A METHODOLOGY AND TOOL CHAIN TO DEVELOP INTEGRATED SAFETY SYSTEMS

Tijssens, Martin
Bosma, Freerk
TASS International
The Netherlands

Kietlinski, Kajetan
TASS International
Germany

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ABSTRACT

This paper presents a methodology that enables designing integrated safety systems. The advantages of the methodology are demonstrated by applying it to a passive safety system that is supplemented by an AEB active safety system. The passive and integrated safety systems are compared through simulations with a set of vehicles and occupants subjected to load cases obtained from regulations. The methodology reveals changes in injury mechanisms and advantages of the addition of AEB.

INTRODUCTION

Road vehicles are increasingly equipped with active safety systems that aid the driver in preventing frontal collisions (for example collision imminent braking (CIB), autonomous emergency braking (AEB) systems) as well as lateral collisions (for example lane departure warning (LDW) and lane keeping assistance (LKA) systems). 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 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 [1,2]. Furthermore, countermeasures like PRE-SAFE ® [3] or predictive pre-pretensioning are effective in reducing the occupant's out-of-position situation provided that the timing of the pre-tensioning of the belt is well-chosen.
In order to develop innovative restraint systems that provide an increased occupant protection, it is important that engineers are able to analyse the effects on the occupants of active systems that take over the control over the vehicle from the driver and understand why and how injury mechanism are altered.
This paper presents a methodology that enables an engineer to simulate various accident scenarios and to develop countermeasures to avoid adverse effects of increased injuries due to active safety system deployment. The methodology is demonstrated in the example case study of a frontal collision preceded by the activation of the AEB.

METHODOLOGY

The Integrated Safety System is a holistic 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 production-level design processes are starting to be adapted to account for a further integration of passive and active safety system design. The methodology is illustrated in Figure 1.

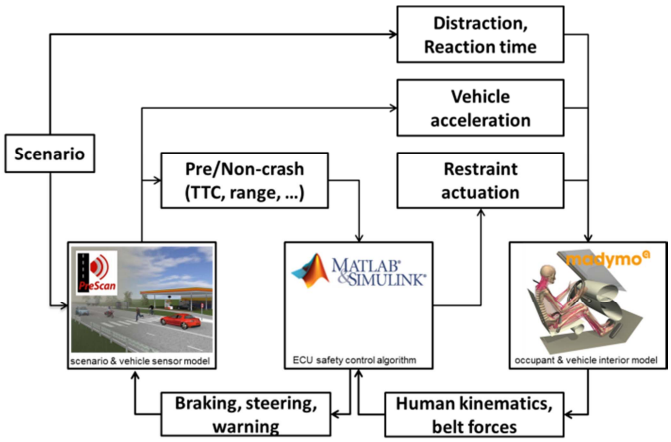

Figure 1. Integrated Safety Methodology

The accident scenario prescribes all boundary and initial conditions with respect to the participating vehicles and the human actors. Traditionally, when active safety system development and passive occupant restraint system development are separated, the scenario delivers information to both designs separately. In Figure 1 this is illustrated with the scenario that is described in an ADA development tool which feeds pre/non-crash information like time to collision, distance to preceding vehicle, etc. into the ECU safety control algorithm. In turn this algorithm provides modifications to the scenario like warnings to be given to the driver or interventions like braking or steering. Separately from this, the scenario provides occupant information like distraction and reaction time as well as vehicle information like its acceleration to enable an in-crash simulation to evaluate occupant safety.
When the ADA system influences the vehicle motion, be it pre- or in-crash, the vehicle motion no longer comes directly from a predefined scenario, but is to be communicated from the evolving scenario in the ADA tool to the occupant simulation to allow the simulation of pre-crash motion of the occupants as well as to determine initial conditions for the in-crash phase. Similarly, when the ADA system influences the restraint actuation, the conditions of the restraint system are to be communicated to the occupant safety simulation to start the in-crash simulation with the proper initial conditions.
Finally, the influence of the occupant restraint system on the occupant and visa versa is to be communicated back to the ECU safety control algorithm to allow for a feedback loop on the restraint actuation. This information can also be used to allow for a feedback loop on the vehicle parameters, i.e. the occupant state influences the strategy chosen to avoid or mitigate the collision.
The following simulation tools are used in this methodology [4]:

