NEW INTEGRATED ASSISTANCE FUNCTIONS FOR REAL WORLD ACCIDENT SCENARIOS

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ABSTRACT

Investigation of several accident databases consistently identified guardrail and embankment accidents as highly relevant in the context of real world accident scenarios that are not in the focus of today's vehicle safety functions. This work demonstrates the potential of future vehicle safety functions to reduce the severity of such accidents. To achieve this, two vehicle lateral controllers are in development that assist the driver in guardrail and embankment accident situations. A Linear Quadratic Regulator (LQR) approach, based on a single track model, is used to stabilize the vehicle in these situations with the goal to reduce the risk of secondary collisions and a rollover of the vehicle. Simulation results demonstrate the potential of the vehicle lateral controllers to stabilize the vehicle after a guardrail collision and to keep it in a safe area next to the guardrail. It is also demonstrated that the risk of a rollover in an embankment due to erroneous driver steering can be reduced. Further research is required to investigate the influence of driver inputs to the controllers in the mentioned accident situations. It needs to be discussed how the new controllers could be incorporated in the existing and future vehicle safety architecture.

INTRODUCTION

According to the World Health Organization (WHO), road traffic accidents are the eighth leading cause of death worldwide and the leading cause of death among young people aged 19-25. While countries with a high income level have been able to reduce this number in the last years, the fatalities in low and middle income countries have increased (WHO 2013). The WHO has initiated the "Decade of Action for Road Safety" with the goal to safe five million lives in road traffic until 2020. The long term goal for countries with high safety standards is the "Vision Zero", meaning zero fatalities in road traffic. Car manufacturers, suppliers and legislative have worked hard on the improvement of vehicle safety in the last decades. The basis of today's passive safety systems is built on international standards and guidelines wherein the central components are highly reproducible crash tests. The PreCrash phase will have to be taken into account to achieve further improvement in the area of vehicle safety. Special attention should be put on real world accident scenarios that are not controllable by today's safety systems. Although the standardized laboratory crash tests are well representative for the majority of field crashes, it seems that a significant number of accident scenarios is not described completely (Allgemeiner Deutscher Automobil Club (ADAC) 2011). This requires the development of new Integrated Safety Algorithms based on the relevance of certain real world accident scenarios.

ACCIDENT RESEARCH

Analyses of several accident databases identified significant accident scenarios that can no longer be neglected in the development of vehicle safety systems. Data obtained from the German In-Depth Accident Study (GIDAS), the United States Fatality Analysis Reporting System (FARS), the General Estimates System (GES) database as well as the ADAC accident research (ADAC 2013), illustrate consistently road departure accidents as the main cause for accidents involving severe injuries. GIDAS data shows that 20% of all accidents involving injured occupants have their root cause in unintentional leaving the road. Road departure as the consequence of a previous accident has been excluded in this analyses. The importance of road departure situations increases even more when the injury value is put into focus. Almost 49% of accidents involving fatally injured occupants have a road departure event as the initial starting point. In consequence, the need for new Integrated Safety Algorithms arises that concentrate on road departure accidents. A deeper analysis of road departue accidents identified situations involving an embankment or guardrail as primary accident event as highly significant in this accident category.

Guardrail Accidents

Accidents that have a guardrail as the primary collision object are identified as the second most relevant scenario in the area of road departure accidents. They stand for 4.5%, or almost 7,000 injured people in the GIDAS analyses and they are also the fifth leading cause of accidents on German highways. Deeper analysis shows that 75% of the vehicles are involved in multiple collisions after they collided with a guardrail. This can either be another guardrail (52%), a vehicle (24%) or a different object (24%) like a tree. This is notable as the injury severity increases with multiple collisions. The delta-velocity, the velocity that is decomposed in the primary guardrail collision, is relatively low with a maximum of 20 km/h for more than half of the accidents. Therefore a high energy potential is left for secondary collisions, as the average collision velocity is more than 70 km/h for 51% of the vehicles during the primary guardrail contact. The analyses show also that the root cause of guardrail accidents are driving situations that relate to loss of control, inattention or fatigue of the driver. If proper reaction by the driver is initiated after the first guardrail contact, the risk of multiple collisions will be reduced. Support of the driver in such situations is therefore goal of the new vehicle safety functions.

Embankment Accidents

Nearly 8% of all accidents involving injured occupants in a passenger car occur in the vicinity of an embankment, while the embankment can either go up or down. This corresponds to 12,000 people in Germany for the year 2010, according to the GIDAS analysis. Two thirds of the vehicles have a follow up collision after leaving the road. It is remarkable that 48% of the vehicles undergo a rollover that can be followed by a frontal or side impact. The initial angle between the vehicle's longitudinal axis and the roadside is for most of the accidents relatively small at the time the road is being departed; the maximum angle reached is 20° for in total 75% of the accidents. If attention is put on the root cause of such accidents, it is striking that over 90% of the accidents occur also due to loss of control, inattention or fatigue. This leads to the conclusion that a relatively harmless starting cause can lead to severe accidents, especially when a wrong reaction by the driver is initiated, like steering upwards in a downward embankment which increases the risk of a rollover. The new vehicle safety function currently under development aims on the support of the driver in such situations. The critical driving situation shall be detected by the function which leads to braking and steering actions by a vehicle lateral controller that brings the vehicle back to a state in which the driver can regain control over the vehicle.

METHODS

The new integrated vehicle safety functions that are currently under development actively mitigate the severity of embankment and guardrail accidents during which the driver unintentionally worsens the situation with false lateral (Steering) and longitudinal (Brake and Gas pedal) control inputs to the vehicle. Existing safety functions like Electronic Stability Control (ESC) might even increase the severity of the situation in case of a panic reaction of the driver. The guardrail and embankment controllers presented in this paper use both longitudinal and lateral control inputs to stabilize and maneuver the vehicle to a safe state. Here, the safe state is defined by the reference trajectory which in case of the guardrail controller is defined as close to and parallel

to the guardrail. The embankment controller's main task is the reduction of the rollover risk by stabilizing the vehicle's dynamics.

Vehicle Lateral Controller for Guardrail Accidents

The guardrail controller stabilizes and keeps the vehicle at a certain lateral distance to the guardrail after a guardrail collision is detected. The states to be controlled are sideslip angle β, yaw rate $\dot{\psi}$, deviation in yaw angle $\Delta\psi$ and deviation in lateral distance Δy. As cameras and other environmental sensors might not deliver trustable information after a collision, the curvature κ_{ref} of the road for the next 80 – 100 m is continuously stored and referred to when a crash impulse is detected. The deviation in yaw angle $\Delta\psi$ and lateral distance Δy is estimated using two fixed coordinate trajectory models, the vehicle trajectory model (VTM) and the virtual vehicle trajectory model (VVTM). The VTM calculates an estimated trajectory of the vehicle based on kinematic equations, while the VVTM acts as a reference trajectory and takes additionally the stored curvature κ_{ref} into account. The controller itself is based on a linear single track model (Rajamani 2006) which can be given in state space representation, Eqs. (1-2).

$$\dot{X} = A(v)X + BU \tag{1}$$

$$\begin{bmatrix} \dot{\beta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} -\dfrac{C_f + C_r}{mv} & \dfrac{-C_f l_f + C_r l_r}{mv^2} - 1 \\ \dfrac{C_r l_r - C_f l_f}{J_z} & -\dfrac{C_f l_f^2 + C_r l_r^2}{J_z} \end{bmatrix} \cdot \begin{bmatrix} \beta \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} \dfrac{C_f}{mv} \\ \dfrac{C_f l_f}{J_z} \end{bmatrix} \cdot \delta \tag{2}$$

$C_{f/r}$ are the tire cornering stiffness on the front and rear axle, m denotes the overall vehicle mass, v the vehicle velocity, $l_{f/r}$ are the distances of the front/rear axle to the vehicle's center of gravity, J_z is the moment of inertia and δ is the steering wheel angle. The model is adapted to suit the needs of a lateral controller. The yaw moment M_z is included as a second input to the model which results after some modifications and approximations in the adapted single track model, Eq. (3).

$$\begin{bmatrix} \dot{\beta} \\ \ddot{\psi} \\ \Delta\dot{\psi} \\ \Delta\dot{y} \end{bmatrix} = \begin{bmatrix} -\dfrac{C_f + C_r}{mv} & \dfrac{-C_f l_f + C_r l_r}{mv^2} - 1 & 0 & 0 \\ \dfrac{C_r l_r - C_f l_f}{J_z} & -\dfrac{C_f l_f^2 + C_r l_r^2}{J_z} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ v & 0 & -v & 0 \end{bmatrix} \cdot \begin{bmatrix} \beta \\ \dot{\psi} \\ \Delta\psi \\ \Delta y \end{bmatrix} + \begin{bmatrix} \dfrac{C_f}{mv} & 0 \\ \dfrac{C_f l_f}{J_z} & \dfrac{1}{J_z} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \delta \\ M_z \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ v \\ 0 \end{bmatrix} \kappa_{ref} \tag{3}$$

The reference curvature κ_{ref} is added as a disturbance to the model. The objective of the lateral controller is to bring the vehicle to stability, i.e. $\beta \to 0, \Delta\psi \to 0, \Delta y \to 0$, by applying active steering and active braking to the vehicle. The controller is designed as a Linear Quadratic Regulator (LQR) controller wherein the states are fed back to the input with a suitable gain feedback matrix $U = -K_c X$ (Lewis 1998). The feedback matrix K_c is calculated by,

$$K_c = R^{-1} B^T P, \tag{4}$$

wherein P is calculated by solving the algebraic Riccati equation,

$$A^T P + PA - BPR^{-1}B^T P + Q = 0. \tag{5}$$

The matrices Q and R are weighting matrices between transient response and control effort. Larger Q causes the states decay faster to zero while larger R implies less control effort, e.g. less steering and/or braking. An approximate estimation method for Q and R is given in (Körtum et. al. 1993). The outputs of the LQR controller δ_{LQR} and $M_{z,LQR}$ are fed into a steer and brake controller respectively to convert steer angle to steer

torque and yaw moment to brake pressure. The steer torque is applied as an assisting torque to the steering wheel to support the driver while the brake pressure is used for wheel selective braking on the front axle to generate the required yaw moment. The complete controller concept is shown in Figure 1.

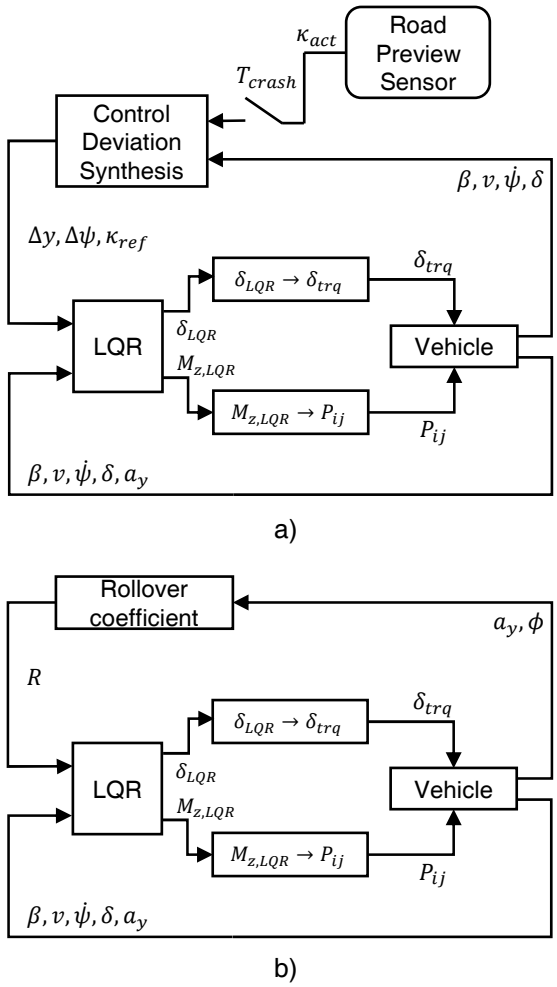

Figure1. a) Flowchart of the lateral guardrail controller. b) Flowchart of the lateral embankment controller.

Vehicle Lateral Controller for Embankment Accidents

The controller developed for embankment situations adopts the LQR approach for the design of the controller. Similar to the guardrail situation a triggering signal for the activation of the controller is needed, which indicates the vehicle is running into an embankment. This can be achieved by using inertial or environmental sensor based algorithms. The calculation of a rollover coefficient is used for the purpose of this work, Eq. (6). It is defined as,

$$R = \frac{F_R - F_L}{F_R + F_L} \qquad (6).$$

The value of R is calculated accordingly to the changes in the normal loads on the wheels on the front axle. For example, if the right wheel lifts off, which is likely to happen in an embankment to the left side, the whole load is on the left wheel($F_R = 0, R = -1$). As the normal loads can usually not directly be obtained from sensors, the calculation of R is approximated as given in Eq. (7), (Imine 2007).

$$R \cong \frac{2(h+h_R)a_y}{Tg} + 2\frac{h}{T}\phi \qquad (7).$$

h is the height of the center of gravity (CoG) of the sprung mass over the vehicle's roll centre, h_R is the height of the roll axis, T is the track width and ϕ is the roll angle. A more general approach of the kinematic single track model is used for the concept of the embankment controller as trajectory planning is not implemented in the current version, Eq. (8).

$$\begin{bmatrix} \dot{\beta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} -\frac{C_f + C_r}{mv} & \frac{-C_f l_f + C_r l_r}{mv^2} - 1 \\ \frac{C_r l_r - C_f l_f}{J_z} & -\frac{C_r {l_r}^2 + C_f {l_f}^2}{J_z} \end{bmatrix} \cdot \begin{bmatrix} \beta \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} \frac{C_f}{mv} & 0 \\ \frac{C_f l_f}{J_z} & \frac{1}{J_z} \end{bmatrix} \cdot \begin{bmatrix} \delta \\ M_z \end{bmatrix} \qquad (8).$$

The steering angle δ and the yaw moment M_z calculated by the model act as inputs to the controller for the stabilization of the vehicle and the reduction of the rollover risk. The calculation of the feedback matrix K_C and the matrix P is done accordingly to the guardrail controller as the controller tries to reduce the states β and $\dot{\psi}$ to a minimum.

RESULTS

Simulated test scenarios have been carried out in IPG CarMaker® to test the vehicle lateral controllers for guardrail and embankment accidents. The results of the tests concerning the guardrail controller are compared to results obtained by an ESC system and the simulated IPG Driver™ as guardrail accidents might also cause action by an ESC system due to high yaw rates induced by the crash impulse from the guardrail. Figure 2 shows a situation in which the vehicle left the road while it was driving through a curve and crashed into a guardrail on the right side of the road.

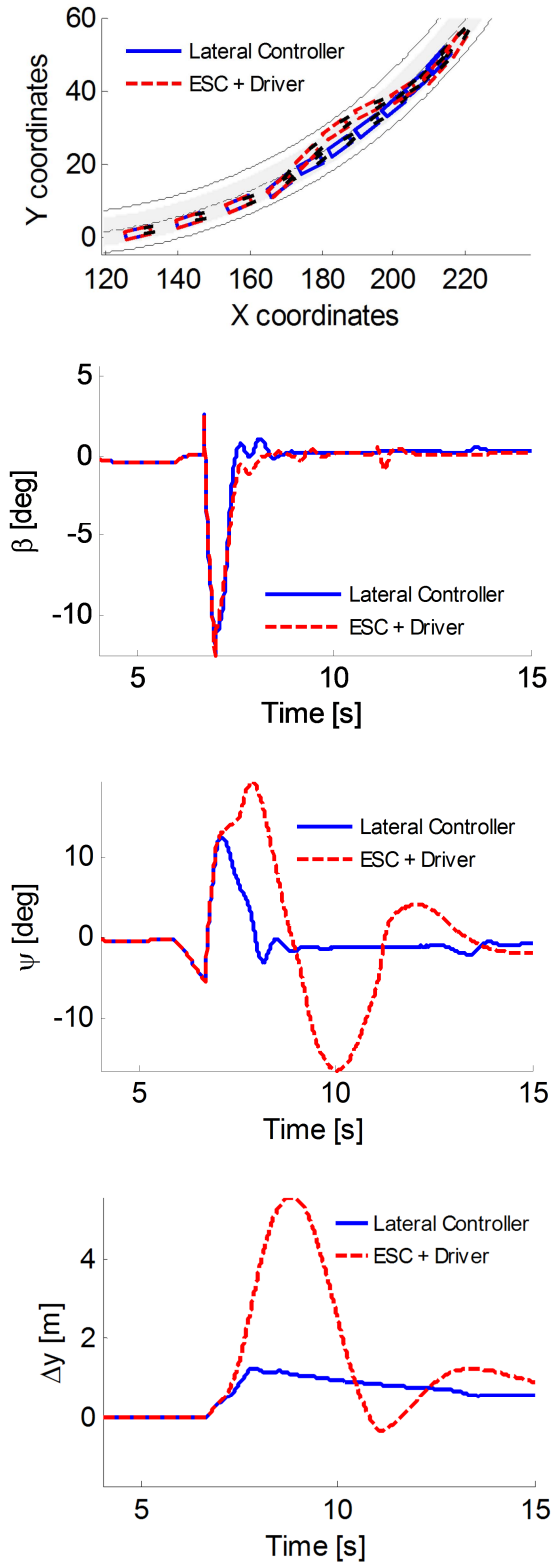

Figure2. Lateral Guardrail Controller, Situation 1: Sideslip angle β, yaw angle ψ and lateral distance Δy.

The initial velocity at the time of the crash was 70 km/h and the impact angle with the guardrail was 5.5°. It can be seen that the vehicle that is only equipped with an ESC system has a secondary impact on the other side of the road (146, 42) while the vehicle equipped with the lateral guardrail controller can be stabilized after the primary collision (139, 12). The sideslip angle and the yaw angle are also reduced faster to a minimum by the lateral guardrail controller as by ESC. Also the lateral distance to the guardrail is well under control as the vehicle stays in the safe area of 0.5 m next to the guardrail. The situation depicted in Figure 3 shows similar results.

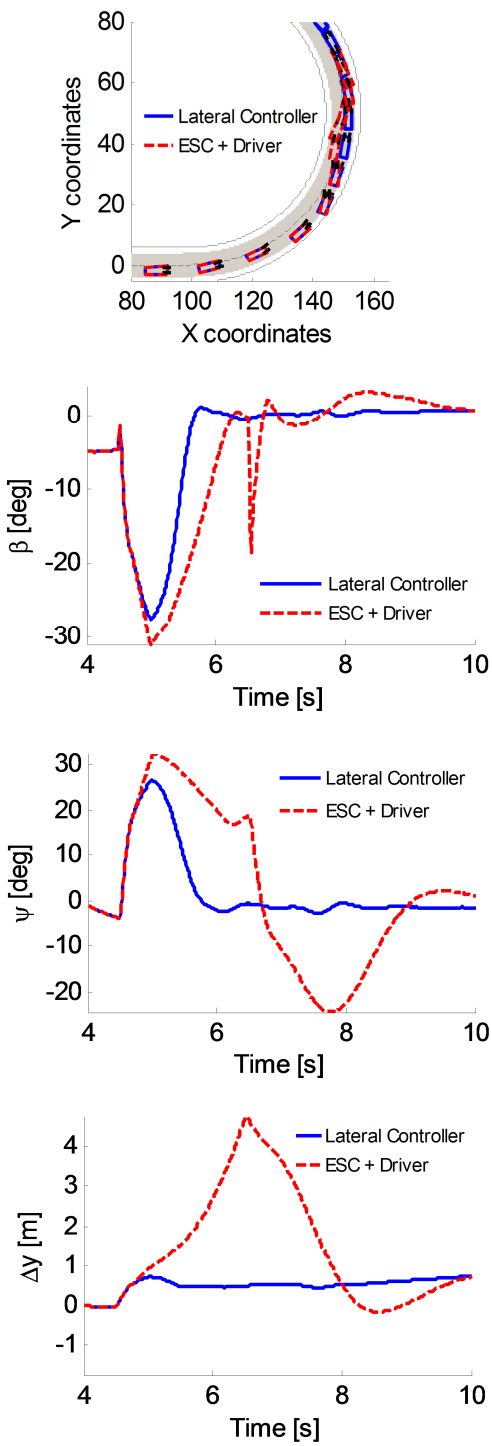

Figure3. Lateral Guardrail Controller, Situation 2: Sideslip angle β, yaw angle ψ and lateral distance Δy.

