for creating safety systems is broken down further to the consecutive steps illustrated in Figure 2. Step 1 represents a reference model with state-of-the-art system configuration developed according to the current development standards (grey box in the Figure 1). In Step 2, the ATD is replaced with an Active Human Model (AHM) that can well predict human behaviour in both low-g conditions (pre-crash) and under high-g conditions (in-crash). Step 3 introduces pre-crash conditions that affect occupant entry state into the in-crash phase. In the investigated case the affecting factor is emergency braking. Step 3 becomes a

reference for the next steps 4 & 5 in which the occupant restraint systems (working both in pre- and in-crash) are being designed in DOE processes to become adaptive to varying crash conditions. In step 4 the laboratory test conditions are varied (e.g. reduced crash speed and occupant out of position due to deployment of AEB) and in step 5 test protocol conditions are fully replaced with the conditions following road accidentology databases. Since any automotive safety system needs to comply with legal requirements and should also perform well in industry recognized consumer testing, in step 6, the adaptive system created in steps 4 & 5 is eventually confronted with the original system under the conditions defined by the respective testing protocols.

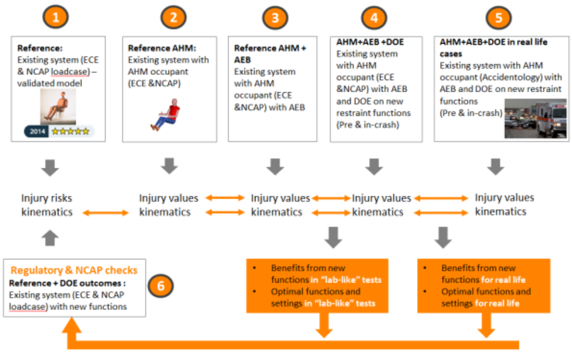

Figure 2. Concept system development & testing process.

The methodology thus builds on and extends currently accepted passive safety development processes and by definition results in integrated safety systems that perform equally well or better than the original system which satisfies the legal and consumer test conditions.

The methodology presented (1) uses the Active Human Model (AHM), a 50%-ile human that can predict occupant kinematics during dynamic manoeuvres in pre-crash phase, as well as biofidelic response in high-g crash conditions (5)(6)(7).

The simulations are all performed in MADYMO: A numerical solver that computes occupant behaviour, its environment, contact interaction and all other physical phenomena relevant for reproducing a complete collision event.

3. APPLICATION

The methodology is illustrated by focussing on a pre-defined frontal collision accident in which an existing passive safety design is supplemented with an AEB system. In a previous study we analysed how this modification affected the occupant's safety by focussing on the human kinematics and the resulting changes in injury mechanisms for a series of generic vehicle models (1). Here we found that the effect of the altered pre-collision conditions as a result of AEB had a positive effect on injury risk due to a pre-tensioning of the safety belts resulting in a softer occupant velocity ride down. Similar findings were later confirmed by other researchers (8).

In this paper we extend our analysis to include all representations of 50%-ile humans, i.e. the Hybrid-III, the THOR and the Active Human and include also effects of the variable impact speed on the crash pulse and airbag trigger time. We necessarily limit the study to one generic vehicle from our model database (a d-class vehicle) in one load-case, the 35mph USNCAP Full Width Frontal test. For this load-case we focus on the estimation of injury risk at lower impact speeds as a result of AEB.

3.1 Crash Pulse Scaling

To be able to perform crash simulations in MADYMO with varying impact speeds, i.e. impact speeds lower than the protocol impact speeds, we developed a method to "predict" the crash pulse at these lower impact speeds. This aims to quantify the benefit of an AEB system and compares effectiveness of different AEB systems and AEB algorithms (9).

With the traditional simulation method the vehicle crash pulse is (inversely) applied to the occupant, or the vehicle crash pulse is applied to the interior vehicle parts (as in a sled test), see Figure 3.