- PreScan: This tool allows to build scenarios, to design active safety systems using the tool's sensor models or by using users' own sensor data to develop and test algorithms of the ECUs. The tool also produces the vehicle's linear and angular velocity and acceleration data when the tool's or third-party vehicle dynamics models are used.
- Active Human Model (AHM): This tool allows to represent real human motion during pre-crash maneuvers with low acceleration levels [5,6,7]. Volunteer testing confirmed that the actual human being (50th %ile male volunteer) behaves differently compared to the Hybrid-III dummy during pre-crash manouvers with low acceleration levels. Hybrid-III dummies were mainly developed for high speed crashes and for in-position crash tests. Therefore Hybrid-III dummies are not adequate to predict human behavior during the pre-crash braking phase.
- MADYMO: MADYMO is a simulation tool to help analyze occupant behavior and calculate injuries during the crash.

APPLICATION

Here the strength of 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. It is analysed how this modification affects the occupant's safety by focussing on the human kinematics and the resulting changes in injury mechanisms.

Accident sequence

The frontal crash is divided in several phases, illustrated in Figure 2.

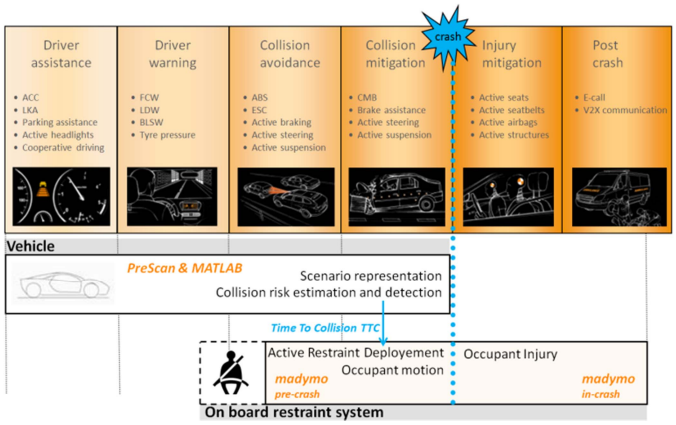

Figure 2. Sequence of the pre-collision and post-collision events

1. Driver warning phase: the radar / camera system detects an object in the path of the vehicle and sends a warning to the driver.
2. Collision avoidance phase: the ECU safety control algorithm determines that under the given circumstances a collision is likely and decides that the AEB system must be activated. The vehicle starts to decelerate with a given moderate deceleration level.
3. Collision mitigation phase: the ECU safety control algorithm determines that a collision can no longer be avoided and decides to apply a more aggressive decelleration strategy as well as to prepare the occupant restraint system for the imminent collision.
4. Injury mitigation phase: the AEB system does not stop the vehicle completely and the vehicle collides, the (activated) restraint system (seatbelts, airbags, etc.) provides protection to mitigate occupant injuries.

Assumptions and limitations

In this study we start from a traditional passive safety restraint system (containing dual stage inflated airbags, belts, belt load-limiters and belt pre-tensioners), used in the injury mitigation phase and wish to extend the safety system into the collision avoidance phase. Validated models for motorized seatbelt pretensioners or other types of OOP countermeasures were not available therefore not used in the analysis.
Furthermore, it is assumed that the crash speed is higher than the airbag deployment threshold speed and consequently the airbags still deploy.
This study is limited to one idealized braking profile, having moderate decelleration in the collision avoidance phase and aggressive decelleration in the collision mitigation phase, illustrated in Figure 3.