The driver of the vehicle only equipped with ESC is not able to keep the vehicle under control after the primary collision (166, 11) with 83 km/h and an impact angle of 4.2°, while the lateral controller keeps the vehicle within the driving lane. Also the yaw angle and side slip angle are reduced to a minimum within 1 s after the impact.
For the test of the embankment controller several downward embankments with an angle of 27° to 39° degree were created in CarMaker®, which represent the range of the standard embankments on German highways. The driving maneuver was constructed in a way that the driver wants to steer back onto the road after the vehicle went off the road and entered the embankment. This behavior is likely to cause a rollover as the lateral forces on the vehicle increase due to the embankment angle. Figure 4 shows a situation wherein the vehicle entered a 27° embankment while driving with 210 km/h.

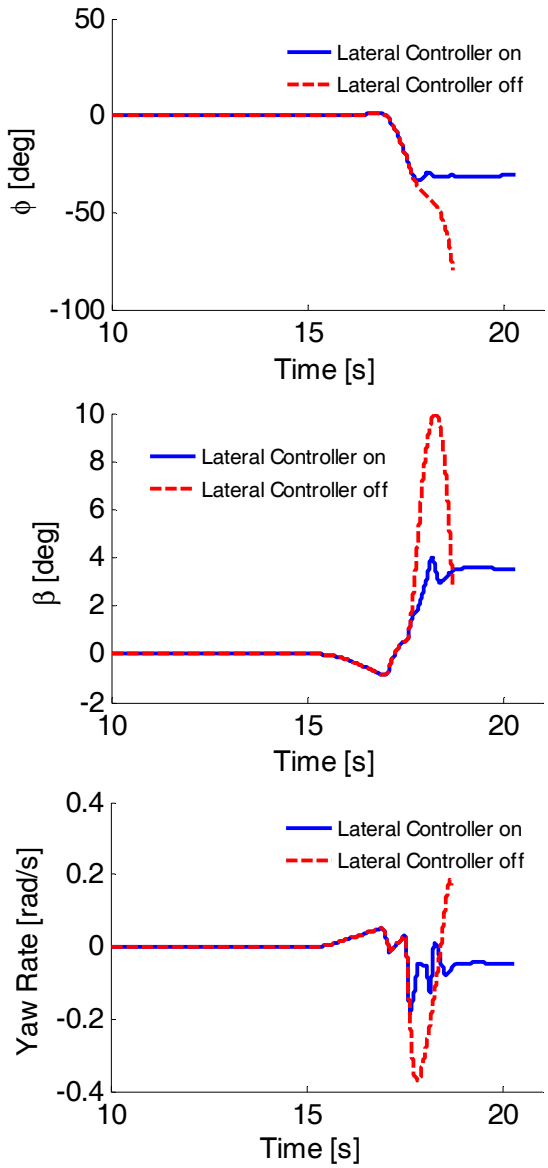

Figure4. Embankment Controller, Situation 1: Roll angle ϕ, sideslip angle β and yaw rate $\dot{\psi}$.

Here, the lateral controller is able to prevent the rollover while the roll angle of the uncontrolled vehicle increases until the simulation stops, around 80°. The same result is achieved for an embankment of 39° at 100 km/h as it can be seen in Figure 5.

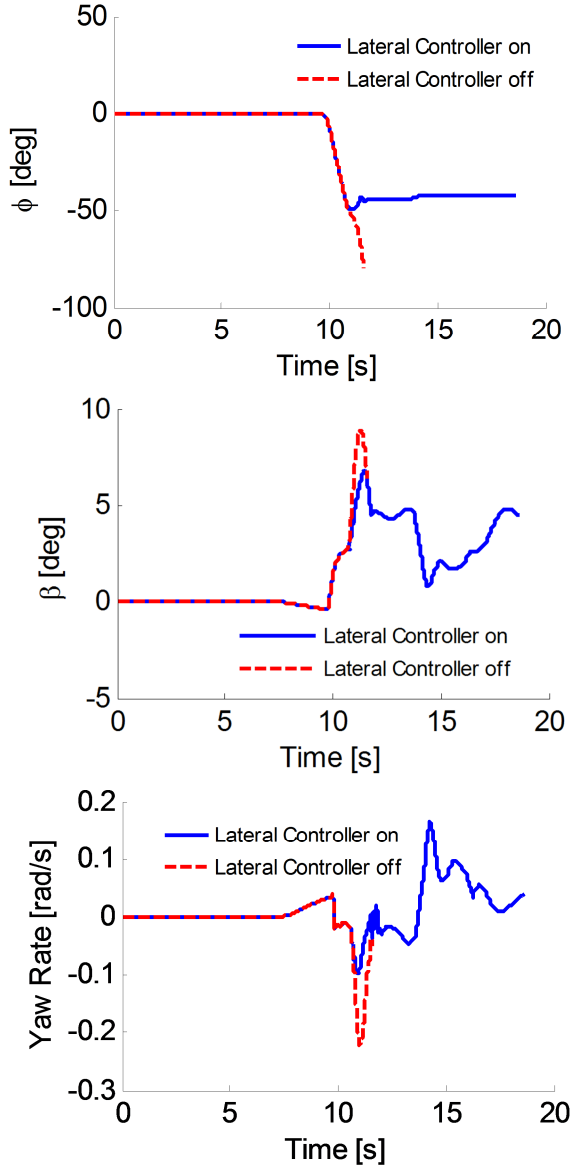

Figure5. Embankment Controller, Situation 2: Roll angle ϕ, sideslip angle β and yaw rate $\dot{\psi}$.

From the further depicted results represented by the side slip angle and the yaw rate of the vehicle, it is shown that the driver's inputs to the vehicle worsen the stability of the vehicle and lead to a rollover. However, if the controller is active then the outputs of the controller act opposite to the driver and prevent the rollover by stabilizing the vehicle.

DISCUSSION AND CONCLUSION

The analysis of several accident databases shows that accidents involving a guardrail or an embankment have a high relevance in the area of vehicle safety technologies. The developed vehicle lateral controllers for these two situations show that they have the potential to reduce the severity of such accidents by braking and steering interventions to the vehicle. Although the first simulation results are very promising, deeper analysis of the interaction between the vehicle and the driver in these situations has to be conducted. Governmental as well as functional safety requirements limit the maximum torque that can be superimposed onto the steering

wheel. This requires real world tests of the lateral controllers to understand the driver reaction to the applied torque. The introduction of an electronic steering and therefore the decoupling of steering wheel and steering axle might be a necessary step towards this topic. It is also necessary to investigate how a driving stability program like ESC interacts with the developed controllers. Usually, ESC tries to follow the desired driving direction of the driver, which in the discussed road departure situations might not always be the right choice. A discussion is needed to establish the new lateral controllers into the existing safety architecture. A highly automated driving level is needed in the mentioned guardrail and embankment situations as they are likely to be uncontrollable by the driver and today's safety functions alone.

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THE AEB SYSTEM WITH ACTIVE AND PASSIVE SAFETY INTEGRATION FOR REDUCING OCCUPANTS' INJURIES IN HIGH-VELOCITY REGION

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ABSTRACT

AEB(Autonomous Emergency Braking) is a representative safety system that assists a driver to avoid forward collision or mitigate crash velocity resulting in reduction of occupant's injury risk using ADAS sensor. This paper focuses on establishing appropriate PSB activation time in order to minimize occupant forward movement and head & neck injuries in the event of collision when it is unavoidable in the aspect of active and passive safety system integration. And also, it is the other goal that decreases the collision velocity by applying more efficient pre-braking profile. For this, AEB test is performed with H-3 5% & 50% human dummy seated in the passenger side. The test vehicle is equipped with Lidar and camera sensor fusion AEB system, PSB(Pre-Safety seatBelt) and a premium ESC module. From this study, the last time to activate PSB considering occupant's injury and the improved pre-brake profile beneficial to collision velocity reduction and occupant's behavior were verified.

INTRODUCTION

AEB(Autonomous Emergency Braking) is a active safety system that can make a vehicle to avoid collision or mitigate the damage by urgently reducing velocity with the informations obtained using ADAS(Advanced Driver Assist System) sensors such as camera or radar. Camera and radar fusion as shown in ***Figure1*** is typically applied to AEB system due to the system's reliablity in recognition performance and it is expected that single sensor is increaingly adopted to the system for general use.

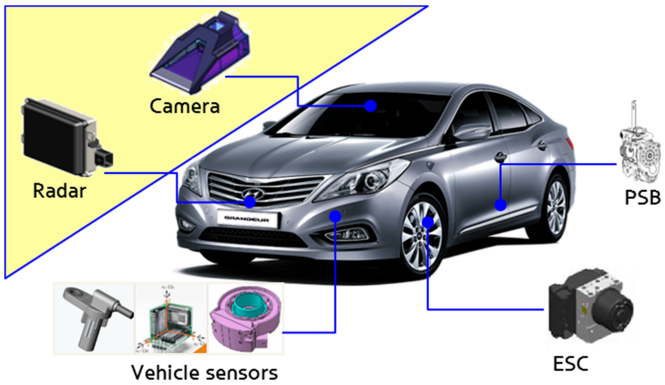


Figure1. Typical AEB system configuration.

From the Thatcham's research report[1] in ***Figure2*** , if the system is applied to the market satisfying the fitmet rate Euro NCAP suggets, it is predicted that the fatalities will be decreased by the 50% of current number. Due to this benefit of the system, Euro NCAP is planning to add AEB-VRU(AEB- Vulnerable Road Users) test to current assesment program with AEB-City/Urban in 2016 and IIHS already evaluate the system for TSP+ requirement in their test protocol.NHTSA is preparing for CIB/DBS tests. AEB system become a most important active safety sytem such as airbag became a essential passive one now after it was firstly adopted and then have made a great contribution to reducing fatalities.

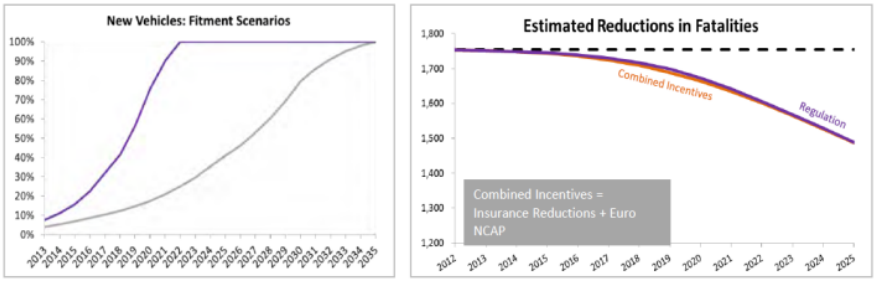


Figure2. Expected reduction of fatalities with the fitment of Euro NCAP AEB.

Now, Euro NCAP AEB test aims that collision is avoided under the relative velocity of 50kph, and IIHS performs their AEB test by 40kph.The AEB system in current test condition is more efficient in reducing occupans' neck injuries in target vehicle by crash avoidance or mitigation in low speed than the one in host vehicle. But it is more important to maximize it's efficiency in high velocity region in order to save more lives and reduce occupants' severe injury, because the relative risk increases rapidly in high velocity region over 60kph resulting in twice the risk per 5kph as shown in ***Figure3.*** And also the increase of head and neck injuries should be seiously considered when conventional driver or passenger airbags are deployed just after occupant's forward movement is produced by AEB system activation in high velocity crash from the viewpoint of passive and active safety system integration.

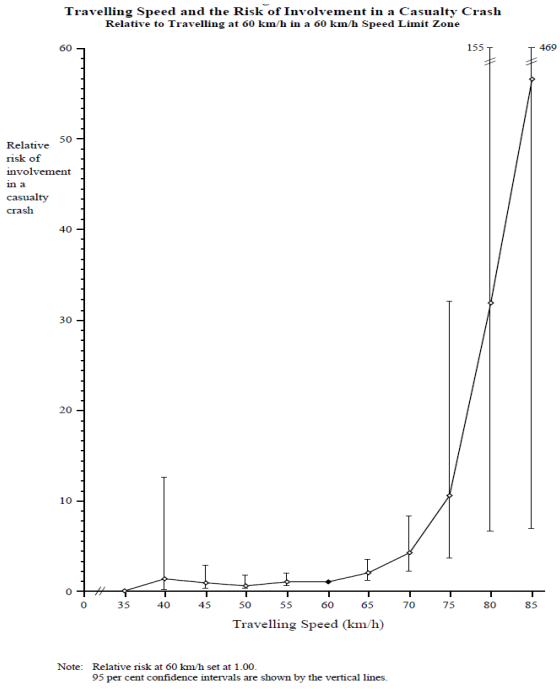


Figure3. Traveling speed and the risk of involvement in a casualty crash.

The main purpose of this paper is to improve both AEB and passive safety system to minimize the occupants' severe injury in the high velocity crash when the collision is unavoidble. The situation is assumed that a driver is in distraction, a vehicle is running in a sigle lane, there are another on-coming or rear lateral vehicles, etc. And the condition of the AEB activation is limited in the range of yaw rate so that the stability of vehiclecan be ensured. From this research, the appripriate PSB(Pre-Safety seatBelt) activation time was founded for reducing occupant's forward motion that affects head&neck injuries when AEB is working. Also, the reduction of crash speed and passenger behaviors are respectively compared according to different braking profile.

THE AEB SYSTEM IMPREMENTATION WITH ACTIVE AND PASSIVE SAFETY INTEGRATION

The Relation between active and passive safety system regarding AEB

AEB system primarilly helps decreasing occupants' injuries because of speed reduction in high velocity region. On the contrary, the increase of injury can be also accompanied due to the combination of occupants' faster behavior and airbag's high pressure deployment when AEB activated and then vehicle proceeded to crash, which is similar with OOP(Out of Position) situation. And if the vehicle's pitching motion is added, the injury can be amplified. Conventional airbags are not designed to cope with this situation, even though they satisfy LRD(Low Lisk Deployment) regulation in the US market. Some kinds of those airbags may give more harmful effect to occupants with their specific deployment mechanism.So, the tests and analisys were performed mainly to minimize the effect to occupants from AEB system and to reduce collision velocity more.

AEB System Configuration and Behavior Measurement Test of Dummy

In this tests, human dummy's behavior was mesured when AEB is activated. The test vehicle consists of Camera and Lidar sensor fusion AEB system, a ESC module of premium level and PSB module. When high speed test is conducted, DGPS device replaces the Lidar sensor because or it's short detecting range.Hybrid-3 5% and 50% dummies were used considering the coditions of US-NCAP frontal and Euro NCAP offset crash test mode. There are much difference on the behavior between dummy and human body when the acceleration under 1g occurs. THOR dummy would be better for this test, if possible. Thus, the timing and relative motion of dummy were focused on when AEB is working with different parameters. Dummy is seated in passenger seat because the motion of dummy in driver seat is smaller with the driver grabing steering wheel in the real situation. The PAB(Passenger Air Bag) deployment area is marked with vertical line and the movement is visually verified by video records as shown in ***Figure4***.

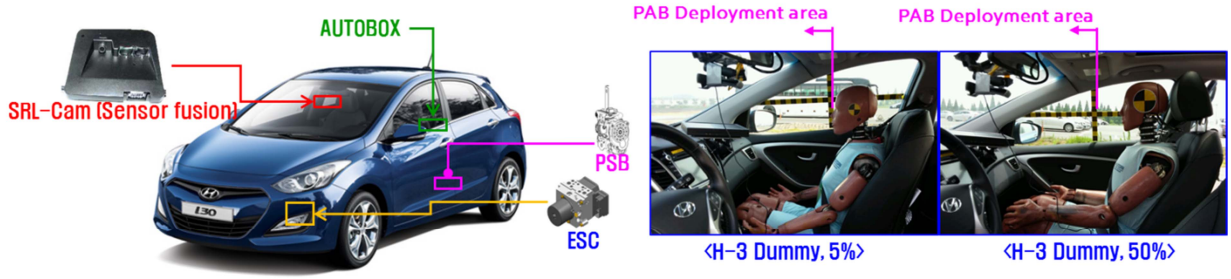


Figure4. System configuration, dummy seating and PAB deployment area.

The PSB Activation Condition for Reducing Occupants' injuries

<u>The Occupants' Injuries from Air bag Deployment</u> In the US NCAP and Euro NCAP crash test protocol, the test is carried out in the constant speed, 56kph and 64kph, respectively. Thus, the dummies are seated statically and there's no relative behavior of dummies with vehicle to the blink of crash. However, the deceleration of vehicle by 1g is generated by emergency braking in case of the AEB equipped one when the collision is expected, and therefore, dummy can get the relative acceleration and moves forward in the vehicle. Also, the vehicle can get pitching motion by the braking and if it collide with frontal car in this situation, the airbag can directly impact the passenger's head and chest causing more amplified effect as shown in ***Figure5***. Even if there's no direct impact due to the small airbag size or a passenger seated in the rear position on the seat track(i.e. H-3 50%), the head and neck injury can be increased by the combination of pitching motion and accelerated head loading on airbag cushion. Especially, PAB modules for US market tend to be designed bigger and closer to the passenger in order to satisfy H-3 50% unbelted frontal test mode. In this case, the distance between airbag deployment region and H-3 5% dummy becomes closer and the bad effect on the passenger's injury also increases.

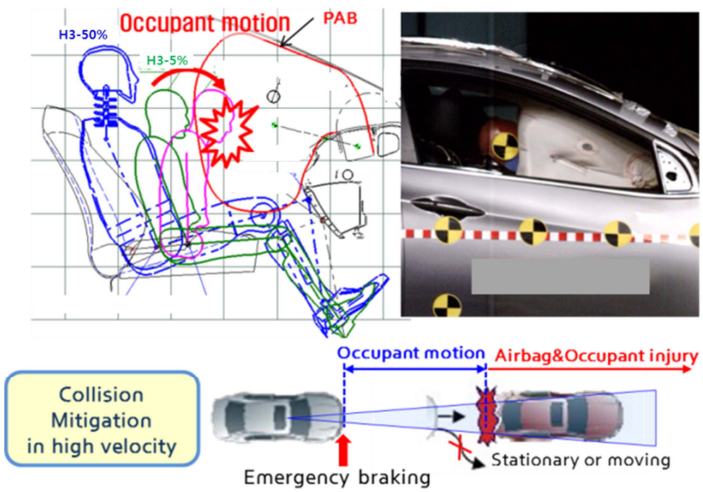


Figure5. AEB activation and the mechanism of head & neck injuries generation.