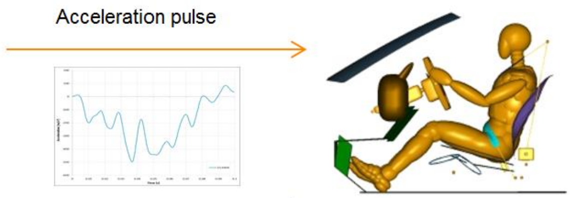

Figure 3. Schematically representation of the traditional method of applying a crash pulse in a MADYMO occupant simulation.

For each crash simulation at a different impact speed the acceleration pulse needs to be modified. In our case we only have the availability of crash pulses of impacts at protocol speed (35mph, USNCAP) . To include the impact speed as a variable in our simulations we base the simulations on a single model validated at protocol speed (35 mph USNCAP) and supplement this with a crash pulse scaling method, see Figure 4.

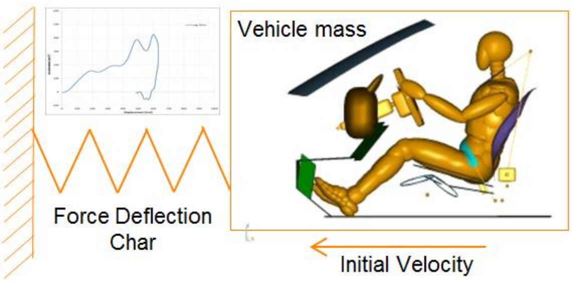

Figure 4. Schematically representation of the Pulse Scale method in an MADYMO occupant simulation.

The interior parts are attached to a body with the vehicle mass which is given the required initial

velocity (=impact speed). The vehicle stiffness is represented by the Force deflection characteristic of the vehicle. The required force deflection characteristic is derived from the vehicle acceleration of the USNCAP crash tests, measured close to the occupant (for example B-pillar base).
More details about the Pulse Scaling method are described in Bosma et. al.(10) .

3.2 Airbag Firing

With the ability to simulate vehicle impacts at different impact speeds we also need to adapt the firing of the safety systems like airbag and belt pre-tensioners. A commonly used general guideline to set the time requirement for this is the so-called 5”-30ms rule (11). This rule is based on the assumption that an unbelted occupant moves 5 inches before the airbag is fully deployed and that full airbag deployment takes 30 ms. In an example where an unbelted occupant moves 5 inches in 50 ms, the airbag firing time requirement then equals 50ms-30ms=20 ms.

For our generic d-class vehicle we performed the fire time calculations according the 5”-30ms rule and plotted these against the impact speed as shown in Figure 5. For the MADYMO simulations we created a construction in the MADYMO input file with DEFINES and regular expressions such that below 20 km/h the airbags are not inflated and above 65 km/h we keep a constant firing time at 8 ms. For the impact speeds between 20 and 65 km/h the corresponding fire time is calculated automatically. In the MADYMO simulations the airbag triggering is then automatically changed when the impact speed changes.

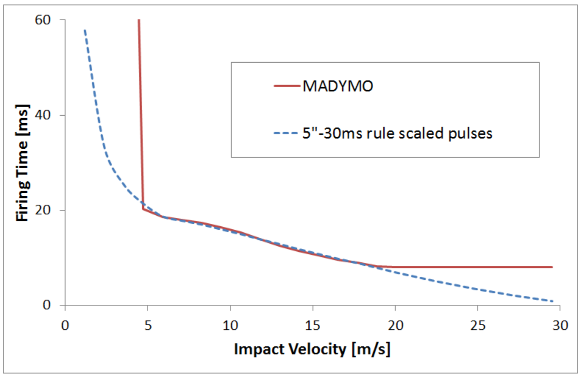

Figure 5. Airbag Firing Time as function of the impact speed.

3.3 Braking Pulse

To simulate the AEB event we chose two deceleration levels, 0.4g and 0.8g. The braking decelerations were taken from a series of volunteer tests that we conducted to enhance the pre-collision motion of our MADYMO AHM. These curves are shown in Figure 6.