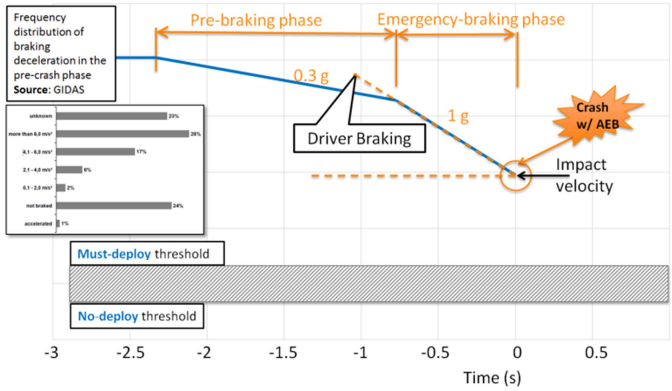

Figure 3. Pre-crash velocity profile

The braking profile contains two distinct phases, i.e. 0.3 g for 1 sec followed by 1 g's for 0.6 seconds. Many automakers use different braking strategies therefore produce different braking profiles. Although the profile is based on those considered by some of our customers, we realize it may not represent real-life braking performance of actual AEB systems currently in production.
In the study 3 MADYMO models are used that represent various vehicle types, i.e. a sports car (vehicle 1), a A/B-class vehicle (vehicle 5) and a C-class vehicle (vehicle 4). All vehicle models were fully validated against actual crash tests. Special attention was given to the models to make sure all occupants remain in an exact equilibrium when no load was applied to make them suitable for use in pre-crash simulations.
Three impact speeds were used in the analysis, i.e. protocol speeds from FMVSS 208 (25 mph, unbelted), US NCAP (35 mph) and Euro NCAP (64 km/h). To ensure that the impact simulations are all done at crash speeds for which the MADYMO models are validated and to exclude any effects on the injury levels from the reduced impact speed, the initial speeds for the AEB simulations were chosen to be 31.8 km/h (19.7 mph) higher as the non-AEB simulations which corresponds to the total reduction of speed of the chosen braking profile.
Besides this technical limitation of our analysis, we believe that although the goal of AEB is to reduce the impact speed, future accident statistics still have to confirm that impact speeds have indeed reduced due to the introduction of AEB. Until then, it seems wise to continue to adopt the accepted protocol speeds for the in-crash scenarios.

Simulation set-up

For each vehicle, 3 occupant models are used, i.e. the Hybrid-III 5%ile ATD, Hybrid-III 50%ile ATD and the Active Human Model 50%. All occupant models were used in both the driver as well as the passenger configuration and each was subjected to three impact configurations, i.e. a rigid wall belted, a rigid wall unbelted and an ODB condition, conforming to the choice of impact speeds. The simulation matrix is illustrated in Figure 4.
For all these 54 combinations a standard impact scenario as well as an impact scenario preceded by AEB was analysed. Note that for vehicle 1 the ODB validation of the model was not available, i.e. in the end 48 different load cases were analysed.

			Impact speeds [km/h]					
			RW -B		RW - UB		ODB	
			std	AEB	std	AEB	std	AEB
Driver	5 % Hybrid-III	Vehicle 01	56	56	40	40	*na*	*na*
		Vehicle 04	56	56	40	40	64	64
		Vehicle 05	56	56	40	40	64	64
	50 % Hybrid-III	Vehicle 01	56	56	40	40	*na*	*na*
		Vehicle 04	56	56	40	40	64	64
		Vehicle 05	56	56	40	40	64	64
	50 % AHM	Vehicle 01	56	56	40	40	*na*	*na*
		Vehicle 04	56	56	40	40	64	64
		Vehicle 05	56	56	40	40	64	64
Passenger	5 % Hybrid-III	Vehicle 01	56	56	40	40	*na*	*na*
		Vehicle 04	56	56	40	40	64	64
		Vehicle 05	56	56	40	40	64	64
	50 % Hybrid-III	Vehicle 01	56	56	40	40	*na*	*na*
		Vehicle 04	56	56	40	40	64	64
		Vehicle 05	56	56	40	40	64	64
	50 % AHM	Vehicle 01	56	56	40	40	*na*	*na*
		Vehicle 04	56	56	40	40	64	64
		Vehicle 05	56	56	40	40	64	64