<u>The Dummy's Behavioral Characteristic according to PSB Activation Time</u> The tests are carried out to study the dummy's behavioral characteristic and to find the last PSB full retraction time so that the dummy's forward motion can be minimized. The test conditions are vehicle's running speed of 85kph and collision velocity of 50kph against stationary target. Firstly, dummy's behaviors were compared in cases of no retraction, the same PSB activation time with full brake by AEB. From the results, dummy was not effectively restrained due to the PSB actuator delay and increased load by relative acceleration. The PSB trigger time and PSB belt tension graph shows this in ***Figure6.*** Also, the time interval between full brake and maximum forward movement of dummy was measured by video and travel calculation. In the next tests, the PSB trigger time was advanced by the time gap considering the maximum forward movement time expressed as below:

Maximum forward movement time

= Signal transfer time (CAN delay) + PSB actuation delay + Dummy's behavioral moving time (1).

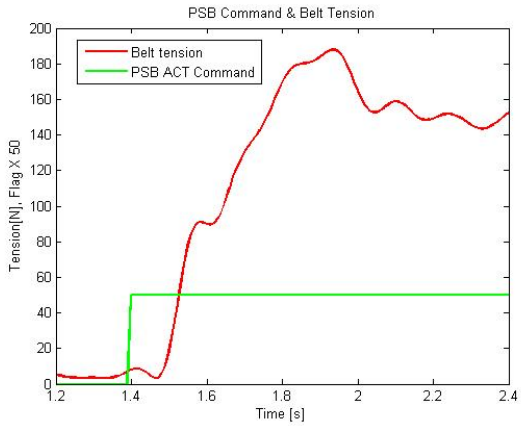
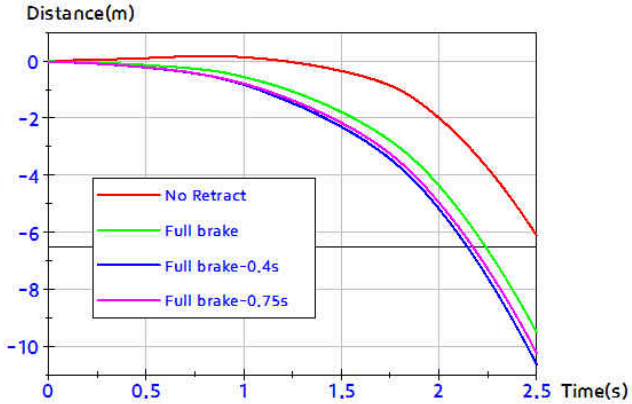


Figure6. The belt tension of PSB in Shoulder and Maximum forward movement time.

PSB actuation delay is defined that the time from it's trigger to reaching to maximum load of belt tension in static test and was measure 250ms. Dummy's behavioral moving time was 400ms, which is almost the same with the belt load reached maximum value shown in ***Figure6.*** Thus, PSB activation time was set 400ms advanced to full brake time. Additionally, the AEB tests were done in conditions of varying PSB activation time by 750ms prior to full brake, same time with pre-brake and 300ms prior to pre-brake.

From the test results in ***Figure7***, there's not much differences on dummy's forward movement when PSB is triggered before the 400ms prior to full brake. Dummy's head moves forward by 120mm with no PSB retraction, whereas, it moves about 50mm and 30mm with the trigger time of full brake and 400ms in-advance test case, respectively. If PSB is activated in the same time of full brake, dummy's head invades the PAB deployment area and then it can additionally goes further by crash impulse before airbag is fully deployed. It can be clearly expected that airbag impacts occupant's head resulting in head & neck injury increase. In case of real crash in the field, human's head would have more forward motion.

(a) Position of dummy at the moment of collision in different PSB activation time(video capture).



(b) Relative displacement of dummy's head from the AEB activation time.

Figure7. Dummy's behavior according to PSB activation time.

Figure8 shows the belt tensions in different cases, such as no retraction, various PSB activation time and pre-bre-brake profile(explained in next section).All of the belt load reach their peak almost same time which is caused by full brake, not by the first trigger time. It would be effective to reduce the forward motion of dummy befor the belt load rise up to it's peak.

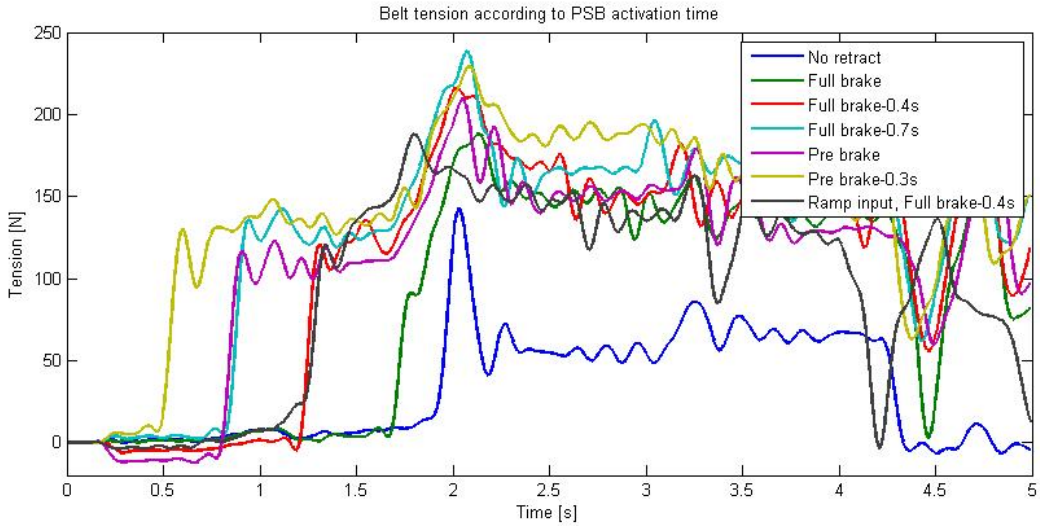


Figure8. Seatbelt tension with various PSB activation time.

It can be concluded that PSB can efficiently help preventing PAB from giving direct impact to occupant's head or reducing head & neck injury if it is triggered at least 0.4s before full brake is engaged. This can be applied to all range of vehicle velocity because there're similar dummy's behavioral characteristics according to different vehicle speed with the same amount of full brake.

The AEB Braking Profile for Reducing collision velocity

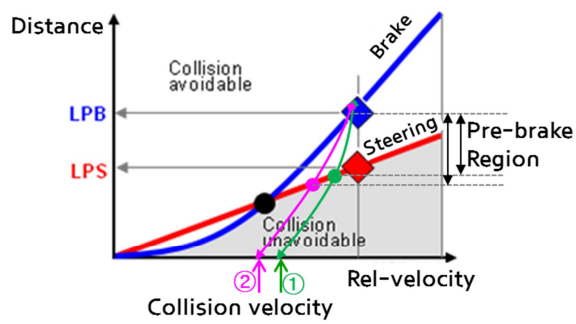
<u>AEB Control Logic</u> LPB(Last Point to Brake) and LPS(Last Point to Steer) are the time or relative distance to avoid collision about forward target vehicle by emergency braking and by steering control, respectively. Those physical quantities are illustrated in ***Figure9 (a)*** and the equations are Eqs. (2~4). Eq. (4) stands for the TTC at each collision avoidable distance and AEB system transmits the command signals to ESC following the control logic in ***Figure9 (b).***

As shown in ***Figure10,*** the collision avoidable distance by braking is shorter than the one by steering control in low velocity region and vice versa in high velocity region. The AEB control login in the test uses only full breke in low speed. In high speed, pre-brake is applied from LPB to LPS and, full brake after passing through LPS.This is for reducing frequent AEB system activation in the field by making the maximum braking at the final moment of collision avoidance by lateral control.

$$d_{brake} = -\frac{v_{rel}^2}{2a_x} \qquad (2).$$

$$d_{steer} = -v_{rel}\sqrt{\frac{2s_y}{a_y}} \tag{3}$$

$$d_{brake} = -\frac{v_{rel}^2}{2a_x} \Rightarrow t_{LPB} = \frac{d_{brake}}{-v_{rel}} = -\frac{v_{rel}}{2\mu g}$$
$$d_{steer} = -v_{rel}\sqrt{\frac{2s_y}{a_y}} \Rightarrow t_{LPS} = \frac{d_{steer}}{-v_{rel}} = \sqrt{\frac{2s_y}{\mu g}} \tag{4}$$



Velocity region	Collision level	Brake profile	
Low	Avoidance	TTC < t_{LPB}	Full brake
High	Mitigation	t_{LPS}< TTC < t_{LPB}	Pre brake
		TTC < t_{LPB}	Full brake

(a)LPB, LPS graph *(b) Control logic*

Figure9. Braking time and AEB Control logic

<u>Collision Velocity Reduction According to Pre-braking Profile</u> Generally, pre-brake with low deceleration is used in AEB system in order to raise the initial cylinder pressure of ESC and to make it easy for driver to avoid front obstacles by string control as the collision risk increases after ADAS sensors detect them. After that, full brake is engaged at the TTC condition when collision is unavoidable. With this scenario, the collision speed is mitigated in high velocity region. In this study, two kind of pre-brake profiles are applied without the change of pre and full braking time. One is step input with0.2g and the other is ramp input from 0g to 1g which is expressed by Eq.(5):

$$A_{brake} = \frac{1}{t_{LPS} - t_{LPB}}(t - t_{LPB}) \tag{5}$$

It seems to be obvious that the crash speed would decrease and the braking distance become shorter in the case of ramp input as shown in ***Figure11.***

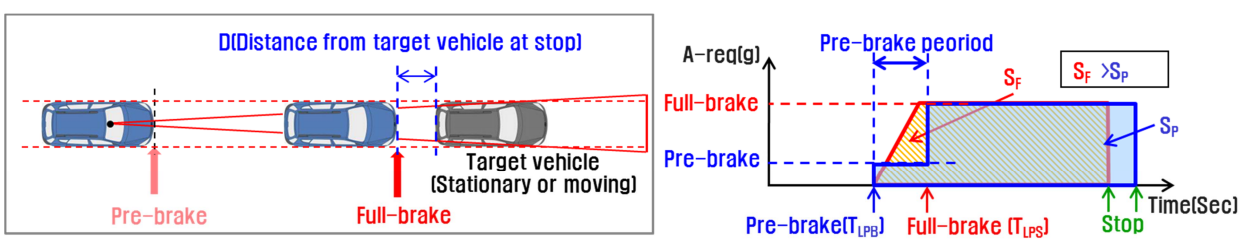


Figure11. Braking point and the concept of braking profile.

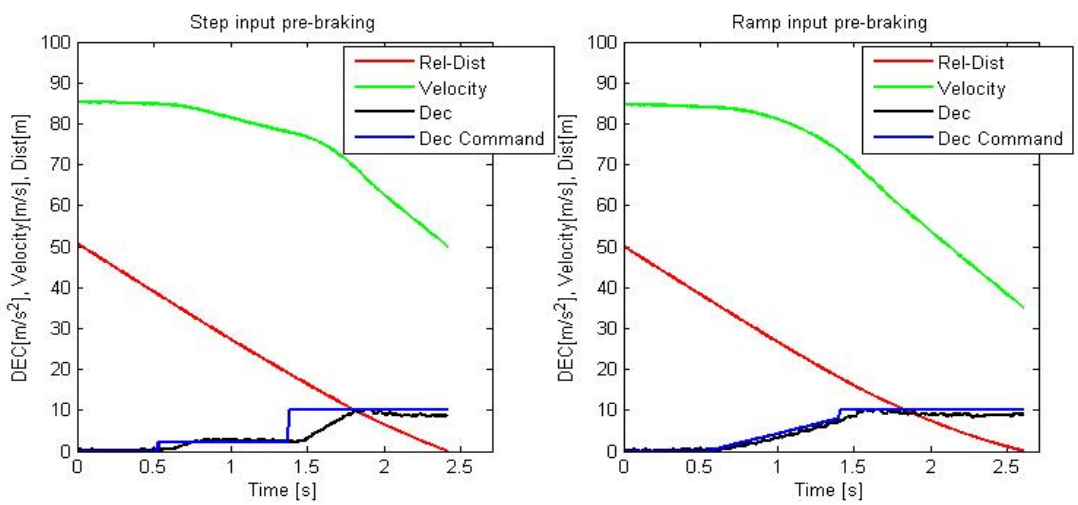
In this tests, the DGPS device is used for mesuring distance to crash point becase of the short detecting rage of Lidar sensor. With the same pre-braking time, the crash speed of ramp input decreases by 15kph in comparison to the step input case as shown in ***Table1***.When the crash occurs in those two conditions, whether PAB is deployed or not can be changed according to collision velocity. And the faster the the initial velocity is, the more the reduction of velocity beome because pre-brake time lasts longer. If this ramp input braking profile is applied to AEB logic, the collision avoidable vehicle speed can be raised maintaing the marketability same as step input. And also the probability of quality problem like frequent or unnecessary emergency braking activation can be reduced because the initial braking time can be set to later time if the collision speed is tuned same each other. This priciple is explained well in ***Figure9(a)*** with the line number ① and ②. In the ② case with ramp input, the reduction of velocuty increase between LPB and LPS, and finally drash speed goes down.

Table1.

Collision velocity according to pre-braking profile.

Braking profile	Initial velocity	Collision velocity	Reduction of crash velocity
Pre-brake 0.2g	85kph	50kph	35kph
Ramp input	85kph	35kph	50kph

Pre-fill and pre-brake input play a roll to make the cylinder pressure of ESC raise faster to full brake level. There's about 450ms delay of full deceleration after the moment when 1g step input command is transferred to ESC, whereas the vehicle deceleration follows the ramp input and full brake signals well in ***Figure12***. This mechnism mainly contributes to decreasing more collision velocity with ramp input. If ADAS sensors and communication performance in vehicle is improved in the future, the collision velocity would be minimized by using feedbak control.



(a) Pre brake : 0.2g Step input ***(b) Pre brake : Ramp input***

Figure12. Vehicle behavior according to pre-braking profile.

Head Acceleration According to Pre-braking Profile The relative acceleration at crash moment affects the occupant's head & neck injuries. In the NCAP frontal crash test, dummy has almost zero acceleration when the test vehicle impacts the barrier, but it gets relative acceleration at the moment with the AEB activation, which varies depending on braking performance and control level. When ramp type of pre-braking profile is used, the rise rate of acceleration and it's peak value are small compared with step input as verified in ***Figure13***. The passenger can also has soft feeling with small jerk. Ramp input signal can be expected to decrease occupant's head & neck injuries.

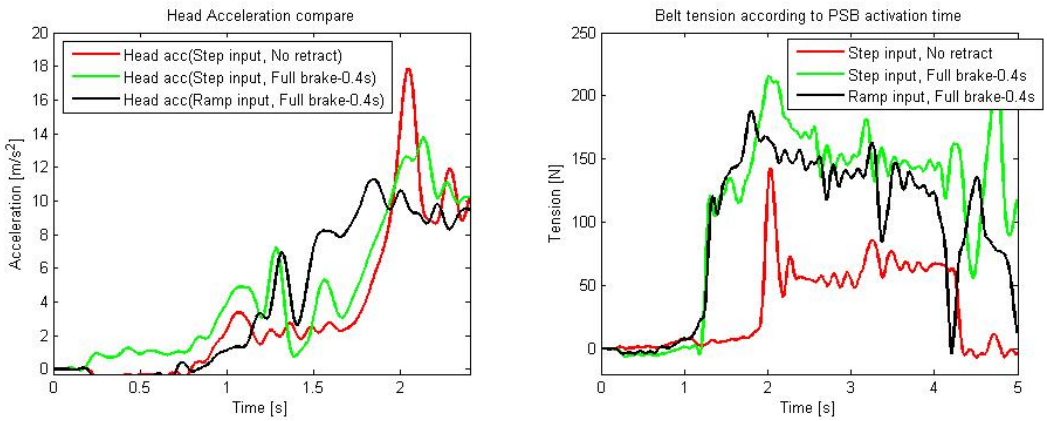


Figure13. Head acceleration and belt tension according t pre-braking profile.

CONCLUSIONS

In the viewpoint of active and passive safety integration, this study aims to find appropriate PSB activation time so that the bad effect by AEB system can be removed and to reduce the final crash speed after AEB is activated by enhance the pre-braking profile. As a result, it was found out that dummy's forward motion is sufficiently decreased when PSB is activated at least 0.4s before full brake time, which can be changed by PSB and ESC performances. As well as this, the pre-brake profile of ramp input is more efficient in reducing crash speed and head's acceleration rather than constant one.

H-3 dummies used in this research have much difference with human body in behavioral aspects. The same tests targeting human or THOR dummy should be carried out to get more accurate data. And the research about various braking profile and feedback control logic to improve AEB performance considering occupants' injuries and marketability is needed in the future.

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Evaluation of Occupant Protection Systems:
FROM A PREVENTIVE TO A PRE-IMPACTING RESTRAINT SYSTEM

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ABSTRACT

The safety of modern vehicles has reached such a high standard that experts view the remaining potential for improvement of conventional restraint systems as nothing more than minimal. However the use of information gathered during the pre-crash phase added to the combination of preventive and conventional restraint systems can reveal additional potential.
One example of this is the reversible pretensioner of the PRE-SAFE® system, launched in 2002, which can hold occupants in their position shortly before a potential collision and thus reduce forward displacement to offer improved protection in an accident.
This approach was further developed with the introduction of PRE-SAFE® Impulse, which debuts in the current S-Class of MJ 2013. PRE-SAFE® Impulse systems rapidly accelerate occupants at an early phase of the crash by moving them in the direction of the impact force so that the difference in kinetic energy between the vehicle and occupants can start to be reduced as early as possible. As a consequence the total energy does not have to be dissipated entirely during the crash itself, but is distributed over a minor initial impact and a major impact whose intensity is reduced accordingly.
The new PRE-SAFE® Impulse Side System, a pre-impacting restraint system, does not only applies this idea for side crash but brings the concept one step further. Previous measures for improving side impact protection were primarily implemented on the vehicle itself and did not directly influence the occupants prior to the crash. With PRE-SAFE® Impulse Side, a defined energy, is transferred to the occupant, who is set in motion already before the collision occurs. Therefore PRE-SAFE® Impulse Side is the very first of a new generation of pre-impacting restraint system whose field of action will be extended prior to the collision due to the integration of active and passive safety.
To this end, the PRE-SAFE® Impulse Side system uses a 360-degree sensor system, which permanently senses the car surroundings, to anticipate an unavoidable collision.
Using numerical simulation as well as sled and vehicle testing, relevant occupant loads have been shown to be reduced by 30 percent on average with the use of PRE-SAFE® Impulse Side.

INTRODUCTION

Due to improved structure, seat belts and airbags the safety level of modern vehicles has reached a very high standard. Even small cars offer an impressive degree of protection.
Further improvement of occupant protection, even implementing modern restraint systems such as adaptive airbags and switchable belt force, is only possible to a certain extent.

To date, occupant protection systems have only been actively deployed after the accident has started to transpire. The enhancement of driver assistant systems offer opportunities to reliably detect accidents in advance, the time window in which restraint systems can offer protection increases dramatically. This, in turn, leads to great potential for further improving occupant protection in a passenger car.

In the future Advanced Driver Assistance Systems will largely contribute to reduce the number of injured occupant by avoiding crashes or mitigating their consequences. However side crashes remain very challenging for sensors to detect. Indeed potential collision partners are often hidden and cannot be properly seen i.e. tracked by the car sensors until the collision is unavoidable. At least when our own car is standing on-board driver assistance systems are incapable of minimize the intensity of the accident or avoid the accident. In that case, the severity of the impact at the side of the vehicle is directly linked to the proactive measures undertaken by the colliding vehicle partner.