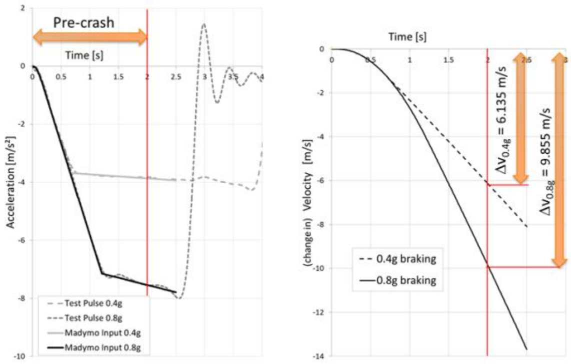

Figure 6. Braking Pulses used in the simulation study.

3.4 Simulation set-up

In the presented study we created separate MADYMO models for driver and passenger with 50%-ile occupants (HybridIII, THOR and AHM). For the pre-collision phase we chose to describe this motion via a FREE_ROT_DISP joint which describes the AEB braking motion. Although in the presented study we focus on AEB, the chosen method allows us to simulate any pre-collision motion via this method (see Figure 7).

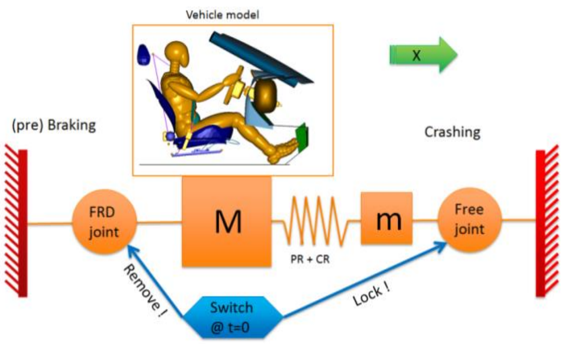

Figure 7. MADYMO model set-up.

In the chosen set-up we simulate 2 seconds of the pre-collision phase. At t=0 the model switches to the crash phase using the calculated crash stiffness derived from the Pulse Scaling Method for this d-class vehicle. Twelve different impact velocities are simulated ranging from 5 to 60 km/h in steps of 5 km/h.

3.4 AIS Injuries

To estimate and quantify the relative benefit of impact speed reduction as a result of AEB we used AIS2+ (see Table *1*) injury risks in our simulation study (12)(13)(14). The AIS severity scale is a relative scale of threat to life. Most protocols are based on the risk of AIS3+ injuries with the objective to reduce fatalities. However, there are also injuries with lower AIS severity (15) which can cause a significant loss in body functions and are therefore considered to be a cost for society. Although we realise that what is missing is a fundamental injury value that addresses this risk of loss of body functions. The calculation of risks for lower severity injuries is a start to assess these kinds of injuries that do not affect fatality numbers but may have a big impact on long term health and trauma.

It must be noted that some of the used AIS2+ functions show a large offset at zero loading resulting in a P_{joint} of 0.316. The absolute injury risk predictions we therefore consider not to be entirely correct. To evaluate the relative injury risk improvements we shifted these functions to zero.

Table 1.
Injury Risk curves for AIS2+ used in this study.

Body Region	Hybrid-III, THOR, AHM
Head (12) *HIC15*	MAIS 2: $[1 + \exp((2.49 + 200/HIC) - 0.00483 \times HIC)]^{-1}$
Neck (13) *Nij*	$p(AIS \geq 2) = \frac{1}{1 + e^{2.054 - 1.195Nij}}$
Chest (13) *Defl. [mm] Chest3ms [g] CTI*	$p(AIS \geq 2) = \frac{1}{1+e^{(1.8706-0.04439Dmax)}}$ $p(AIS \geq 2) = \frac{1}{1+e^{(1.2324-0.0576Ac)}}$ $p(AIS \geq 2) = \frac{1}{1+e^{(4.847-6.036CTI)}}$ $P_{chest}(AIS \geq 2) = \max(P_{Dmax}, P_{Ac}, P_{CTI})$
Femur (13) *Force [kN]*	$P(AIS \geq 2) = \frac{1}{1+e^{(5.795-0.5196*F)}}$
All (14)	$P_{joint} = 1-(1-P_{head})\times(1-P_{neck})\times(1-P_{chest})\times(1-P_{femur})$

4. STUDY RESULTS

For the results of step 1, 2 and 3 of the methodology we refer to Tijssens et.al. (1) for a detailed description. In this paper we focus to present the results of step 4.