64	Impact speed of model used for study [km/h]
na	No material available for study
std	Standard Loadcase as defined per protocol
AEB	With braking, scenario (impact speed = protocol impact speed)
RW - B	Rigid Wall Belted - FMVSS208/USNCAP 35 mph test
RW - UB	Rigid Wall Un-Belted - USNCAP 25 mph test
ODB	Offset Deformable Barrier - EuroNCAP 64 km/h

Figure 4. Simulation Matrix 2

Belt retractor model

In order to mimic real life situations as closely as possibly, the belt retractor model, including a detailed locking mechanism was used in the simulations. Similar to a real-world example, a small ball triggers the locking mechanism after it has travelled 2 mm of distance against a sloped surface. The angle of this surface represents the acceleration level at which the locking device should trigger. The mechanism is designed to trigger only when subjected to accelerations of more than 0.30 g, see Figure 5 for an illustration.
In order to prevent seat belts from slipping down on the occupant during the pre-braking phase, a continuous retraction force of 5N is applied to the retractor belt output, until the locking mechanism is triggered.

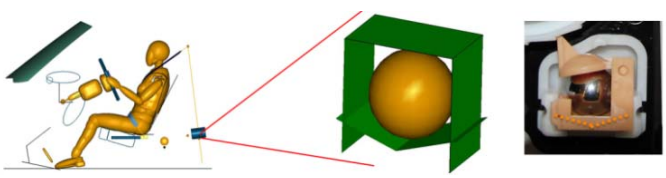

Figure 5. Simulation model of the belt locking mechanism

Using these models, a series of simulations were run to assess injuries and injury mechanisms of occupants by intentionally introducing the braking effect before the crash. In this study, the simulation was done as follows:

1. The pre-defined vehicle acceleration illustrated in Figure 3 was applied to the MADYMO model with occupants to predict the position of the occupants;
2. Subsequently, the occupant was subjected to the crash pulse belonging to the specific load case being analysed, see Figure 4;
3. Injury numbers from MADYMO models were obtained and normalized to the injury targets specified in Table 1. The new injury numbers were compared to the baseline injury numbers from models without braking effect.

RESULTS

The objective of this study is to identify any changes affecting the occupant safety level from the activation of AEB, for example changes in injury mechanisms. In order to compare all simulation results, a selection of injuries is made based on what is common for US and EU regulations such that the four main areas (Head, Neck, Chest and Femurs) of an occupant are covered in the comparison. For each of the areas a target performance was selected based on maximum values allowed in various protocols. These target performances, see Table 1, are only used to calculate the relative improvement or degradation of a "crash situation with AEB" compared to the standard crash situation without AEB, i.e. the calculated percentage is a percentage of the Target Performance. For the Active Human Model the injury target values for the Hybrid-III 50%ile dummy are used.

Table 1.
Summary of the target injury performances

Type	Region	Injury	Unit	Target	Ref.
Hybrid-III 5%ile	Head	HIC15	-	700	3
		a 3ms	g	80	1
	Neck	Nij	-	1	3
	Chest	Chest deflection	mm	52	3
		a 3ms	g	60	3
	Femur	Load LHS/RHS	kN	6.805	3
Hybrid-III 50%ile	Head	HIC36	-	1000	1
		a 3ms	g	80	1
	Neck	Nij	-	1	2
	Chest	Chest deflection	mm	50	1
		a 3ms	g	60	2
	Femur	Load LHS/RHS	kN	9.070	1
Active Human Model 50%ile	Head	HIC36	-	1000	1
		a 3ms	g	80	1
	Neck	Nij	-	1	2
	Chest	Rib deflections	mm	50	1
		Rib 3ms	g	60	2
		a 3ms	g	60	2
	Femur	Load LHS/RHS	kN	9.070	1