Nevertheless if restraint systems (passive safety) and driver assistance systems (active safety) taken individually cannot offers great improvement for side crash scenarios, the integral safety approach, combining both active and passive safety components in one system appears extremely promising.

In this paper a solution will be proposed that shows to what extent the pre-accident phase can be taken into account to prepare the occupant for a side collision impact.

OPERATIVE MECHANISMUS

Side Impact

Mechanisms of action in a side impact depend on the distance between occupant and vehicle structure as well as on the intrusion or contact speed of the vehicle structure to the occupant.

Compared to frontal impact there is less absorption way and time to protect the occupant in side impacts. There are only limited distance between the occupant and the struck side of the vehicle as well as short time between the beginning of the collision and the moment when the occupant is loaded by the impact of the door.

The vehicle's dimensional design usually limits the distance between the occupant and the vehicle structure. Potentials to reduce the intrusion velocity have been primarily achieved through structural measures. Present airbags for side protection are designed and dimensioned to be activated shortly after the beginning of the impact. Those conditions limit the performance of possible passive safety countermeasures.

Involving the occupant in the sequence of an accident event earlier or even prior to a collision has not been considered till now.

PRE-SAFE® Impulse

Today, occupant restraint systems are classified as reactive systems. The downside of these occupant protection systems is that they only take effect once the accident has already started. Occupants are then decelerated with a considerable time delay with respect to the initial collision sequence. Energy only begins to be dissipated once the

occupant has traveled a required distance within a specific time as a result of his or her forward excursion. In this time window, valuable deformation space has already been used to decelerate the vehicle but not the occupant.

The aim of PRE-SAFE® Impulse restraint systems is to couple the occupant as early as possible to the vehicle deceleration by distributing the total impact energy over a minor initial impact and a major impact whose intensity is reduced accordingly.

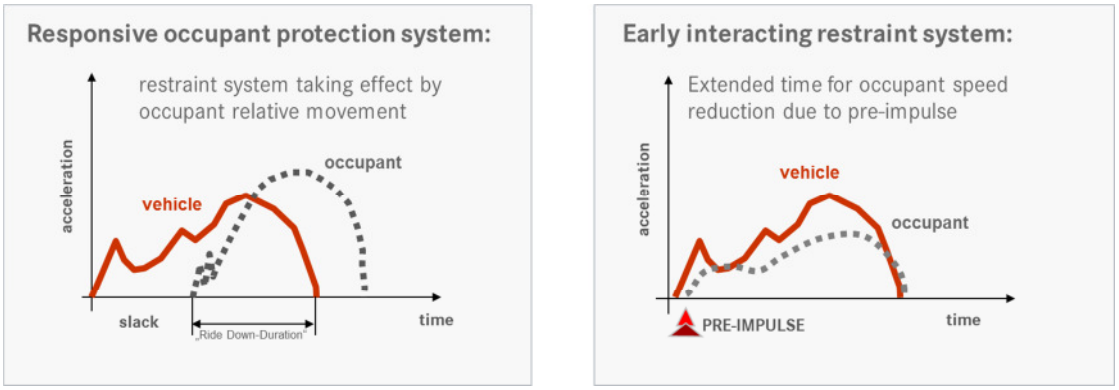

Figure 1: Comparison of responsive and early interacting occupant restraint system

Figure 1 shows a reactive and an early interacting restraint system. With an early interacting restraint system, the occupant is jolted in a very early phase of the accident, when the vehicle deceleration has not yet acted on him. The occupant perceives this as an acceleration impulse. This results in occupant deceleration, the occupant is briefly slower than the vehicle in which he is seated. The occupant is moved opposite the impact direction. The displacement path gained by the relative speed can be released again over the course of the accident via energy dissipation.

Such a restraint system influences the ride-down effect and occupant kinematics and can reduce the occupant load values via the longer deceleration period.

Assuming that the impact is known properly, the principle of reactivity can be augmented by actively moving the occupant in a defined direction. Prior to the impact occupants are not yet subjected to impact-specific inertial forces and can therefore be moved using little energy reaching comparable improvement with a lower pre-loading of the occupants (Figure 2).

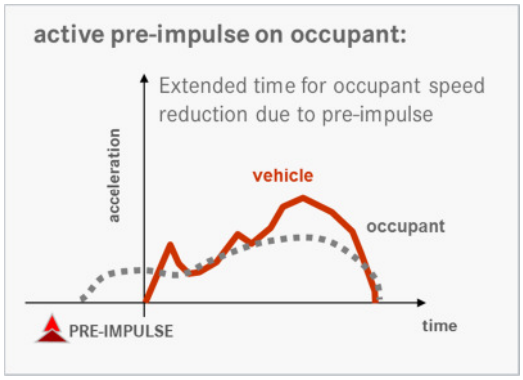

Figure 2: Active pre-impulse on occupant enable the change of velocity over the maximum of time

PRE-SAFE® IMPULSE SIDE - occupant protection system for side impacts

The PRE-SAFE® Impulse Side protection system demonstrates how a pre-impacting system could work. PRE-SAFE® Impulse Side is the very first of a new generation of pre-impacting restraint system whose field of action will be extended prior to the collision due to the integration of active and passive safety.

Occupant Impact as Operative Mechanism

At a precisely calculated time prior to the side impact, the occupant of a vehicle is laterally displaced by a movement of the backrest side bolster. This small impulse moves the occupant toward the center of the vehicle before the impact occurs.

Actively moving the occupant toward the center of the vehicle increases the distance between the upper body of the occupant and the door panel so that the side airbag can be safely and efficiently deployed.

The contact time between intruding structure and occupant also occurs later and therefore with reduced intrusion speed. In addition, the occupant is already moving at a certain speed in the direction of the impact. His/her relative velocity regarding to the intruding structure is smaller thus less kinetic energy has to be dissipated by the contact with the restraint system and/or the car structure.

PRE-SAFE® Impulse Side, like all other PRE-SAFE® systems, acts as an additional measure that does not replace the conventional restraint system, but enhance it.

PRE-SAFE® Impulse Side Actuator

The seat was equipped with a dynamic multi contour seat component. There, in the side bolster of the driver and passenger seat backrests, an air bladder is inserted that can be filled to improve lateral support during cornering.

To generate the impulse on the occupant, this air bladder was modified in terms of their size and filling characteristics so that they are strong enough to initiate the movement of the occupants toward the center of the vehicle. This process takes place within the seat without any damage and can therefore be repeated. The challenge with this setup is to create an upholstery concept, which on the one hand must allow sufficient movement, but on the other hand has to meet customer requirements in term of design and comfort.

Methods and Tools

The methodology for the assessment of the benefit of the PRE-SAFE® Impulse Side airbag is based on three tools: FEM crash simulation, sled tests and vehicle tests. In a first step FEM simulation was done to identify the optimal parameters of the airbag (pressure, geometry, volume) to reach the expected benefit. In static tests, the airbag design and deployment characteristic were performed and optimized. Sled tests were conducted to assess the reduction of the occupant injuries using PRE-SAFE® Impulse Side during a side impact. As final step the performance of the pre-impacting actor was ensured by vehicle tests.

Once a first prototype seat was available, the first step was to take some measurements of lateral excursion using different dummies in order to define a first set of parameter for the system and so insure the feasibility of the system. At each step, the data collected on dummies were validated against tests persons, both in static tests. For dynamic test validations, sled and car tests were compared to numerical simulation using Human Body Model to make sure that pre-impacting restraint systems do not induce any unwanted side effects.

Results

Like every PRE-SAFE® system, PRE-SAFE® Impulse Side unfolds its fully potential in real life accident scenarios. To show the benefit of the system in this paper two common side crash scenarios have been chosen: a pole and a barrier test.

Pole test The pole test has following configuration: impact speed: 29 km/h, angle: 90°, ES2re-Dummy. Compared to conventional restraint systems, the benefit of PRE-SAFE® Impulse Side vary between 25% in lower rib up to 35% in middle and upper rib (Figure 3). The potential in the upper area is the highest and decreases slightly with respect to the lower rib. The effect of the displacement is at its greatest in the upper thorax region and corresponds to the acceleration of the occupants.

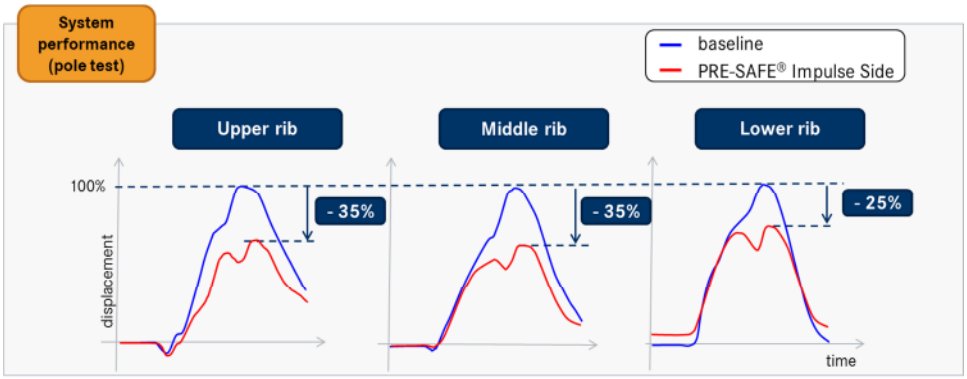

Figure 3: Benefit of PRE-SAFE® Impulse Side in pole test with ES2re dummy

Barrier test The barrier test was done according following configuration: impact speed: 50 km/h, movable deformable barrier with a mass of 1450 kg, SID2s-Dummy.
The PRE-SAFE® Impulse Side effect can also be seen in the barrier load case. Due to the lateral excursion, the loading of the shoulder begins later as it can be seen on the shoulder force curve in Figure 4. As a consequence, the rib intrusion value is also significantly reduced.

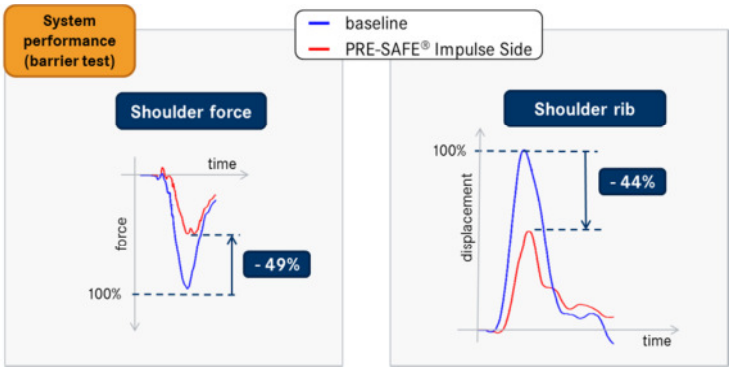

Figure 4: Benefit of PRE-SAFE® Impulse Side system for barrier test configuration

This improvement can further be observed on the thorax and the abdominal ribs. The PRE-SAFE® Impulse Side effect in the lower thorax region is also less pronounced than in the upper one in this load scenario, same tendency as for the pole load case (Figure 5).

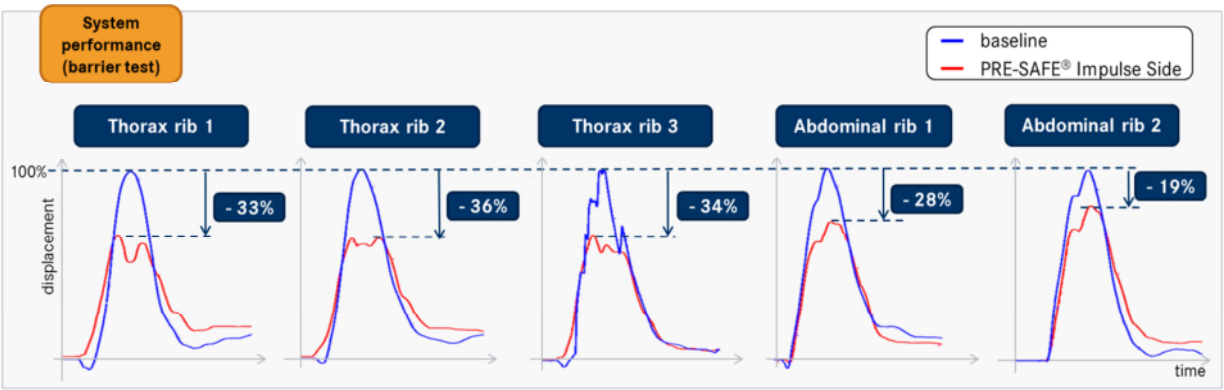

Figure 5: Benefit of PRE-SAFE® Impulse Side in barrier test configuration

System robustness

As PRE-SAFE® Impulse Side is the very first pre-triggered restraint system it was crucial to realize a robust system. The robustness of the system regarding to variation of the triggering time was analyzed. Investigations were undertaken in a PRE-SAFE® Impulse Side actuator time window starting from half a second prior to crash up to t0. An optimal operating point has been found and the response of the system around this point has been analyzed.

With a 25% error in the triggering time of the actor, the benefit compared to the baseline remains significant, showing the robustness of the PRE-SAFE® Impulse Side system (figure 6).

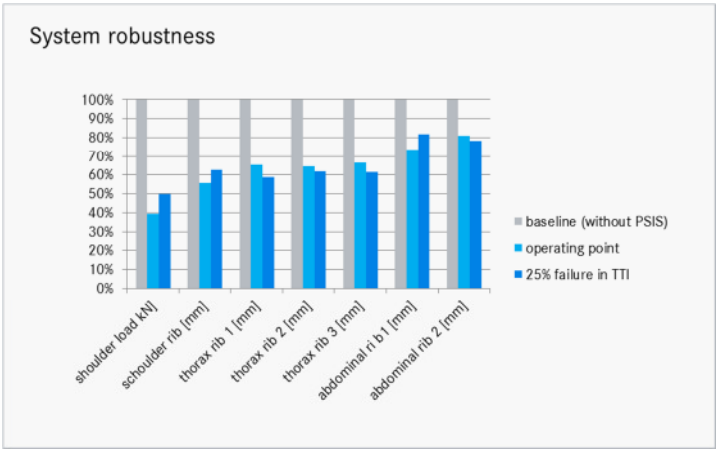

Figure 6: System robustness: Displacement of SID2s Dummy with 25% failure in TTI (time to impact)

SENSOR SYSTEM AND AREAS OF COVERAGE

Capturing and recording the environment, which primarily encompasses radar sensors, but also cameras and ultrasonic sensors, has established itself as an enabler for assistance systems in modern vehicles.

These sensors as used for driver assistance systems could also be used to develop spin-off applications that offer protection in an accident.

For this purpose, special algorithms were created that analyze the sensor data to detect directly "collision objects". Such detection can be realized independently of the assistance functions and operating status of the vehicle. The overarching objective is to detect "objects on a collision course", whereby this detection refers to the vantage point of the respective sensor. From this perspective, a passing vehicle in oncoming traffic is just as much an "object on a collision course" as a bridge pillar that the appropriate vehicle is approaching. Potential collision objects can also be detected when the vehicle is stationary.

The relevant space of time for detecting collision objects begins nearly half a second before the impact. From this time onwards it is possible to predict whether the collision is unavoidable or not. As a consequence the short distance area to the vehicle (typically under 15 meters) must be covered by the sensor system for such functions.

In the event of an impending frontal or rear-end collision, graduated preventive safety measures are activated. These measures are up to now always reversible in line with the underlying idea of the PRE-SAFE® concept.

Current Mercedes-Benz carlines equipped with a driving assistance package utilize targeted algorithms to detect collision using forward-facing sensors and the sensor in the rear bumper.

To realize the PRE-SAFE® Impulse Side function sensors that monitor the side area near to the car are needed. Accident analysis data were used to establish a basis for the observation area. Figure 7 (left) shows the distribution of impact angles in side crashes based on analysis of GIDAS (German In-Depth Accident Study) compared with today crash test scenarios required by regulations and ratings.

These areas on both side of the car have to be covered by the sensors. Figure 7 right illustrates the installation location and visibility of these sensors, whereby angles α and β depend on the exact application constraints and sensor concept.

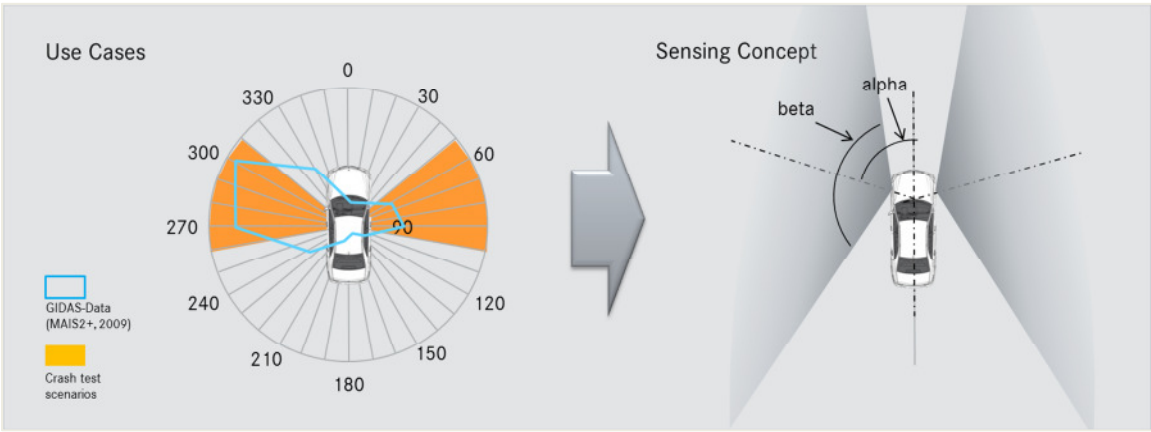

Figure 7: Schematic illustration of the sensor visibility areas required for PRE-SAFE® Impulse Side

The sensors needed for the PRE-SAFE® Impulse Side function filled the existing gap in the sensor coverage (Figure 7) achieving a 360-degree monitoring of the car surroundings.

SYSTEM RELIABILITY

Driving assistance

While the functional development for so-called "fire cases" (collisions that are detected in the pre-crash phase and for which a system enable is required on demand) is typically conducted on test tracks and using corresponding "soft targets", validation against false deployment must be handled parallel in two ways.

First, specially equipped test vehicles – as is the case with the development of driving assistance systems – are operated in normal, international road traffic in order to encounter as many different traffic and road-based situations as possible. As actual, "accident-critical" situations only arise very rarely, however, this type of testing must be supplemented with deliberately induced accident scenarios conducted on test tracks. In the process, very close drive-by or swerving situations must also be taken into account as well as conceivable special or misuse situations.

Testing and validating these "no-fire cases" is very expansive in scope when it comes to development.

As "PRE-SAFE® Impulse Side" and all other PRE-SAFE® measures always refer to additional, proactive measures that supplement the conventional basic occupant protection system, a deployment strategy must be chosen that prevents firing, or enabling, in the event of uncertain situations. PRE-SAFE® Impulse Side will help to further reduce occupant loads, however.

Customer Acceptance Study

Due to the triggering character of the PRE-SAFE® Impulse Side system, the function could be activated in the absence of a subsequent crash in isolated cases. Should this happen, the design of the system has to ensure that the driver is not influenced in his or her driving task.

To investigate this issue, the moving based driving simulator was used to analyze the effect of PRE-SAFE® Impulse Side activation completely free of risk and with a high rate of reproducibility.