4.1 Step 4: Reference and AEB

In Tijssens et. al. (1) we reported that the AHM showed a significantly larger forward motion due to an activation of AEB compared to a Hybrid-III under the same loading conditions. In our recent study we now compared the forward motion of the occupants when subjected to the 0.4g and 0.8g braking pulse with and without the activation of new restraint functions. In the current study we added a Motorised Seat Belt (MSB) to the models that is activated at the same time of AEB.

We calculated the relative displacements of the occupants and compared these with the initial positions. The chosen output locations are shown in Table *2*.

Table 2.
Relative displacement location outputs.

AHM	Hybrid-III	THOR
Head	Head	Head
T1	NeckPlateLow	ThoracicSpineUp
T12	ThoracicSpine	ThoracicSpineLow
	LumbarLC1	
Pelvis	Pelvis	Pelvis

Looking at the relative motions between the three simulated occupants we have seen that the AHM shows more forward motion compared to the Hybrid-III and THOR.This can be seen in the left row of motions for the passenger in Figure 8. Comparing these results with the volunteer tests that we conducted we clearly see that the AHM is closer to what we measured in these tests on the volunteers. Although the Hybrid-III and the THOR also show a forward motion it is found that the performance of the AHM is closer to a real life situation.

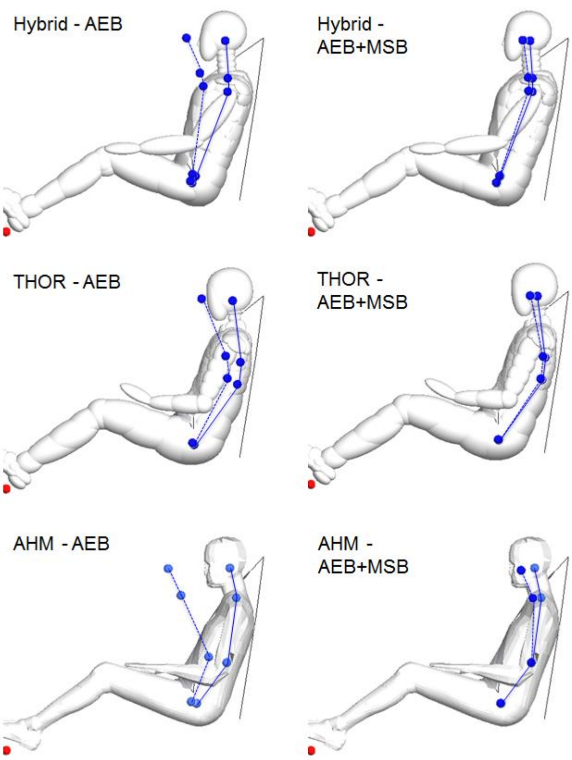

Figure 8. Passenger AEB positions compared with Initial positions with 0.8g braking.

With the activation of the MSB we observed a significant reduction of the forward motion of the occupants, see the right column of occupant motions of Figure 8, where the AHM still shows a significant larger forward motion compared to the Hybrid-III and THOR.

4.2 Step 4: DOE results

In the presented study we have used the impact speed as a variable in order to quantify relatively the benefit of an AEB system for a standard state-of-the-art restraint system. We performed these simulations using the AHM, Hybrid-III and THOR for both driver and passenger. With the performed simulation study we are able to plot the AIS2+ risk values as a function of the impact speed, showing the relative benefit of the AEB system, see
Figure 9.

From the graphs we observe that when the impact speed decreases from 16 m/s to approximately 12 m/s there is a significant reduction in AIS2+ Injury Risk. When the impact speed decreases further to approximately 5 m/s we observe a horizontal trend in the achieved benefit from the impact speed reduction due to AEB. Comparing the Hybrid-III, THOR and AHM a similar trend is shown. Between 12 m/s and 16 m/s impact speed a similar Injury Risk prediction is estimated. Below 12 m/s impact speed the THOR shows a somewhat higher Injury Risk prediction compared to the Hybrid-III and AHM. Analysis of the individual injury results shows that the main contributor to the mentioned horizontal trend is the chest injury risk.