*1 ECE R95 - injury limit values for a Hybrid-III 50%ile
*2 FMVSS 208 - injury limit values for a Hybrid-III 50%ile
*3 FMVSS 208 - injury limit values for a Hybrid-III 5%ile

The comparison between the injuries calculated from the 48 standard and 48 AEB load cases shows that the majority of the injuries *improves* due to pre-crash braking even though the impact velocities for standard and AEB load cases are the same, see Figure 6. The comparison also shows that injury mechanisms may change due to the pre-crash braking which results in an increase of some injuries. In the next section we will investigate the mechanisms responsible for these changes in more detail, using two cases for which an injury becomes worse by more than 20% and for which the injury value is close to the target value.

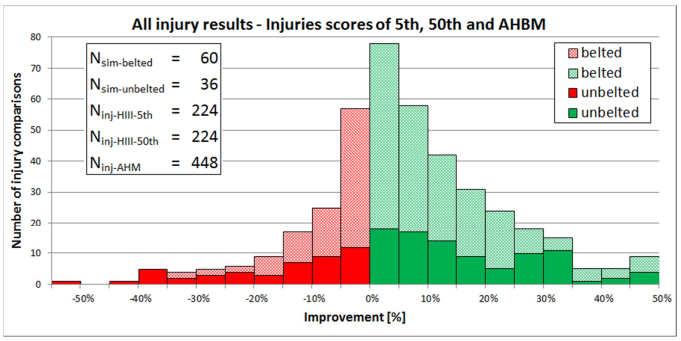

Figure 5. Distribution of injury scores comparisons between the collisions with and without AEB activation

Changed belt loading

Generally, it was observed that the pre-crash braking pulse causes the Hybrid-III 5%ile, 50%ile and Active Human to slide forward on the seat due to the pre-crash braking decelleration. For the Hybrid-III 5%ile this results in a change in injury mechanism observed in vehicle 1.

Compared to the standard case, the occupant loads the restraint system differently in the AEB case which causes the lap belt to slip off the illiac wings of the Hybrid-III 5%ile and submarining occurs. This results in an increased risk of abdominal injuries. The submarining additionally results in a further increased forward motion of the pelvis, i.e. the lapbelt is less effective in restraining the pelvis. Subsequently this results in a heavier impact of the femurs on the IP and consequently higher femur forces (see Figure 7).

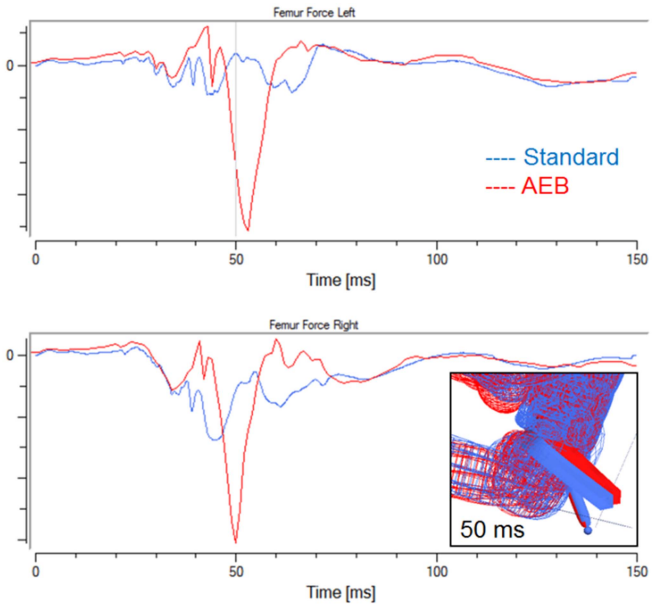

Figure 6. Illustration of the different belt loading causing higher femur forces and possible abdominal injuries.