During the driving simulator study, the driver's response to PRE-SAFE® Impulse Side activation in normal driving situations and the resulting reactions were assessed. Acceptance of false deployment was likewise examined. Three driving situations were constructed to activate the function and verify two driving situations with comparative natural disruptions (crosswind and flying stones). The driving route consists of urban scenarios, country road, and highway sections. The situation was incorporated into the route with 4 variants.

Data of objective measurement for assessing the driver response (driver behavior, driving dynamics, lane tracking, and environment) were recorded. In the study 175 PRE-SAFE® Impulse Side deployments and 54 comparative disturbances were evaluated.

PRE-SAFE® Impulse Side activation during the driving study has not shown any influence on lane tracking in the urban scenarios. On highway, the influence of PRE-SAFE® Impulse Side is less disturbing than experiencing a crosswind while passing another vehicle. Activation of the PRE-SAFE® Impulse Side induces driver responses that do not lead to critical driving situations and can be compared with natural disturbances such as crosswinds.

CONCLUSIONS

To date, occupant protection measures have only been actively deployed after the accident has started to transpire. In response to this, Mercedes-Benz launched PRE-SAFE® in 2002, the first reversible protection system that acts before the accident starts to take place.
As future possibilities encompass the opportunity to reliably detect accidents in advance, the time window in which restraint systems can offer protection increases dramatically. This, in turn, leads to great potential for further improving occupant protection in a passenger car.
To this end, the PRE-SAFE® Impulse Side pre-impacting restraint system utilizes initial information about the unavoidable side impact to optimally prepare the vehicle's occupants. This is achieved by coordinating actions with the 360-degree environment sensor system, which senses the relevant areas of the vehicle and provides the required signals and information for triggering the protective system.
With PRE-SAFE® Impulse Side a defined force and energy is exerted to actively integrate the occupant in the side impact at an early stage when the vehicle has not yet started to decelerate or has just begun to slow down. Analysis in numerical simulation, sled and vehicle testing, show that occupant loads could be significantly reduced by the benefit of the system.
As PRE-SAFE® Impulse Side is a preventive protection system and false deployment of it cannot be ruled out entirely, a driving simulator study was conducted to investigate the effects on a driving situation and the driver's acceptance of undesired activation.
To ensure adequate validation, the highest priority and challenge is to avoid undesired deployment, even if this means missing an opportunity to deploy when needed.
As PRE-SAFE® Impulse Side is an "on top" protection system, when it does not deploy, all protection capability of the side airbag will be still there.
Automated driving functions directly or indirectly will change the basic conditions associated with passive safety. Synergies with sensor technologies and situation assessment enable further innovative occupant protection strategies, like PRE-SAFE® Impulse Side, to be implemented in the future.

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RUN OFF ROAD SAFETY

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ABSTRACT

Run off road events are frequent and can result in severe consequences. The reasons for leaving the road are numerous and the sequence the car is subjected to differs in most events. The aim of this study is to holistically address safety improvement in run off road events, presenting methods for evaluation as well as examples of countermeasures for the whole sequence from normal driving to post-crash.
Real world data, comprising statistical and in-depth crash data as well as driving data from Volvo Cars' database in Sweden, forms the basis for understanding of influencing factors and mechanisms related to occurrence of the event as well as occupant injury. Countermeasures are presented along with the test methods which were developed based on the mechanisms identified. The test methods include road off road avoidance test methods, complete vehicle crash tests, and rig tests; such as occupant positioning using a robot rig and vertical loading tests using a drop tower rig.
Countermeasures addressing run off road safety are developed and verified using the identified test methods and integrated into vehicle design. Examples of systems addressing road departure avoidance aspects are Driver Alert Control and Lane Keeping Aid. Countermeasures specifically addressing occupant protection are occupant positioning by detecting run off road events and activating an electrical reversible safety belt pretensioner, as well as unique energy-absorbing functionality in the seat. Post-crash measures are enhanced by added activation of eCall in some run off road scenarios.
Optimally, avoiding the run off road is most beneficial and this study provides some initial steps illustrated by production systems. However, if run off road occurs, one priority is to reduce vertical occupant loadings when landing on the wheels after a free-flight, a rollover or when going into a ditch and impacting an embankment. This type of loading could result in thoracic-lumbar spine fractures. The design of the unique energy absorbing functionality in the seat, put into production 2015, will help provide important enhanced occupant protection. Additionally, injury outcome is influenced by the occupant position during the event: head and arms flinging around impacting the interior, bent postures reducing the tolerances of spinal injuries, and sub-optimal occupant positioning relative to protection systems. The unique run off road detection and safety belt pretensioning early in the events, together with the seat backrest's side supports, will assist the occupant to stay positioned during the event and help improve protection.
This study is based on a holistic approach to safety, covering the whole event from normal driving to crash care, introducing world first production technology enhancing occupant protection in these diverse and complex events. It goes beyond standardized safety evaluation of today and it provides an illustrative example on how safety systems can take action across the entire crash sequence and the interaction of different types of systems adding to the effect of addressing real world protection needs.

INTRODUCTION

Run off road events are frequent and can result in severe consequences. In the United States, single vehicle roadway departure crashes accounted for about 20% of all police-reported crashes (Wang and Knipling, 1994). In Germany, 33% of all fatal crashes were run off road crashes (Statistisches Bundesamt, 2011). In Sweden since 2003, single car crashes is the most common type when it comes to fatal accidents (Hillerdal, 2011). Injuries can be sustained to any body part (Jakobsson et al. 2014). Among injury types highlighted as related to run off road events are thoracic and lumbar spine injuries. Although found in all crash situations, Jakobsson et al. (2006) showed that AIS2+ thoracic and lumbar injuries were mostly found in multiple events; a high proportion of the cases being run off road crashes.

Occupant posture, such as forward bending was highlighted as an influencing factor, with the injury mechanism of spinal axial loading with different degree of flexion leading to compression and anterior wedge fractures, especially seen in run off road events with complex occupant kinematics.
In the context of crash avoidance, numerous test methods and evaluation procedures address situations triggering potential run off road crashes, such as sleepiness (Anund et al., 2009 and 2011, Fors et al, 2013) and distraction (NHTSA, 2010, Hanowski, 2011, Fitch et al. 2013). Additionally, test methods evaluating specific technology such as Electronic Stability Control (ESC) and Lane Departure Warning (LDW) are found within legal and public domain testing. However broad test methods addressing run off road safety effectiveness on multiple factors influencing causation (driver behaviors, friction, weather, etc) in the avoidance phase are scarcer, although first steps are taken e.g. within the Advanced Crash Avoidance Technologies Program at NHTSA (Gordon et al., 2010).
Leaving the road can result in a variety of more or less complex events. While some vehicles quickly come to a rest position without any severe event, other vehicles leave the road into a free flying event, landing on the wheels or continue into a roll or turn-over event or interact multiple times with the environment. In-depth studies in Austria highlight the effect of guardrails leading the vehicle to "take off" as well as vehicles jumping into road side objects such as traffic sign poles or overpasses (Tomasch et al., 2010). Jakobsson et al. (2014) reported that important mechanisms addressing run off situations include drifting and avoidance of animals on the road. Being a complex event, not one single test method addresses this whole area of concern. Some parts of some events, such as skidding sideways and impacting a tree, are addressed in standardized lateral pole impact tests. Additionally, standardized frontal barrier tests address parts of events ending up into a large rock or a brick wall. However, neither influence of potential change in occupant posture before impact, nor reasons for leaving the road are covered in these standardized crash tests.
Addressing run off road safety poses a variety of challenges, ranging from understanding the reasons for leaving the road to means of evaluating the potential injury outcome, all put into the overall context of run off road safety. The objective of this study is to address run off road events, presenting methods for evaluation as well as examples of countermeasures addressing the whole sequence from normal driving to post-crash. This is done by summarizing influencing factors and mechanisms to target when developing test methods; and briefly presenting some newly developed test methods along with production systems/technology addressing run off road safety.

INFLUENCING FACTORS AND MECHANISMS

Based on real world data, crash causation mechanisms and injury causing mechanisms were identified and presented by Jakobsson et al. (2014). The purpose of these mechanisms was to, in a structured way, address the complex and diverse area of run off road safety and to guide development of test methods with a holistic approach.
There are several reasons for leaving the road exemplified by driver distraction, sleepiness and fatigue, inadequate speed and vehicle interaction in relation to the traffic situation and maneuver for avoidance of animal crashes and other objects on the road (Najm et al., 2002, Liu and Subramanian, 2009, Jakobsson et al., 2014). Factors potentially influencing crash causation of run off road events are essential to take into account in test method developments targeting evaluation of road departure avoidance.
For the run off road situations, especially occupant kinematics as well as occupant retention were highlighted and differ from on-road occupant protection situations. The occupant kinematics, longer duration and less acceleration as compared to on-road crashes, exposes especially the upper extremities and the head for non-optimal positions from a protection point of view. Occupant retention addresses the upper body positioning during the run off road event. Several potential injury causing mechanisms are seen during the wide and diverse types of events. Analyzing real world data, Jakobsson et al. (2014), highlighted the different types of environments, such as rough terrain, ditch types and whether multiple events occur, as important mechanisms contributing to the occupant injury. Numerous different impact objects are probable as well as differences in impact configuration, including complex rollover events. Complex vehicle kinematics due to the run off road environment, occupant kinematics and occupant retention affect the occupant posture which depending on the impact, influences the occupant injury consequences in run off road crashes. Important occupant protection mechanisms concern impacts to interior structures, vertical loading on the occupant through the seat, as well as keeping the occupant in a favorable position during the event (Jakobsson et al. 2014 and 2015).

TEST METHODS

Based on the identified factors and mechanisms, a variety of test methods were developed to address occupant protection aspects as well for evaluating technology assisting the driver to stay on the road. The whole context is

described in Jakobsson et al. (2014) and the test methods specifically addressing the countermeasures presented in the present study will be covered in this chapter.

Road Departure Avoidance Test Methods

Systems addressing road departure avoidance aspects, such as Driver Alert Control (DAC) and Lane Keeping Aid (LKA), are tested with virtual methods, simulator tests as well as test track and on-road tests. Driver representation is important in all types of test methods. Depending on the level of critical event and repeatability issues, the choice of method is made.
The virtual test methods consist of virtual representations of the driver as well as the vehicle and environment (Gordon et al., 2010; Markkula, 2015; Benderius, 2014). The driver model is designed based on knowledge from testing with drivers in specific real world situations, and can be more or less advanced, depending on the application. Virtual test methods allow that a large number of tests can be performed using the same model just varying the vehicle systems or the environment. Other benefits are the possibilities to use it in early phase technology developments.
In tests evaluating warnings (e.g. Driver Alert Control) and vehicle interventions to prevent road departures by drifting (e.g. LKA), driver reactions on these warnings and interventions are evaluated. The driver reactions can be tested both on test tracks and in driving simulators (Petersson and Svanberg, 2013) while the whole run off road scenario only can be tested in a driving simulator for test repeatability as well as safety reasons. Data from the test track tests can be used to build a driver model to incorporate into a virtual test method, which provides an additional tool beneficial when evaluating a large number of specific scenarios of e.g. run off road speeds and angles. The evaluation target in this testing is to avoid road departures as such, with a special focus on the drifting behavior.
The Driver Alert Control and Lane Keeping Aid systems target pre-crash driver states such as sleepiness, fatigue and distraction as these are identified as important pre-crash parameters in run off road crashes. Test methods evaluating these aspects comprise test track and on-road testing and using driving simulators. For sleepiness testing the set-up is usually a several hour long drive on a highway (speed limit 110km/h) where the driver just drives the car, with no critical situations or distraction tasks induced. The tests can be designed using different levels of sleep deprivation (over several days) and the characteristics of the participants are carefully selected. The evaluation target during the test is typically to decrease the time driving in a sleepy state. For distraction testing, the driver is asked to repeatedly perform a number of secondary tasks sequentially, exemplified by using in-vehicle HMI, such as phone or radio. The evaluation target is to increase drivers' eyes-on-road and reduce glances over a certain duration time on the secondary tasks. A description of a related test method is described in Ljung Aust et al (2013).

Occupant Protection Complete Vehicle Test Methods

Three complete vehicle crash test track methods, called Ditch, Airborne and Rough Terrain were developed to simulate some main run off road vehicle kinematics potentially causing occupant injury. These methods can be used for evaluating the consequences of combination of low acceleration and high acceleration parts of the event on vehicle and restraint system performance as well as provide insight into potential occupant kinematics. The tests were run at Volvo Cars Safety Centre in Sweden, using Test Track 2 which is a moveable covered test track with semi-directional electrical propulsion system. The tests were run towards the outdoor crash test environment, where different run off road scenarios are built. The car is launched from the test track, just before entering the run off road scenario, by a position triggered system. Crash test dummies are used as human representation in the tests. Important feature of a crash test dummy for this purpose is good flexibility in shoulders and upper body, hence the Thor dummy with modified shoulder (Törnvall et al., 2008) was used.
During the Ditch method the vehicle is launched at 80 km/h and drifts with an angle of 12-15 degrees into a ditch (Figure 1). The ditch is 80 cm deep with a slope of 30-40% from the road surface. Approximately 20 m after leaving the road, entering the ditch and traveling along the bottom of the ditch, an embankment is reached forcing the vehicle into an upward motion. The embankment has the same slope as the ditch, and represents a crossing road. This test method captures the characteristics seen in real world cases when the vehicle is drifting into the ditch in a rather narrow angle, travels in the ditch, thereafter impacting an embankment leading to underbody interaction to ground, causing high vertical loading into the occupant through the seat.
During the Airborne method the vehicle is launched at 50-80 km/h leaving the road in a range of angles (30 degrees in Figure 1) into a steep slope introducing a phase of free flight of the vehicle, before landing on smooth surface and continue onwards. The height difference is 80 cm, resulting in a hard impact on the wheels, causing vertical forces.

During the test method called Rough Terrain the vehicle is launched at 70-80 km/h perpendicular from the road into a rough terrain environment (Figure 1). The rough terrain causes a bumpy ride producing substantial lateral vehicle motions (rolling motions) in combination with vertical and longitudinal vehicle motions.
In all the three crash test track methods, the occupant will be subjected to acceleration changes in different directions and intensities through the event, due to the vehicle kinematics in several directions simultaneously. This could expose the different parts of a restrained occupant (especially the upper extremities and head) to potential impacts to the interior, partial ejection as well as changes in upper body positions posing the spine into flexed postures.

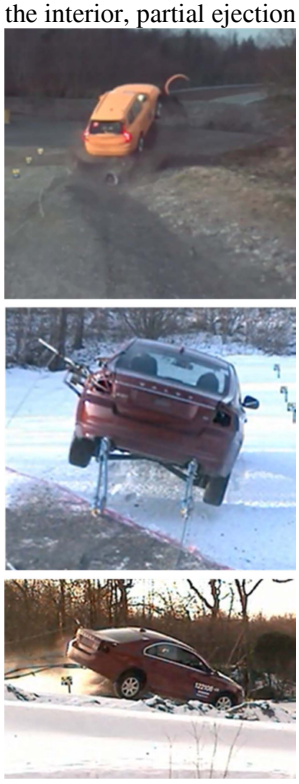

Figure 1. The complete vehicle Run off road crash test methods; Ditch (top), Airborne (middle) and Rough Terrain (bottom).

Occupant Protection Rig Test Methods

Rig test methods were developed to replicate sequences from the whole vehicle test methods in a repeatable and reproducible way. The two main areas of interest were the occupant kinematics when subjected to varieties of loading directions and intensity, and the vertical occupant loading. Two rig test methods were designed to address these two areas.
A robot controlled test setup, called 'Robocoaster', was used to simulate occupant kinematics. It provides a flexible and multi-purpose test set-up evaluating occupant positioning and occupant retention. A vehicle seat and restraint system is mounted on a multi-axial robot (ABB IRB 6600 industrial robot) and can be used together with a crash test dummy (Figure 2). The robot can be programmed to, in repeatable manner, simulate the occupant kinematics in one of the three test track methods, or any variations of a run off road crash, within the limitations of the robot used.

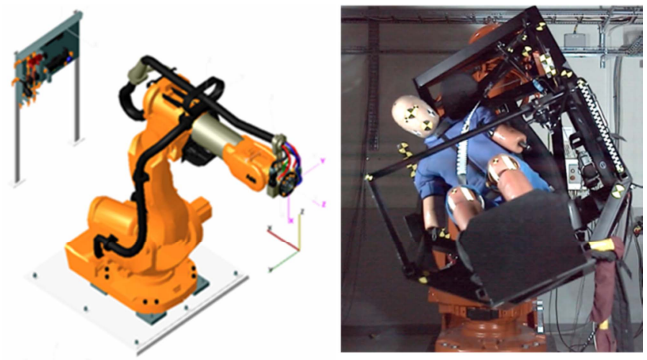

Figure 2. Rig test method 'Robocoaster'.

A rig test method simulating the vertical loading through the seat was developed (Figure 3). It provides a simplified and repeatable test set-up for vertical occupant loading, which can occur at hard landing on the wheels after a free flight or during the undercarriage interaction, e.g. with the embankment in the Ditch method. A seat is attached to a frame which moves on vertical rails on a drop tower. The desired vertical acceleration in the physical test set-up is achieved by releasing the frame from a specific height and stopped using the deceleration-sled principle of bending steel. The rig test method also has a virtual counterpart. A crash test dummy is positioned in the seat during test. For the physical test, a HIII 50%-ile male dummy is used while in the virtual test-set up the BioRID (50%-ile male) is used. The z-component of the pelvis accelerometer is monitored and used as the injury criteria measure 'vertical occupant acceleration'. The test method is described in detail in Jakobsson et al. (2015).

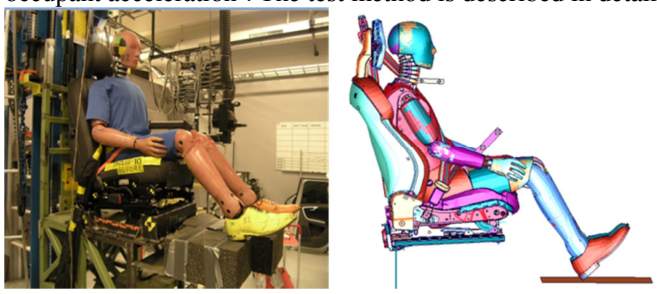

Figure 3. Rig test methods for vertical occupant loading; physical test setup (left) and virtual test setup (right).

COUNTERMEASURES

Countermeasures addressing run off road safety, which are integrated into vehicle design, were developed and verified using the test methods. As illustrated in Figure 4, the countermeasures address run off road safety in a holistic way. Examples of production systems addressing run off road avoidance aspects during normal driving are Driver Alert Control and Lane Keeping Aid. Countermeasures specifically addressing occupant protection are occupant positioning by detecting run off road events and activating an electrical reversible safety belt pretensioner, as well as unique energy-absorbing functionality in the seat. Post-crash measures are enhanced by added activation of eCall in some run off road scenarios.