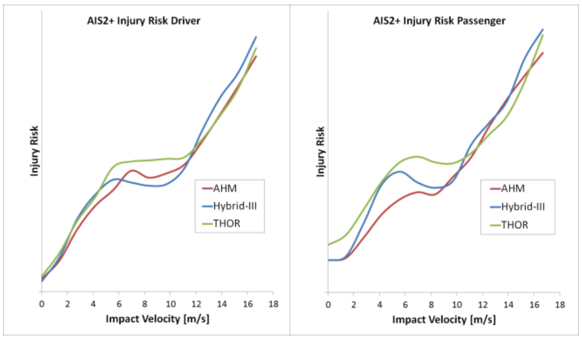

Figure 9. AIS2+ Injury Risk for driver(left) and passenger(right) with standard restraint system.

Further in step 4 we ran several DOE's in which we changed restraint parameters together with the impact speed. Of these we report 2 DOE sessions in this paper, DOE1 and DOE2. The chosen variations and settings are shown in Table *3*.

Table 3.
DOE Simulation matrix.

Setting	DOE1	DOE2
No. of runs / occupant	144	72
Impact speed [m/s]	1 - 16.6667	4.4 - 16.6667
Load Limiter Level [N]	400 - 3600	400 – 3600
MSB	Activated	Activated
Airbag	Activated	De-activated

For the generation of a random set of designs we used the Latin Hypercube algorithm from Altair HyperStudy as shown in Figure 10. The shown designs were exported to the XMADgic Simulation Generator (16) that generated all MADYMO simulation input decks.

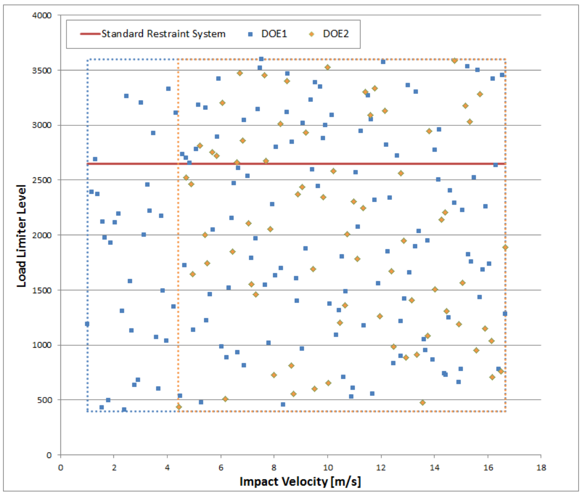

Figure 10. DOE design variables.

For DOE1 and DOE2 we ran a total of 1296 simulations with a simulation time of 2.13 s. With an average runtime of 4 hours per simulation and with each simulation run on 1 CPU we required 5300 hours of CPU time. The simulations ran on a Linux cluster with 72 CPU's, keeping it occupied for 3 days.

As an example the results of the DOE runs of the drivers and passengers are shown in Figure 11 - Figure 16. We observe that:

- The performance of the restraint system in the development range (impact speed 15.6 m/s) shows an optimal performance with the standard restraint system.
- For the lower range of impact speeds, up to 12 m/s significant improvements in Injury Risk can be achieved.
- With a de-activated airbag (with activated belt-pretensioners) also an improvement of the AIS2+ injury risk appears to be feasible.
- It clearly shows the benefit of the airbag at higher impact speeds, especially for the AHM driver and passenger. Above impact speeds of 12 m/s the AIS2+ Injury Risk increases significantly which is mainly caused by neck injury risk.
- For impact speeds between 4 m/s and 8 m/s, for the Hybrid-III and AHM driver, the best performance is achieved without firing the airbag.