Out-of-position effect

Another general observation is that due to the pre-crash braking the occupants bend forward. Although this was observed for the Hybrid-III's as well as the Active Human, the Hybrid-III dummy does not represent the human behaviour accurately enough under low acceleration loading conditions [6,8].
In all belted cases the Active Human Model shows a more forward motion for both driver and passenger than the standard Hybrid-III dummy, see Figure 8. The increased forward motion is mainly present in the neck and head region due to the higher flexibility of the human compared to the Hybrid-III dummy. The unbelted load cases show that the occupants bend forward significantly and that, whereas the Hybrid-III dummy falls forward onto the IP, the Active Human model is able to withstand the out-of-position effect due to the braking decelleration by active muscle tensioning and predicts a more realistic (initial) position prior to the crash, see Figure 9.
The change in injury mechanisms for all these cases result either in different neck or different head injury values and in all cases this is related to the airbag hitting the occupant (bag slap).

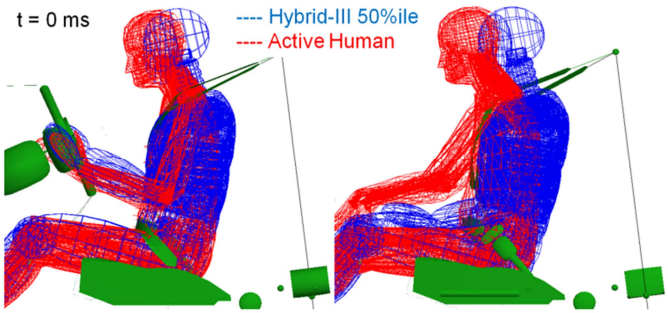

Figure 7 Forward motion of the Hybrid-III 50%ile compared to the Active Human driver (left) and passenger (right) for vehicle 05

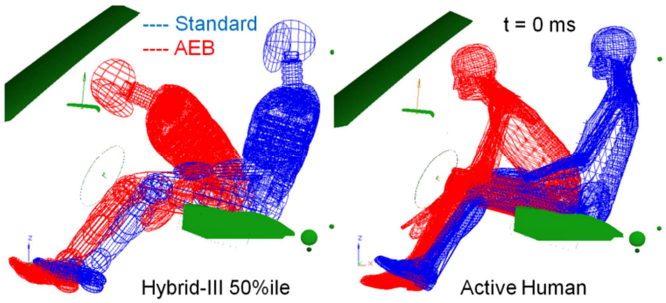

Figure 8 Illustration of the FMVSS 208 unbelted load case for the Hybrid-III 50%ile and Active Human passenger for vehicle 05

Ride-down effect

The analysis also revealed an improvement of the occupant injuries when AEB was activated. To understand the mechanism that gives this positive effect the ride down velocities of the occupant's head, thorax and pelvis were calculated and compared for all simulations. The comparison shows that activation of AEB results in an earlier and softer "Ride Down" compared to the standard crash case. This effect is visible for most of the simulated cases and is expected to have a positive effect on the occupant injuries.

To illustrate the ride-down effect, Figure 10 shows the ride-down velocities and the femur forces for the Hybrid-III 5%ile dummy in the FMVSS208 unbelted loadcase for both the standard crash condition as well as the case where AEB was activated. In the standard case the knees have an initial distance to the kneebolster which results in an almost constant forward velocity of the occupant's pelvis until the knees impact the knee bolster. From that moment (around 70ms) the pelvis velocity drops and the "ride down" of the pelvis is much steeper compared to the vehicle deceleration. In the situation where AEB is activated the occupant slides forward during the pre-crash braking phase which causes the knees to touch the kneebolster prior to impact. As a result the ride-down of the occupant's pelvis follows the ride-down of the vehicle much more closely which in turn results in lower femur forces.