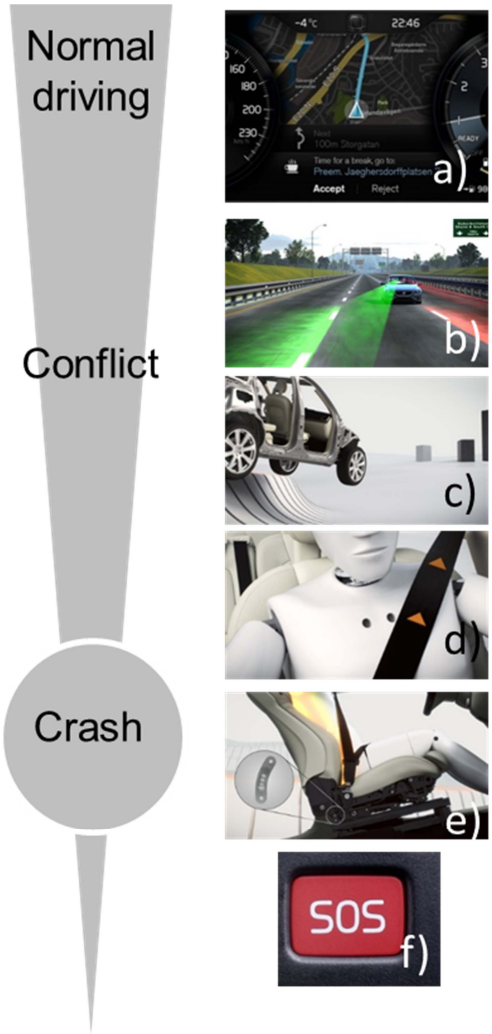

Figure 4. Holistic approach including countermeasures; Driver support system exemplified by a) Driver Alert Control with Rest Stop Guidance and b) Lane Keeping Aid, occupant protection systems exemplified by c) run off road detection, d) electrical reversible safety belt pre-tensioning and e) energy absorbing functionality in seat, and f) post-crash measure such as eCall activation.

Driver Alert Control detects and warns tired or inattentive drivers. In the 2015 Volvo XC90, it is enhanced with a new Rest Stop Guidance (Figure 4a), which directs the driver to the nearest rest area. Lane Keeping Aid (Figure 4b) helps the driver stay on track by applying extra steering torque if the car is about to leave the lane unintentionally. As a post-crash measure, eCall offers safety benefits in providing information to the Call Center who can contact the occupants in the car as well as call for assistance when needed (Figure 4f). Real world activation of eCall is dependent of detection capabilities including interpretation of the detection. Conventional triggering of eCall is based on activation levels for pyrotechnical devices, e.g. pretensioners and airbags. Triggering in situations beyond those requires knowledge of the event. Run off road events are challenging being diverse and complex. The test methods developed and presented in this study provide such knowledge and have been used to further refine the eCall activation capabilities included in the 2015 Volvo XC90.
For occupant protection, controlling the occupant position together with the energy absorbing functionality provides benefits in a large range of situations. By keeping the occupant in an upright posture while cushioning a potential vertical enables a combined benefit since the spine in more tolerable when straight. The details on detection algorithm and activation logic, as well as the electrical reversible safety belt pretensioner and seat design are presented below.

Detection Algorithms and Activation Logic

The new detection algorithms in the restraint control module are able to detect new run off road scenarios, such as Ditch, Airborne, and Rough Terrain. This is enabled by using sensor data from the vehicle's restraint control module along with information from the vehicle bus. As compared to prior vehicles, no hardware is added, while extensive work on algorithms has been carried out. A major challenge is to address all relevant real world crash scenarios and take action to help protect the vehicle occupants accordingly. The sensor functionality is an important step towards addressing crashes beyond the standardized crash test methods. In order to make this happen and to control the triggering, data from complete vehicle real world like events are necessary. Hence, the development of the complete vehicle test methods was essential for this important functionality. Sensor data gathered from the complete vehicle crash tests was taken as input to the calibration process, wherein algorithm parameters were tuned in multiple simulation loops. The input data set included both scenarios where activation of one or more protection components is required (Fire tests), and scenarios where there shall be no activation of protection components (No Fire tests), in order to assess the robustness of the algorithm methods and the calibration. The development of detection algorithms and activation logic is further described in Nilsson et al. (2014).

Electrical Reversible Safety Belt Pretensioner

If a run off road scenario is detected, an electrical reversible safety belt pretensioner is activated, provided the occupant is belted. The safety belts are electrically tightened to retract and keep the occupants in position (Figure 4d). The electrical reversible pretensioner has two force levels, which are used depending on the estimated severity of the scenario (i.e. medium force in low severity events, high force in high severity events). Full retraction is achieved within 250 ms, belt force is up to 300 N, and the belts are kept firmly tightened as long as the car is in motion. Once the run off road scenario has ended, as determined by global acceleration level, the belt tension is released. The electrical reversible pretensioner forces are strong enough also to retract forward leaning occupants (Lorenz et al. 2001, Develet et al. 2013).
In case of a sufficiently severe secondary impact in the course of a run off road scenario, e.g. to a tree, an embankment, another obstacle or a rollover event; the pyrotechnical safety belt pretensioners will be activated on all seven seating positions, provided the occupants are belted. Additionally, other restraints, such as airbags and inflatable curtains will be activated when needed.

Seat Design

An important part of the run off road safety package is the all new seat design as introduced in the 2015 Volvo XC90. The protruding side bolsters of the seat backrest helps to provide occupant support together with the safety belt retraction. The seat has been designed addressing spinal protection in case of a vertical load through the seat. A deformation element is built into the inner rear part of the seat connection to the seat frame. In case of vertical loads, the seat will slide in the slot while deforming the deformation element (Figures 4e and 5). The deformation element allows for a controlled vertical deformation of up to 25 mm. The space under the seat is cleared to allow for total occupant movement up to 150 mm. This movement is achieved mainly by compressing the seat foam and extending the springs in the seat cushion, which together with the deformation element provide energy absorption. The deformation element is triggered by force during the event. The force is dependent on occupant weight in combination with acceleration amplitude and direction. Vertical forces of a certain limit will trigger the deformation of the element as well as allow the occupant to move into the seat cushion. These vertical forces can occur in rollover events when landing on the wheels, as a result of a free flight event or any other crash sequence where there is a vertical force component, such as in the Ditch test situation. The deformation element also plays a part in the Whiplash protection system (WHIPS), activated by the torque occurring when the occupant sinks into the seat backrest during the rear end impact event.

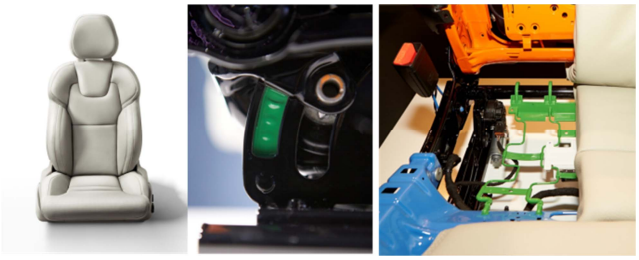

Figure 5. Overview of seat design including side bolsters (left). Close-up views of energy absorption functionality; side view of deformation element (middle), top view of seat cushion including springs (right).

Figure 6 shows a comparison of vertical occupant acceleration, comparing the new seat design to a prior Volvo seat, available in e.g. Volvo S40, XC70, S80, S60 model years 2011-2013. The rig test method for vertical occupant loading, simulating a sequence from the embankment interaction during the Ditch whole vehicle test, is used for this comparison. The seat is exposed to a maximum acceleration of approximately 90m/s2, pulse duration about 100ms and 'change of velocity' of 6,5m/s. In this loading situation, the vertical occupant acceleration is reduced by 32% in the new seat design as compared to the reference seat. The chosen situation is representative of a situation where spinal injuries can occur in real world crashes.

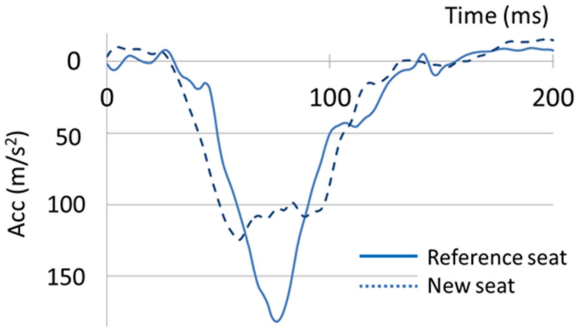

Figure 6. Pelvis vertical acceleration comparing new seat and reference seat using the virtual loading rig test method (Jakobsson et al. 2015).

DISCUSSION

This study addresses the area of run off road events which has, up until now, been in limited focus within automotive development. Test methods as well as countermeasures addressing the whole sequence in run off road events present a first step within this area and will help to reduce real world consequences. The study presents a holistic approach, including production systems addressing run off road avoidance aspects during normal driving, countermeasures specifically addressing occupant protection post-crash measures.

A holistic approach is necessary when addressing run off road safety. The reasons for running off the road are several and the characteristics of the events are numerous. The way behind this study was to base the knowledge of real world situations, identifying influencing factors and possible mechanisms, developing test methods and by this creating both a deeper understanding as well as countermeasures. This process is described further in Jakobsson et al. (2014).

Optimally, avoiding a run off road event is most beneficial and this study provides some initial steps illustrated by the Lane Keeping Aid and Driver Alert Control production systems. Further steps are needed to address all the reasons for running of the road and offer support in those situations. In addition, prototype road departure avoidance technologies have been presented, however so far not ready for production. The challenges mainly concern detection issues; identifying the large variety of different types of road edges and to separate them from e.g. cracks and other damages on the road.

Figure 6 shows that by adding energy absorbing functionality in the seat together with improved clearance under the seat, vertical occupant acceleration can be substantially reduced in situations where thoracic and lumbar spine injuries could occur in real world situations (Jakobsson et al. 2015). Combining this with keeping the occupant in an upright posture will help reduce spinal injuries even further. Injury outcome is influenced by the occupant position

during the event: head and arms flinging around impacting the interior, bent postures reducing the tolerances of spinal injuries, and sub-optimal occupant positioning relative to protection systems. The unique run off road detection and safety belt pretensioning early in the events, will assist the occupant to stay positioned during the event and help improve protection. This is a robust way of addressing occupant protection in run off road situations, keeping the occupant in a controlled position, enabling the protective safety systems to help the occupant in different upcoming events.

The present study goes beyond standardized safety evaluations of today. Firstly, it is an area that still is to be addressed in regulatory and consumer testing. Secondly, it combines in an effective way safety of the total sequence of an event; including active, integrated and passive safety technology. Both of these are necessary in order to improve the relatively large amount of injuries occurring in these types of events. Obviously, run off road being complex and diverse events, a limitation of this study is that not all events and potential consequences are addressed. However, the approach of this study and methods developed based on influencing factors, provide a path to build further studies and countermeasures on. Going beyond standardized safety evaluation of today, it provides an illustrative example on how safety systems can take action across the entire crash spectrum and the interaction of different types of systems adding to the effect of addressing real world protection needs.

CONCLUSIONS

This study is based on a holistic approach of safety, covering the whole event from normal driving to crash care, introducing world-first production technology enhancing occupant protection in these diverse and complex events. It goes beyond standardized safety evaluation of today and it provides an illustrative example on how safety systems can take action across the entire crash spectrum and the interactive play of different types of systems adding on the effect of addressing real world protection needs.

Unique test methods including complete vehicle run off road crash tests, and rig tests addressing occupant positioning and vertical loading using a robot rig and a drop tower rig, respectively, are developed to evaluate the countermeasures as introduced in the 2015 Volvo XC90. The world-first run off road protection package includes detection of run off road events and activation of an electrical reversible safety belt pretensioner, together with unique energy-absorbing functionality in the seat. The cascade of countermeasures covering the whole event from normal driving to crash care systems, also including systems acting to avoid crashes such as Driver Alert Control and Lane Keeping Aid as well as added activation of eCall will provide improved safety in an important number of run off road events.

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ENHANCEMENT OF OCCUPANT SAFETY IN OFFSET FRONTAL VEHICLE COLLISION: USING NOVEL MATHEMATICAL MODELLING ALONGSIDE VEHICLE DYNAMICS CONTROL SYSTEMS

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ABSTRACT

Occupant safety is one of the most important issues for vehicle manufacturing. Active safety plays an important role to protect the occupant during the crash events. In this paper, vehicle dynamics control systems (VDCS) are used to enhance the occupant safety in offset frontal vehicle collision. VDCS are activated to optimize the vehicle in impending collision. A new mathematical modelling of the vehicle alongside VDCS is developed to study the effect of vehicle dynamics control systems on vehicle collision mitigation. A multi -body occupant mathematical model is developed to capture the occupant kinematics during frontal offset collision. Different cases of vehicle dynamics control systems have been used to show their effect on the occupant dynamic response. The occupant deceleration and the occupant's chest and head rotational acceleration are used as injury criteria. It is shown from the numerical simulations that the occupant behaviour can be captured and analysed quickly and accurately. Furthermore, it is shown that the VDCS can affect the crash characteristics positively and the occupant safety is improved.

INTRODUCTION

The most well-known pre-collision method is the advance driver assistant systems (ADAS). The aim of ADAS is to mitigate and avoid vehicle frontal collisions. The main idea of ADAS is to collect data from the road (i.e. traffic lights, other cars distances and velocities, obstacles, etc.) and transfer this information to the driver, warn the driver in danger situations and aide the driver actively in imminent collision. There are different actions may be taken when these systems detect that the collision is unavoidable. For example, the brake assistant system (BAS) [1] and the collision mitigation brake system (CMBS) [2] were used to activate the braking instantly based on the behaviour characteristics of the driver, and relative position from the most dangerous other object for the moment.

During frontal vehicle collision, it is found that the vehicle body pitch and drop play an important role in driver's neck and head injury [3, 4]. Vehicle body pitch and drop have normally been experienced in frontal crash tests. Chang et al. [3] investigated frame deformation upon full-frontal impact using a finite element (FE) method and discussed the cause and counter-measures design regarding vehicle body pitch and drop. It was found that downward bending generated from the geometric offsets of the frame rails in the vertical direction during a crash is the key feature of the pitching of the vehicle body.

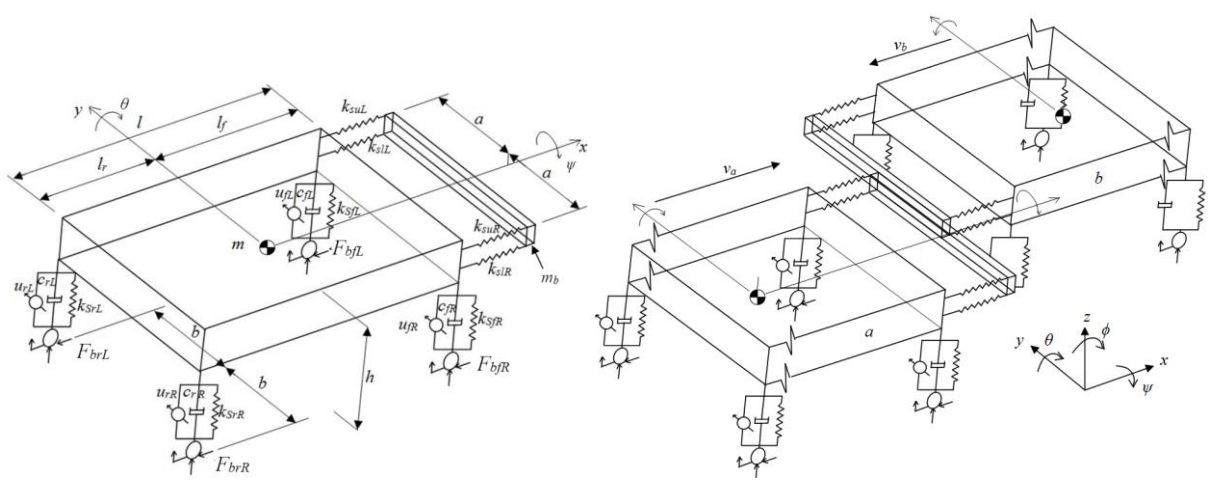
Using mathematical models in crash simulation is useful at the first design concept because rapid analysis is required at this stage. In addition, the well-known advantage of mathematical modelling provides a quick simulation analysis compared with FE models. Vehicle crash mathematical modelling is used to represent the vehicle front structure [5]. Also, other analyses and simulations of vehicle-to-barrier impact using a simple mass spring model were established by [6]. A simple lumped-parameter model is used, discussed the applicability of providing variable energy-absorbing properties as a function of the impact speed [7]. The occupant can also be modelled mathematically as a one-mass model [8], a two-mass model [9], a three-mass mode [10] or a multi-mass model [11]. In the most of these studies, the researchers claimed that simple occupant mathematical models can obtain usefully similar results to sophisticated analytical and experimental work.

Vehicle dynamics control systems (VDCS) play an important role in improving vehicle stability, ride characteristics, and passenger safety. On the other hand, the effect of VDCS on vehicle crashworthiness and collision mitigation is considered in several studies. The influence of the braking force on vehicle impact dynamics in low-speed rear-end collisions was studied [12] and this confirmed that the braking force was not negligible in high-quality simulations of vehicle impact dynamics at low speed. The effect of vehicle braking and anti-pitch control systems on the crash routine have been investigated by Hogan [13], who also investigated the possibility of using VDCS to improve vehicle collision performance in full and offset frontal vehicle to barrier collision.

However, there are no studies have been found that investigate the effect of VDCS on the occupant safety.
From the existing literature, it is clear that research work done on the effect of VDCS on the occupant safety is rare. Hereafter the current study is fulfilled to determine the occupant response in offset crash scenario with different cases of VDCS. To accomplish this study, a mathematical multi-body occupant model has been developed.

THE NEW VEHICLE DYNAMICS/CRASH MATHEMATICAL MODELLING FOR PRIMARY IMPACT

The primary impact indicates the collision between the front-end structure of the vehicle and an obstacle (another vehicle in this paper). This section describes a 6-DOF vehicle dynamics/crash-mathematical model, shown in Figure 1, which has been former developed by the author [14], for one vehicle and in case of a crash scenario between the two vehicles, where subscript *a* denotes vehicle (a) which is equipped with the VDCS and a subscript *b* denotes vehicle (b) which is used in a free rolling case for all crash scenarios. This model has been used to study the effect of vehicle dynamics control systems on vehicle collision mitigation.