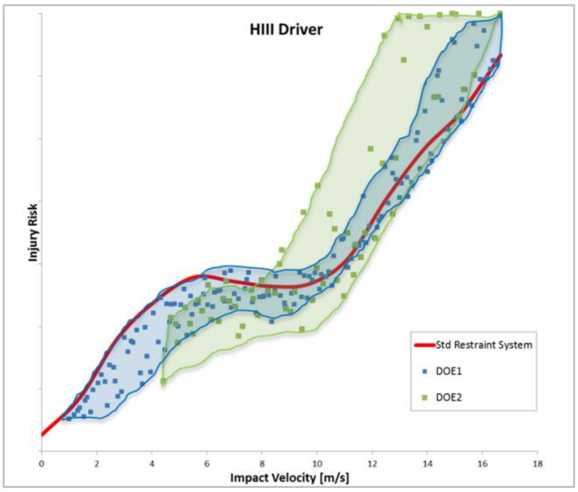

Figure 11. DOE AIS2+ results for HybridIII 50%-ile driver.

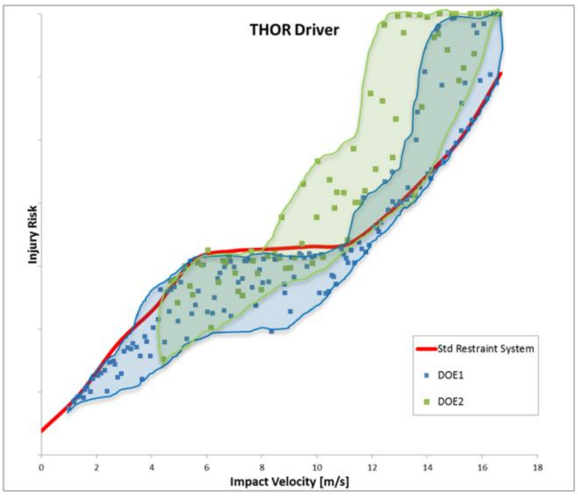

Figure 12. DOE AIS2+ results for THOR 50%-ile driver.

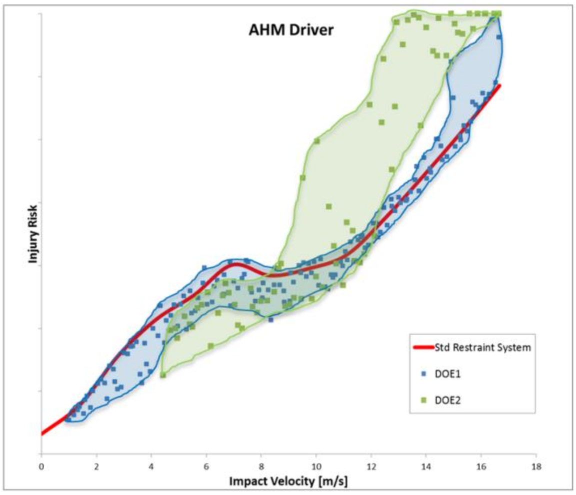

Figure 13. DOE AIS2+ results for AHM 50%-ile driver.

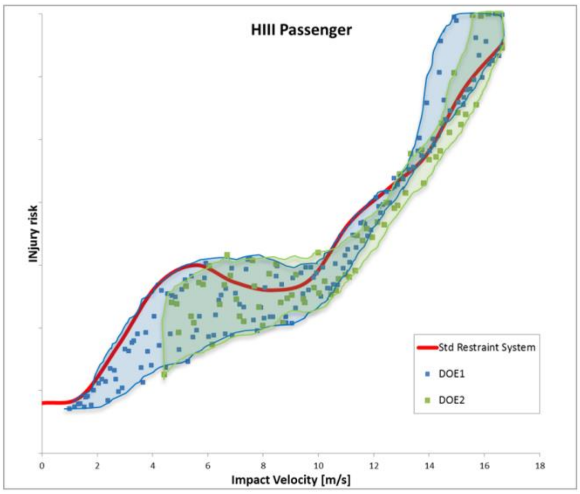

Figure 14. DOE AIS2+ results for HybridIII 50%-ile passenger.