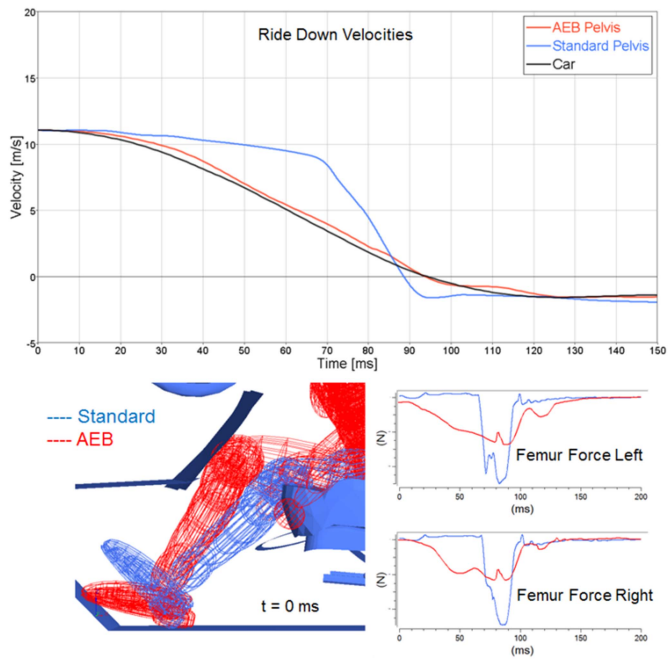

Figure 9. Ride down example femur forces and pelvis ride down velocities of the Hybrid-III 5%ile in vehicle 04 for FMVSS208 unbelted

Figure 11 shows an example of a (belted) USNCAP case with a Hybrid-III 50%ile passenger dummy. It is observed that in the AEB case there is an earlier and softer ride down for the head, thorax and pelvis, which improves the head acceleration and chest deflection. Additionally a slight improvement of the femur loads is observed.

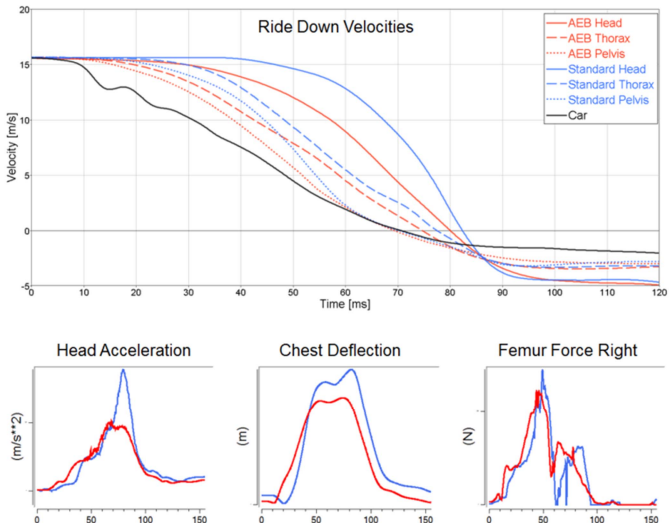

Figure 10. Comparison of the "ride down" effect during the in-crash phases with and without AEB activation in 35 MPH US NCAP crash simulation for vehicle 05 Hybrid-III 50%ile passenger

Although we expect that the earlier ride down generally has a positive contribution to the improvement of injuries, this is not confirmed in all simulations with actually improved injuries. In Figure 12 this is illustrated with the results for the Hybrid-III-50%ile driver of vehicle 01 in which differences for the chest deflection are observed. In this situation the chest deflection is increased for the AEB case. The reason for this increased chest deflection is mainly attributed to a changed belt routing caused by the AEB activation. Referring back to the feedback loop in Figure 1, the occupant restraint system may be adapted to prevent this change in belt routing in the pre-crash phase.