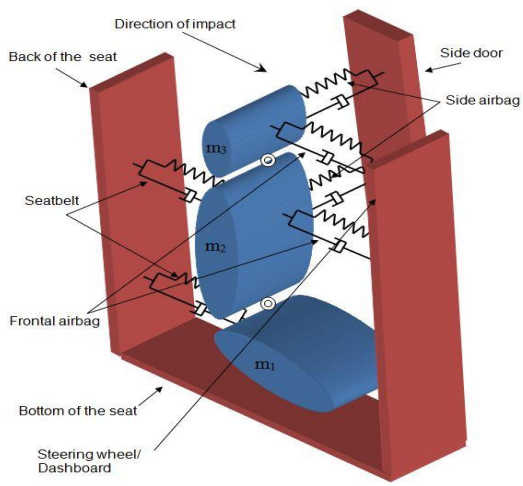
6-DOF one vehicle model ***vehicle-to-vehicle offset crash scenario***

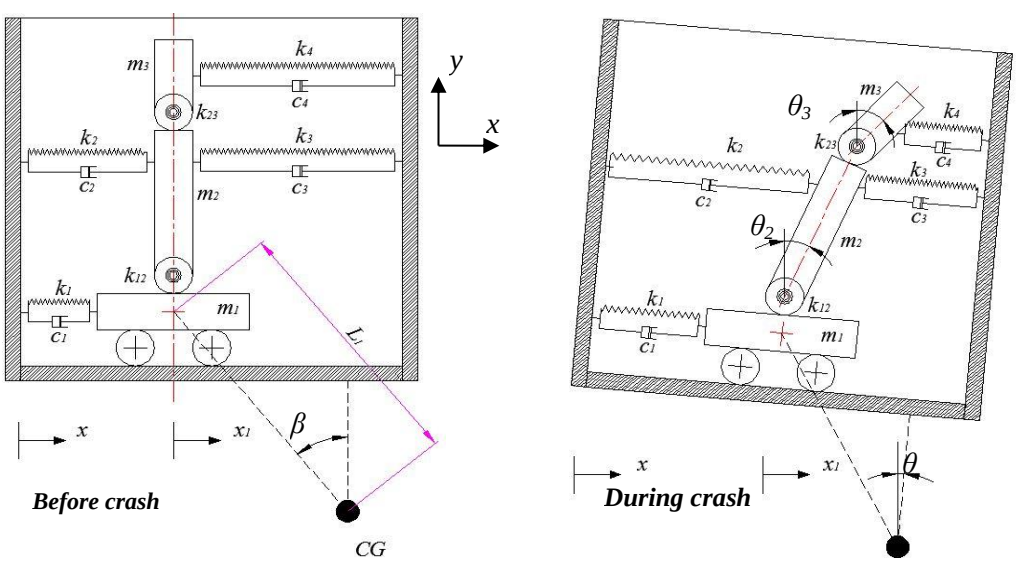
Figure 1. Vehicle dynamics/crash-mathematical model

As shown in Figure 1, four spring/damper units are used to represent the conventional vehicle suspension system. Each unit has a spring stiffness k_S and damping coefficient c. The subscripts *f, r, R* and *L* denote the front wheels, real wheels, right wheels and left wheels, respectively. The ASC system is co-simulated with the conventional suspension system to add or subtract an active force element u, and the ABS is co-simulated with the mathematical model using a simple wheel model to generate the braking force F_b. To represent the front-end structure of the vehicle, four nonlinear springs with stiffness k_s are proposed. Two springs represent the upper members (rails) and two springs represent the lower members of the vehicle frontal structure. The subscripts u denotes the upper rails while the subscript *l* denotes the lower rails. The bumper of the vehicle is represented by a lumped mass m_b and it has only a rotational motion about the point of collision. The equations of motion and control systems have been described in details in a previous study by the author [14] to predict the vehicle deceleration, pitching angle and acceleration, and yawing angle and acceleration. These outputs from the vehicle model are used as input data for the occupant model.

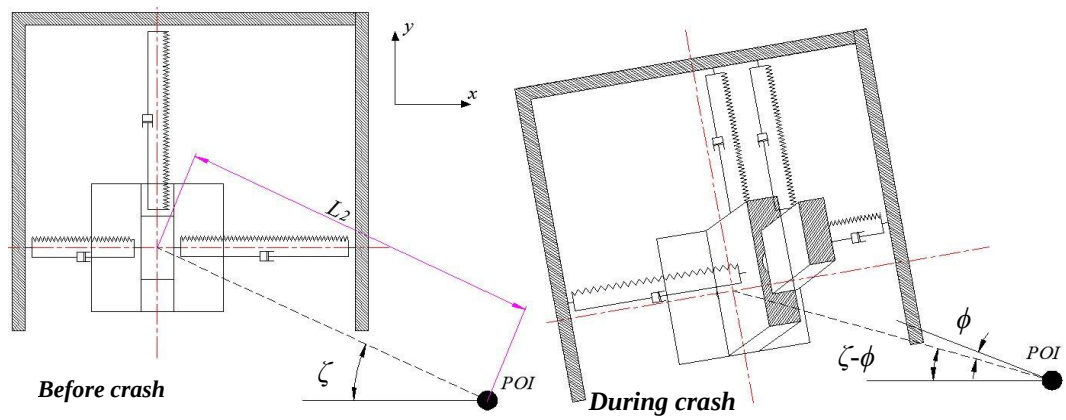
MULTI-BODY OCCUPANT MODEL (SECONDARY IMPACT)

The occupant biodynamic model, with its different views before and after the crash shown in Figure 2, is developed to evaluate the occupant kinematic behaviour during the secondary impact. The secondary impact is the interaction between the occupant and the restraint system and/or the vehicle interior due to vehicle collisions. The human body model consists of three bodies, with masses m_1, m_2 and m_3. The first body (pelvis), with mass m_1, represents the legs and the pelvic area of the occupant and it is considered to have a translation motion in the longitudinal direction and rotation motions (pitching, rolling and yawing) with the vehicle body. The second body (chest), with mass m_2, represents the occupant's abdominal area, the thorax area and the arms and it is considered to have a translation motion in the longitudinal direction and rotation motion around the pivot between the pelvis and the chest bodies (pivot 1). The third body (head), with mass m_3, represents the head and neck of the occupant and it is considered to have a translation motion in the longitudinal direction and rotation motion around the pivot between the chest and the head (pivot 2). A rotational coil spring is proposed at each pivot to represent the joint stiffness between the pelvis and the chest areas and between the chest and the head areas, respectively. The seatbelt is represented by two linear spring-damper units between the compartment and the occupant; the frontal and side airbags are represented by tow linear spring-damper units for each one.

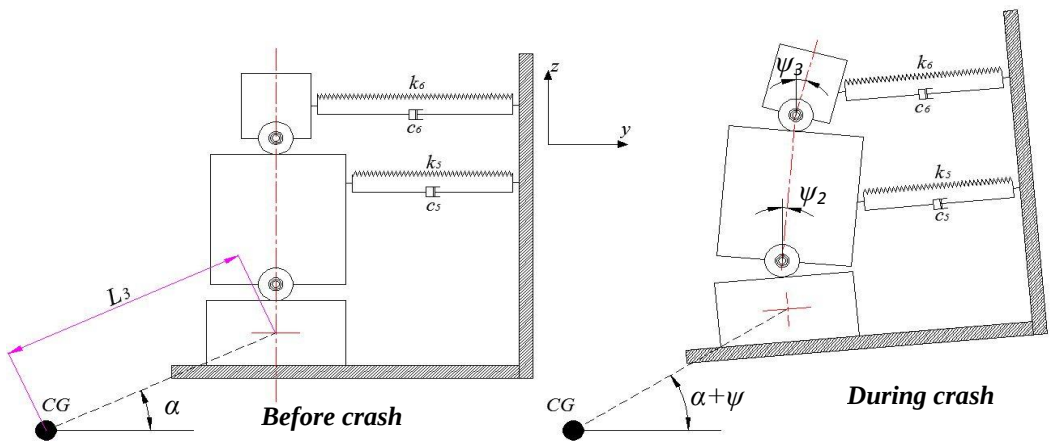




Side view of the occupant model



Top view of the occupant model (POI: Point of Impact)



Frontal view of the occupant model

Figure 2. Multi-body occupant model (secondary impact) and its different views before and during the crash

Equation of Motion (EOM) of the Human Body Model

Due to the complexity of obtaining the equation of motions directly from the system, Lagrange's equations have been used to describe the general motions of the multi-body human model as follows:

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{x}_1}\right)-\frac{\partial E}{\partial x_1}+\frac{\partial V}{\partial x_1}+\frac{\partial D}{\partial \dot{x}_1}=0 \tag{1}$$

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\theta}_2}\right)-\frac{\partial E}{\partial \theta_2}+\frac{\partial V}{\partial \theta_2}+\frac{\partial D}{\partial \dot{\theta}_2}=0 \tag{2}$$

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\theta}_3}\right)-\frac{\partial E}{\partial \theta_3}+\frac{\partial V}{\partial \theta_3}+\frac{\partial D}{\partial \dot{\theta}_3}=0 \tag{3}$$

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\psi}_2}\right)-\frac{\partial E}{\partial \psi_2}+\frac{\partial V}{\partial \psi_2}+\frac{\partial D}{\partial \dot{\psi}_2}=0 \tag{4}$$

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{\psi}_3}\right)-\frac{\partial E}{\partial \psi_3}+\frac{\partial V}{\partial \psi_3}+\frac{\partial D}{\partial \dot{\psi}_3}=0 \tag{5}$$

where E, V and D are the kinetic energy, potential energy and the Rayleigh dissipation function of the system, respectively. x_1, θ_2, θ_3, ψ_2 and ψ_3 are the longitudinal movement of the occupant's pelvis, the rotational angle of the occupant's chest about (y) axis, the rotational angle of the occupant's head about (y) axis, the rotational angle of the occupant's pelvis about (x) axis and the rotational angle of the occupant's head about (x) axis, respectively. $\dot{x}_1$, $\dot{\theta}_2$, $\dot{\theta}_3$, $\dot{\psi}_2$ and $\dot{\psi}_3$ are their velocities, respectively. To get the components of the equations 1, 2, 3, 4 and 5, the differentiations of the kinetic energy, potential energy, and Rayleigh dissipation function are determined. To solve these equations, they have been put in an integratable form and then rewritten in a matrix form. After that, different occupant's bodies responses (x_1, θ_2, θ_3, ψ_2 and ψ_3) can be determined based on the input data from the vehicle model by solving the equations numerically.

NUMERICAL SIMULATIONS OF VEHICLE-TO-VEHICLE OFFSET-COLLISION SCENARIO

Two different cases of VDCS are investigated in this section and their associated results are compared with the free rolling case scenario. These different VDCS cases are described as follows:

Case 1: Free rolling: - in this case the vehicle collides with a barrier/vehicle without applying any types of control.
Case 2: Anti-lock braking system (ABS): - in this case the anti-lock braking system is applied before and during the collision.
Case 6: Anti-lock braking system alongside under-pitch control system (ABS + UPC): - in this case, the vehicle is taken a reverse pitching angle before crash using an ASC system.

The injury criteria in this paper have been taken as occupant's pelvis deceleration, occupant's chest rotational acceleration, and head rotational acceleration. The vehicle output data (deceleration and pitching and yawing acceleration) due to the collision [14] are transferred to the occupant as a sudden deceleration to all the body. The following data is used in the numerical simulation: m_1 = 26.68 kg, m_2 = 46.06 kg, m_3 = 5.52 kg, k_{R12} = 280 Nm/rad, k_{R23} = 200 Nm/rad, l_2 = 0.427 m, l_3 = 0.24 m [10]. The total stiffness of the two seatbelt springs is 98.1 kN/m with a damping coefficient of 20% [8], and then it distributed between the upper and lower seatbelt springs by ratio of 2:3, respectively [15]. Airbag's spring stiffness is 5 kN/m and the damping coefficient is 20%. The slacks of the seatbelt springs are assumed zero, and the slack of the airbag is 0.05 m.

For the occupant's pelvis relative displacement for vehicle (a), it is shown that it increases forward to reach its maximum position and then returns due to the lower seatbelt springs. It is observed that there are insignificant differences between the values of the maximum relative displacement of the occupant's pelvis in the different cases of VDCS. Regarding to the lower-body deceleration of the vehicle (a), it is shown that it increases during the collision to reach its maximum values at the end of impact and then reduces after the effect of collision is ended. There is a sudden decrease of the deceleration at the end of collision, this is due to the reverse effect of the braking force when the vehicle changes its direction and starts to move backward. It is observed that the maximum deceleration is almost the same for all cases with very small differences. These small differences mean that the VDCS do have an insignificant effect on the pelvis relative displacement and deceleration.

The rotation angle of the occupant's chest about y axis for all cases of vehicle (a) is shown in Figure 3. The occupant's chest starts the collision with different rotational angles according to each case of the VDCS. The occupant takes this angle in the period of 1.5 sec prior collisions when the VDCS is applied. After that, the rotational angle of the occupant's chest remains constant for about 0.03 sec, then it increased to reach its maximum value after the end of the collision. The maximum rotation angle is observed in case 2, while the minimum one is observed in case 3 (ABS + UPC). The rotational acceleration about y axis of the occupant's chest is captured. The chest rotational acceleration increases gradually to reach its maximum positive value and then reduces to reach its maximum negative value. The maximum positive rotational acceleration is monitored in case 1 and the minimum one occurred in case 2, while the maximum negative rotational acceleration is shown in case 3 and the minimum is in case 2.

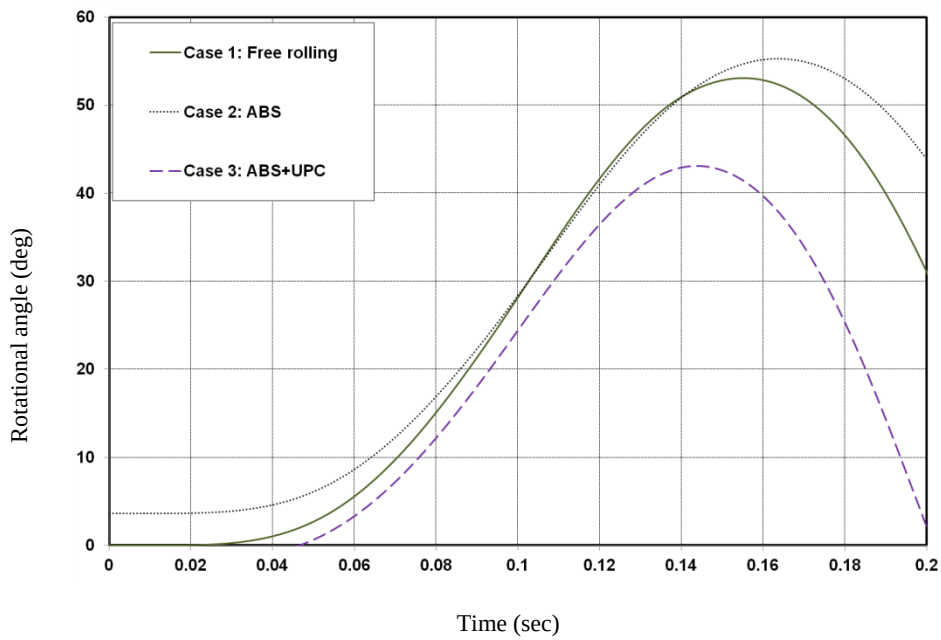


Figure 3. **Rotational angle of the occupant's chest about y axis (Offset frontal vehicle-to-vehicle impact), vehicle (a)**

The rotation angle of the occupant's head about y axis is depicted in Figure 4. The head rotation angle increases rapidly for a period of time, which occurred during the increase of the chest rotation. Then, it increases fast due to the return of the occupant's chest to reach its peak value (maximum value). The peak value of the head rotational angle is observed in case 2, while the minimum one is detected in case 3. The rotational acceleration of the occupant's head is also shown, the acceleration increases with a different manner according to each case to reach its maximum value. These maximum values occurred in different time related to each case. In other words, the maximum acceleration in cases 1 and 3 occurs approximately at 0.07 sec, while in case 2 it occurs approximately at 0.08 sec. The minimum negative acceleration is observed in cases 2, while the maximum negative values are seen in cases 1 and 3.

The rotation angle about x axis of the occupant's chest for all cases of vehicle (a) is depicted in Figure 5. When the occupant's chest reaches its maximum rotational angle, it stays in this position for a period of time while the vehicle rotates around the point of impact. The maximum rotation angle is observed in case 1 (free rolling) while the minimum angle is observed in cases 3 (ABS + UPC). The rotational acceleration of the occupant's chest about x axis for all cases of vehicle (a) is obtained. There are three sudden changes in the acceleration during collision. The first one is due to the activation of the side airbag, while the second one is due to the reverse braking force. The third sudden change of the chest acceleration is due to the deactivation of the vehicle's front-end springs, which causes a sudden decrease of the vehicle pitching, yawing and rolling. The maximum positive rotational acceleration of the occupant's chest about x axis is observed in cases 1, while the minimum value occurs in case 3. The maximum negative rotational acceleration happens in case 1 and the minimum is observed in case 3. These negative acceleration values occur due to the force generated by the lower spring-damper system of the side airbag.

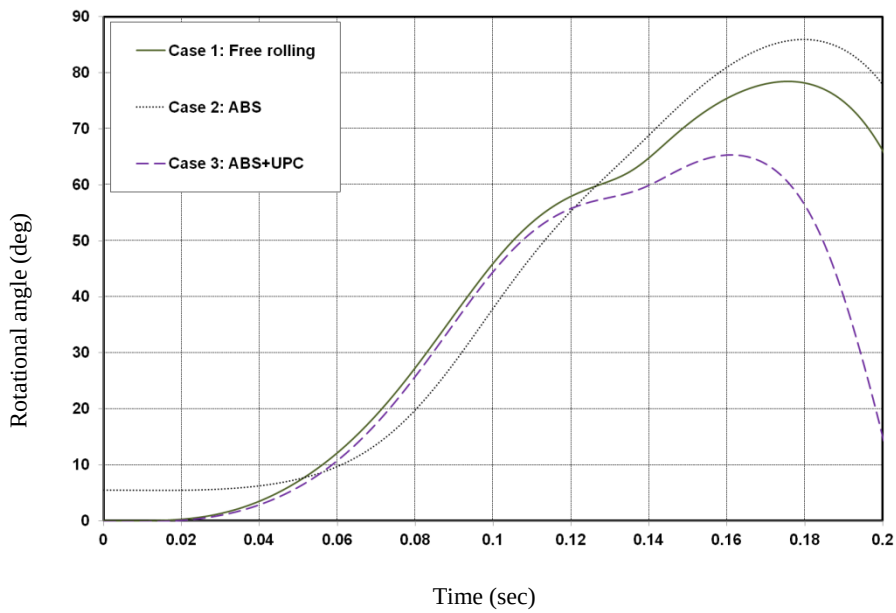


Figure 4. Rotational angle of the occupant's head about y axis (Offset frontal vehicle-to-vehicle impact), vehicle (a)

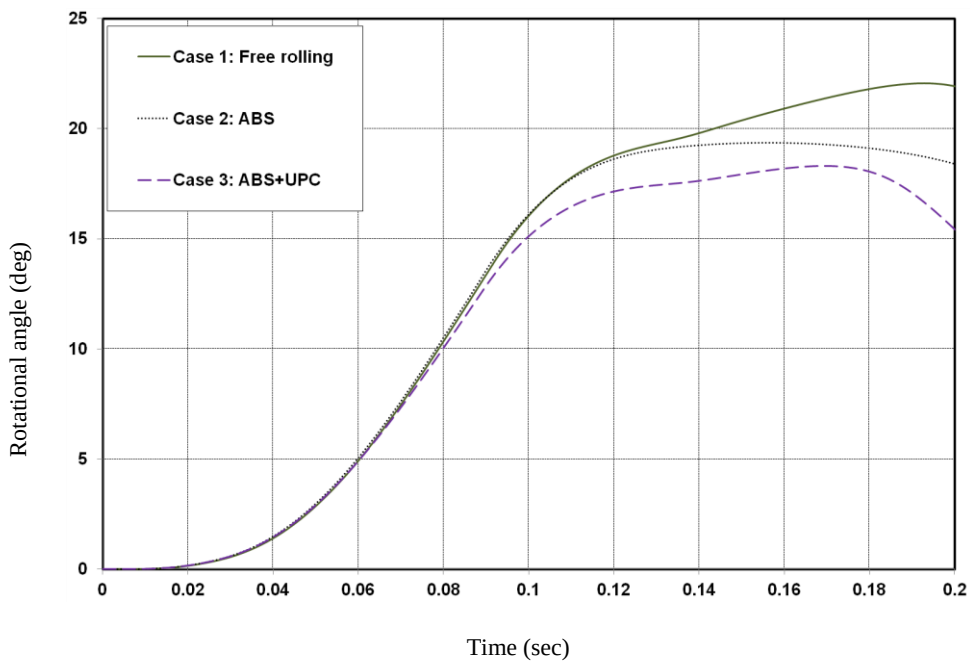


Figure 5. Rotational angle of the occupant's chest about x axis (Offset frontal vehicle-to-vehicle impact), vehicle (a)

The rotation angle about x axis of the occupant's head for the vehicle (a) is shown in Figure 6. At the beginning of the collision, while the chest takes a positive acceleration and starts rotating towards the vehicle's side door, the head takes a different negative small rotation value related to each case, all these values are close to 5 deg. The positive maximum value of the head rotational angle is observed in case 3, while the minimum peak angle is seen in case 2. The rotational acceleration about x axis of the occupant's head in all cases has been gained. The effect of the reverse braking force is observed at the end of the collision. The maximum positive acceleration (in the period from 0.06 to 0.1 sec) is almost the same for all cases, while the maximum negative acceleration (in the period from 0.1 to 0.16 sec), caused by the side airbag force, is observed in case 1 with relatively a higher value. The minimum negative acceleration is detected in case 2.