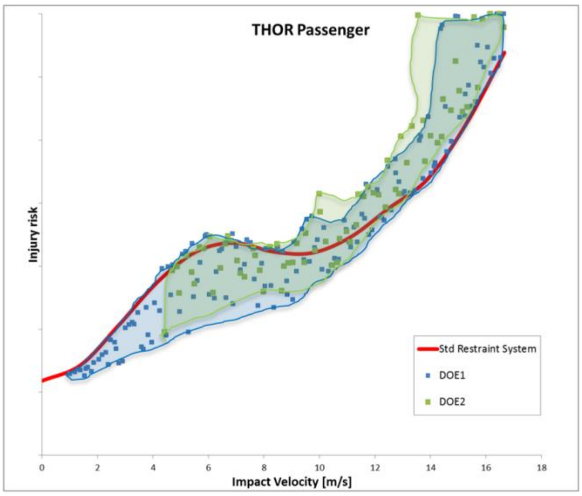

Figure 15. DOE AIS2+ results for THOR 50%-ile passenger.

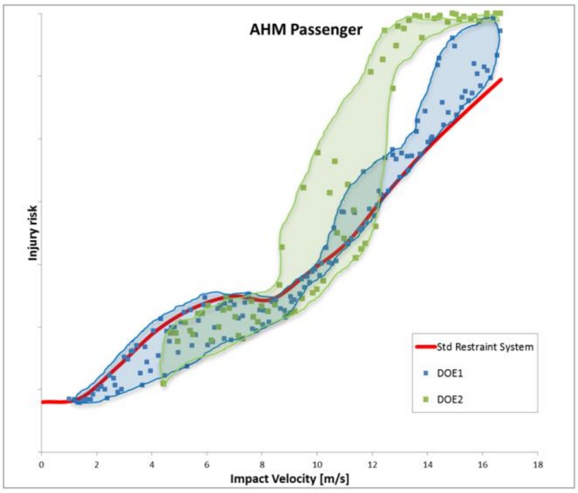

Figure 16. DOE AIS2+ results for AHM 50%-ile passenger.

The improvement potential of the restraint system as a function of the impact velocity is illustrated in Figure 17 and Figure 18 which shows this potential relative to the theoretically lowest AIS2+ injury risk value (0.316).

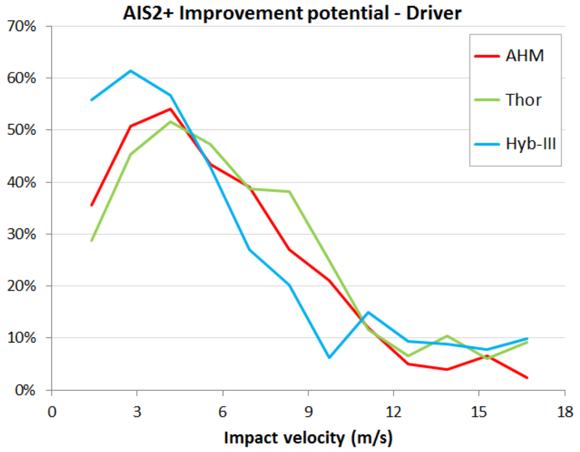

Figure 17. Theoretical Improvement Potential AIS2+ as function of the Impact Velocity for Driver.

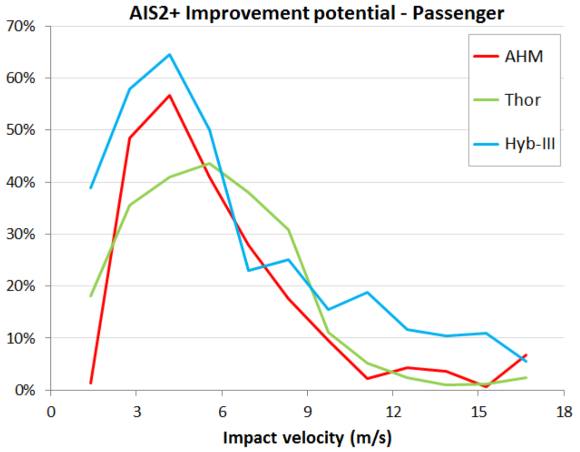

Figure 18. Theoretical Improvement Potential AIS2+ as function of the Impact Velocity for Passenger.