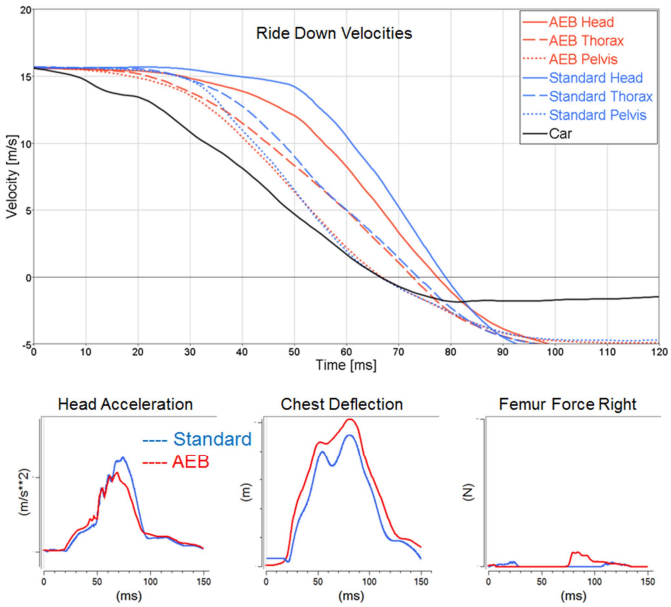

Figure 11. Comparison of the "ride down" effect during the in-crash phases with and without AEB activation in 35 MPH USNCAP crash simulation for vehicle 01 Hybrid-III 50%ile driver

However from our studies we noted that developing a restraint system for only the standard crash conditions can result in a sub optimal solution. An additional verification of the restraint system in cases where AEB is activated is recommended.

CONCLUSIONS

This paper presents a methodology and tool chain that allows to design Integrated Safety systems, i.e. safety systems in which the active safety systems and passive safety systems are designed as one system aiming to protect the occupant. The tool chain's effectiveness is illustrated by analysing the changes in injuries and injury mechanisms for a traditional passive safety system which is supplemented with active pre-crash braking.
The study shows the effect of altered pre-collision conditions on the injuries as a result of activation of AEB. In most cases the pre-tensioning of the safety belts due to the occupant's pre-crash ride-down results in a reduced injury risk in the subsequent crash. In some cases, the earlier and softer ride-down is compromised by, for example, a changed belt routing or an out of position situation prior to the crash. The more accurate representation of human motion with the Active Human Model helps to predict the initial occupant position before the crash and therefore helps to identify countermeasures for these situations.

Figure 13. Current situation where Active and Passive safety systems work independently

At present passive safety systems and active safety systems are often designed independently from each other and countermeasures may often be identified "off-line", i.e. without a further integration of the passive and active systems. We advocate that the Integrated Safety System is a total vehicle safety system in which active safety systems and passive safety systems communicate and collaborate with each other all the time and exchange information such as occupant status, vehicle speed, braking status, etc. in order to provide the maximum protection to the occupants. The methodology described here allows to analyse potential benefits as well as address potential risks of unexpected increased occupant injuries from the (un-)coordinated activation of active and passive safety systems.

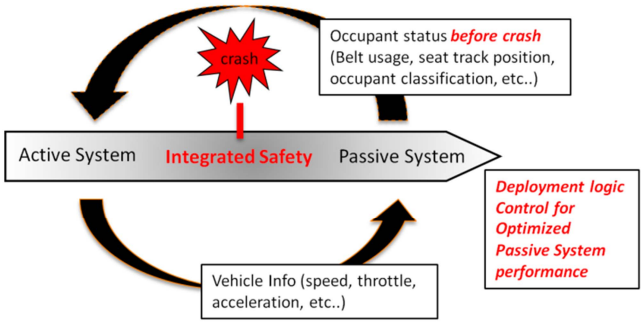

Figure 14. Integrated Safety System Development concept of TASS International.

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