Analysing the results it shows that for the lower range of impact speeds a Load Limiter that works at a lower force level could offer the AEB system the expected benefit as shown in Figure 17 and Figure 18. As an example of this we plotted the AIS2+ injury risk for chest deflection of the AHM driver as function of the impact speed for all calculated DOE1 results from our study, see Figure 19. In this plot the AIS2+ injury risk for the standard restraint system with a load limiter value of 2650N (orange) is compared with a system with a load limiter value of 400N (blue). This example shows that for the higher impact speeds (protocol impact speeds) the standard restraint system offers best protection. For impact speeds up to approximately 9 m/s a load limiter value of 400N shows the best performance.

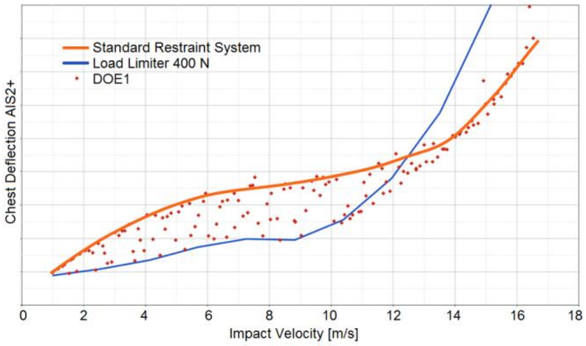

Figure 19. AHM driver chest deflection AIS2+ injury risk.

5. DISCUSSION

With the presented study a simulation method is introduced to assess the relative improvement of the AIS2+ Injury Risk for impact speeds lower than the protocol impact speeds. As such this study could be a start to quantify the effectiveness of an AEB system. It is clearly visible that AEB systems offer a lot of benefit for occupants, since they aim to effectively reduce the impact speed. However we note that in our study the achievable benefit reduces when the impact velocity is lowered below approximately 12 m/s. By varying some restraint parameters we see opportunities to balance the various restraint systems (MSB, airbag, belt load limiters) such that a more optimal performance can be achieved for the lower range impact speeds using the currently available passive safety components. A safety system that for example adapts to the crash situation would in this case offer the maximal benefit of an AEB system. Therefore we believe that for the development of the next generation restraint and safety systems it is important that they are developed in an integrated way, taking into account both active and passive systems at the same time.

LIMITATIONS OF THE STUDY

Our study focussed on one "generic" d-class vehicle type and results may differ for other vehicles. In the presented study we only included 50%-ile occupants "in" position for one crash loading condition. Crash pulses are based on a USNCAP crash pulse only. With more research on additional loading conditions like ODB, car to car and possibly car to any object, this methodology could be further enhanced.

SUMMARY AND CONCLUSIONS

This paper presents a methodology and tool chain that allows designing Integrated Safety systems, i.e. safety systems in which the active safety systems and passive safety systems are designed as one system aiming to optimally protect the occupant. We have shown the effectiveness of the methodology through an example simulation study.

A crash pulse scaling method was developed in this study based on a full width flat wall impact using the available 35 mph crash pulse of a vehicle. With the presented method it appeared possible to use the impact speed as a variable in DOE's.
A method to fire the airbags based on the so-called 5"-30ms rule was developed which automatically links airbag firing to the impact speed in the MADYMO simulations.

In our presented study we used real braking pulses from volunteer tests to simulate the AEB event.

As a start we included lower severity injuries (AIS2+) that may not primarily affect fatality numbers but may have a big impact on long term health and trauma.

The simulation method showed to be effective in running a DOE study and helped to assess the benefit of reducing the impact speed with an AEB system. The simulation results showed that current state-of-the-art restraint systems may work sub-optimal for the lower impact speeds ranging from 5 m/s to 12 m/s. A safety system that adapts to the crash situation, in the presented case, is expected to offer the full benefit to an AEB system.

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