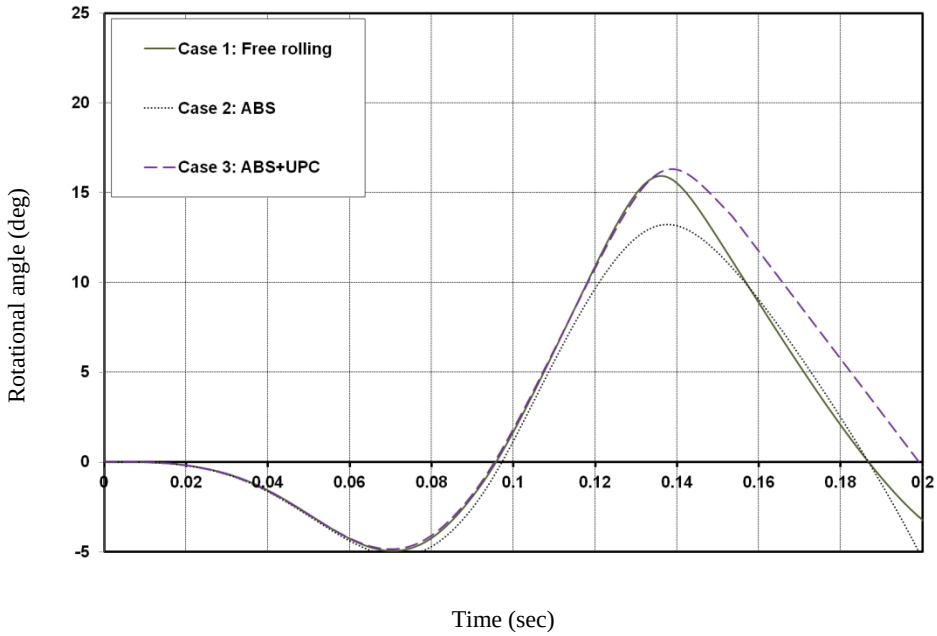


Figure 6. Rotational angle of the occupant's head about x axis (Offset frontal vehicle-to-vehicle impact), vehicle (a)

The occupant behaviour of the occupant of the vehicle (b) is also captured for all cases of the VDCS. It is shown that applying the VDCS for vehicle (a) has insignificant effect on the other vehicle.
Related to the occupant injury criteria, the occupant's head rotational accelerations appeared to be the major cause of strain-induced brain injury which it contributed to more than 80% of the brain strain and the peak amplitude of rotational acceleration must not exceed 9.4 krad/s^2 (538.5 kdeg/s^2) [16]. The results show some improvement in the occupant injury criteria, which makes the crash event more survivable. Use of under pitch technique (case 3) can help reduce the chest and head rotation angle, and head rotational acceleration. The VDCS affects the occupant's behaviour with different ways related to the applied case, and it can be seen that the applied of frontal UPC alongside ABS (case 3) can be taken as the best case due to its effect on the occupant's head (the most important part of the occupant's body). The future study, as extensions to this work, will be focused on the optimization of using different integrated VDCS.

CONCLUSIONS

A multi-body occupant mathematical model has been developed to study the effect of VDCS on the occupant dynamic response during vehicle collision. Different cases of the VDCS have been investigated in case of vehicle-to-vehicle frontal offset collision. The results obtained from a previous vehicle model have been used as the input data for the occupant model. The results show that the effect of the VDCS is quite minimal in terms of occupant relative displacement and deceleration. However, there are a significant effect on the rotations angle and acceleration of the occupant chest and head, which are greatly enhanced.

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THE INTEGRATED SAFETY CONCEPT OF THE ULTRA-COMPACT ELECTRIC VEHICLE Visio.M

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ABSTRACT

A great opportunity for increasing range and decreasing the production costs of battery-powered vehicles is to lower vehicle weight as far as possible. To this end, designers not only can incorporate lightweight materials, but also reduce the size of the vehicle and limit the equipment installed as excellent weight-saving strategies. Since this strategy could lead to crash incompatibility, ultra-compact electric cars are subjected to enormous loads in the event of a collision with a heavier vehicle. The high structural rigidity and limited deformation paths produce a high crash pulse, with higher forces acting on occupants than are experienced in conventional vehicles. The objective of the safety task force within the Visio.M project funded by the German government was to draft, implement, and test a concept that resolves these conflicting interests and provides sufficient protection for ultra-compact vehicles. Using an analysis of the potential accident scenario involving ultra-compact electric vehicles as a starting point, specific safety requirements were derived for these vehicles. To meet these requirements, a strategy for an integrated safety design was developed to reduce the occupant loads. The integrated safety concept incorporates pre-crash systems, occupant protection systems, and a CFRP monocoque, among other features, and was developed using numeric simulations. Verifiable proof of the operative function and benefit of the safety concept was provided by leveraging numerical simulation techniques, carrying out comprehensive component tests, and conducting a series of full-scale crash tests using a Visio.M prototype. In the end, the integrated safety strategy is the key to realizing a sufficient level of protection for sub-compact vehicles.

INTRODUCTION

According to targets set by the German federal government, one million vehicles powered by alternative technologies should be running on German roads by 2020. By 2030, this figure is expected to grow to 6 million. Efficient, electrically powered small motorized vehicles have the potential of driving the expansion of electromobility forward. Yet most previous concepts have either been too heavy or too expensive, or do not reach the safety level expected by the market. Traffic experts have expressed concern that the current safety level for vehicles of the L7E homologation category (quadricycle category) is insufficient for mass traffic. Tests by Euro NCAP partially revealed serious deficiencies in vehicles of the L7E homologation category. Currently, safety requirements in the quadricycle category are low, but safety experts are demanding effective occupant protection if the number of ultra-compact vehicles circulating on roads should increase. The Visio.M Consortium has taken on

this challenge and is developing concepts for electric vehicles that are not only efficient and cost-effective to manufacture but are also considered to be safe. In particular, the Safety workgroup led by Daimler AG was working with its partners Autoliv, IAV and the Technical University of Munich on developing and implementing an integrated safety concept (See Figure 1) and verifying its worthiness.

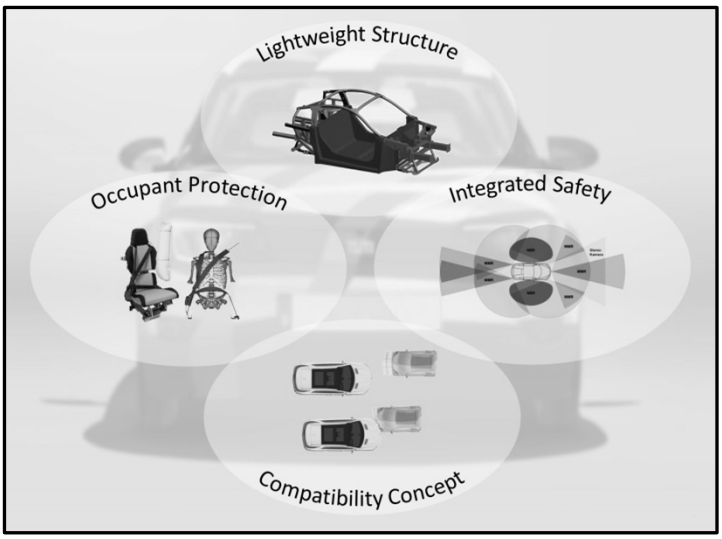

Figure1. The integrated safety concept of the ultra-compact vehicle Visio.M.

BOUNDARY CONDITIONS

Ultra-compact vehicles and safety

Discussions concerning the appeal and acceptance of battery-powered vehicles center on their limited range. A major opportunity for increasing their range while decreasing production costs is to lower vehicle weight as far as possible. Weight-saving strategies with considerable potential that are being employed by designers are the incorporation of lightweight materials, the reduction in vehicle size and limiting the equipment installed in the vehicle. This opens up new possibilities in terms of vehicle homologation. Vehicles with a curb weight of up to 400 kg (450 kg beginning in 2016) without an energy storage unit and a maximum continuous output of 15 kW are not considered to be conventional passenger cars of the M1 vehicle class, but can be homologated as category L7E vehicles. The limited requirements that apply to vehicles of this category, which are similar to today's passenger cars both in terms of their characteristics and usage, result in the risk that important yet non-regulated safety standards will be disregarded. Ultra-compact vehicles that circulate on public roads are particularly vulnerable to the high forces which occur during a collision with heavier vehicles since their reduced weight and the resulting large differences in mass to conventional vehicles on the market today lead to crash incompatibility. The necessarily high structural stiffness as well as the smaller deformation zones inherent to ultra-compact vehicles lead to a high crash pulse and, compared to conventional vehicles, to considerably higher forces that act on the occupants. In conjunction with reduced safety features, this crash incompatibility results in a greater risk to the occupants. However, to avoid negatively impacting the broad acceptance of electric vehicles and to ensure occupant safety, there should be no discrepancies to conventional vehicles regarding the level of occupant protection in actual accident situations. Against this background, the approach used in the Visio.M project, which is to align the vehicle target weight with the weight limit of the L7E approval category, presents a major challenge to the design of the occupant protection systems. Despite the limited requirements for this category, the vehicle should reach an adequate safety level that is in accordance with the specific requirements dictated by how the vehicle is used and the expectations of

customers and society. An analysis of the actual accident situation is the basis for defining the requirements placed on the safety concept of the Visio.M. The goal is to evaluate the potential risks of this vehicle type under the boundary conditions related to its specific usage in general traffic situations.

Analysis of potential accident situations of ultra-compact vehicles

In cooperation with the traffic accident research department at the Technical University of Dresden, one aspect of the Visio.M project was to analyze the potential accident situations of ultra-compact vehicles in comparison with current general accident situations. The analysis is based on the GIDAS (German In-Depth Accident Study) database, in which around 2000 accidents from the greater Dresden and Hannover areas have been documented and reconstructed since 1999. Based on accident data from all accident passenger cars of model year 1995 or later, which were used as the control group, general statements were first made on the overall accident situation in Germany. In contrast, however, there are almost no accident data on ultra-compact vehicles because of their limited presence on the market at this time. The potential accident situation of these vehicles was therefore analyzed using the GIDAS data for passenger cars most closely related to ultra-compact vehicles because of their small size, usage characteristics and use conditions. The analysis concentrates on making a prognosis of the accident situation that can be expected to develop in the next several years for electric ultra-compact vehicles. The evaluation of the accident data shows a significant shift of the accident type toward urban scenarios for ultra-compact vehicles compared to other groups (See Figure 2). Thus, compared to accidents in general, ultra-compact vehicles can be expected to be considerably less involved in front/rear collisions yet will be more subject to lateral collisions due to the growth of intersection accidents. The analysis of the impact distribution shows that the great majority of front/rear collisions are frontal impacts in which a considerable overlap occurred. Side pole collisions, which frequently lead to serious injury in accidents in general, played a subordinate role in accidents involving ultra-compact vehicles in urban use. While the share of collisions with bicyclists increased for ultra-compact vehicles in urban use, no difference could be determined between the two groups regarding the frequency of pedestrian collisions, rollovers and tipping. The shift of accident situations toward urban accident scenarios means that only approx. two in three urban accidents result in an endangerment of occupants.

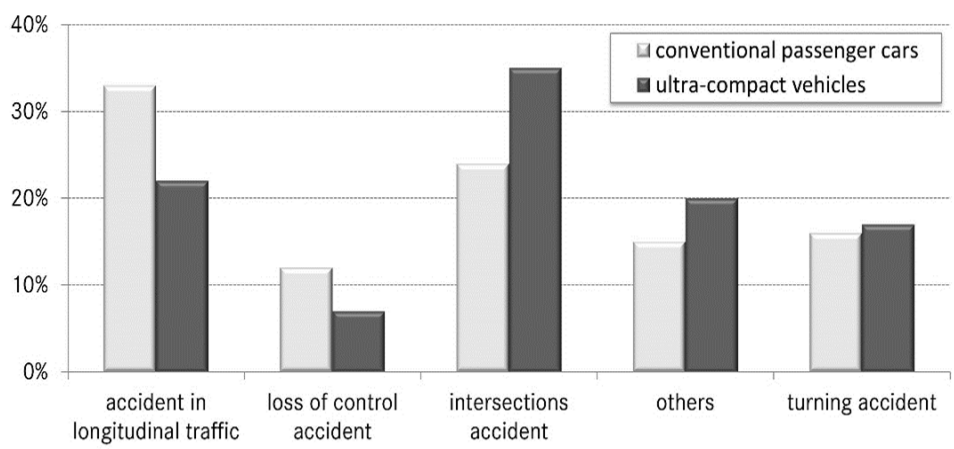

Figure2. Distribution of accident types for conventional passenger cars and ultra-compact vehicles.

The analysis also showed that because accident situations involving ultra-compact vehicles are concentrated in urban traffic regions, collision speeds are considerably lower. In conjunction with the low mass of ultra-compact vehicles, this results in a general reduction in the overall collision energy. However, in a collision with a heavy accident counterpart, these smaller and lighter vehicles can only partially benefit from this advantage since they must absorb a large share of the collision energy. The accident severities resulting for an ultra-compact vehicle with a curb weight of approx. 450 kg in frontal and side collisions were predicted by the accident analysis based on energy-equivalent computations. To evaluate the accident severity of frontal collisions, the respective energy equivalent speed (EES) was computed. The distribution functions of the respective EES values show that ultra-compact vehicles are subjected to an EES of more than 30 km/h in 40% of all frontal collisions, while this is the case in only 20% of all frontal collisions of accidents in general. The majority of frontal accidents expected for ultra-compact vehicles have an EES of up to 55 km/h. To estimate the accident severity of side collisions, the energy-equivalent value was calculated for the collision speeds observed for the group of ultra-compact vehicles relative to the mass of the side impact barrier used by Euro NCAP. A comparison with the distribution of the equivalent collision speeds of the impact vehicles in the current accident situation in general shows that similar accident severities can be expected on average for both groups.

Requirements placed on the safety of the Visio.M vehicle

The evaluation and assessment of accident data show that special safety requirements exist for electric ultra-compact vehicles compared to conventional passenger cars due to the urban nature of the accident situations, crash compatibility and the associated changes in the collision speeds. The test scenarios used to verify the crash safety of electric ultra-compact vehicles in frontal and side impacts under the current traffic and infrastructure conditions are orientated on the predicted energy-equivalent values, taking into account the expected impact constellations. The performance of the vehicle structure should be in accordance with today's established safety standards: It must ensure a stable passenger compartment and prevent battery intrusions while providing deformation areas specifically designed for energy absorption. These considerations along with assessments of the potential risk for the group of ultra-compact vehicles give rise to the demand for equipping these vehicles with comprehensive integrated safety systems that prevent accidents or reduce their severity. In addition, the vehicle structure and occupant protection systems should be designed for the following load cases:

- Frontal impact: 40% offset, ODB, 64 km/h; Euro-NCAP
- Side impact: MDB, 50 km/h, ECE R95
- Criteria:
  - Stable passenger cell, no battery intrusion
  - Occupant load values fulfill legal requirements, ideally Euro NCAP 5 stars

For both load cases, the design is confirmed in full scale crash tests with a prototype. In addition, further load cases such as rear crashes as per ECE R32, pole side impacts as per Euro NCAP configuration and a roof depression test were examined and verified by simulation with respect to the vehicle structure. Based on these requirements, an overall safety concept was drafted initially and the individual elements were then designed and worked out in detail.

Safety concept

The requirement for a stable passenger compartment results in a very stiff design of the vehicle structure in small and very light vehicles. In conjunction with the great speed changes that ultra-compact vehicles experience due to the differences in mass of the collision partners, this high stiffness leads to a hard crash pulse and thus to high occupant loads. This must be taken into account by the occupant protection concept. In addition to these requirements, steps should be taken to reduce the accident severity or ideally to prevent

accidents altogether. This results in an integrated safety concept consisting of a vehicle assistance system, pre-crash and in-crash measures and a hybrid vehicle structure. A comprehensive system consisting of radar and camera sensors provides 360° detection of the vehicle environment and thus forms the basis of accident prevention and collision mitigation systems such as autonomous emergency braking and lane departure warning systems. To counteract the increase in turning/intersection accidents, an intersection assistance system is considered to have great potential. In addition, to prevent impending rear collisions, various strategies are being examined that enable vehicle evasion toward the front. In this connection, the electrical drive and the low weight of ultra-compact vehicles are proving to be highly advantageous. During an accident, the vehicle structure plays a key role. In the defined load cases, it must provide for a stiff passenger compartment to secure the occupant survival space on the one hand, while also providing a sufficient deformation range for absorbing collision energy on the other. The lightweight structure concept of the Visio.M vehicle is therefore based on an aluminum and carbon fiber reinforced plastic (CFRP) hybrid design. The closed passenger cell is built using an innovative, multi-part monocoque of CFRP and is characterized by a particularly high degree of stiffness. The structure of the front and rear sections of the vehicle consists of aluminum profiles to achieve the highest possible defined energy absorption with sufficient strength and stiffness. However, because of the small dimensions of ultra-compact vehicles, the deformation path made available by the crash structures in the front and rear sections of the vehicle are limited. The innovative safety concept being developed therefore focuses on a needs-oriented extension of the effective deformation zones in the front and side areas of the vehicle in the form of pyrotechnically deployed structure-airbags. To ensure that the deformation zones required to absorb the impact energy are available at the time of the collision, these crash-active systems must be triggered in the pre-crash phase, in the last few milliseconds before an accident that has been assessed as being unavoidable occurs. The crash pulse resulting from frontal impacts in ultra-compact vehicles, which exerts a larger influence on occupants than in conventional vehicle designs, is counteracted by means of an innovative seat belt system consisting of a three-point seat belt and an additional two-point seat belt. Because there is a high risk of serious injury to occupants on the impact side of the vehicle due to the close distance between the door and the occupant in ultra-compact vehicles e.g. caused by vehicle elements intruding into the passenger compartment, an active lateral displacement of the occupant on the impact side of the vehicle toward the middle of the vehicle is provided in the final milliseconds prior to a side collision. As a result of this pre-acceleration, the crash pulse acting on the occupant can be further reduced. The integral protection strategy can be summarized as follows, subdivided into the particular load cases:

- Frontal impact: Pre-crash sensing / initiation of automatic emergency braking / active extension of the crash length through deployment of a structure-airbag / positioning and optimal restraint of the occupants with high performance belt tensioners and a 3+2-point seat belt system / energy absorption through the crash structure / prevention of intrusions through sturdy CFRP monocoque / controllable force limitation/deployment of airbags to prevent collision with hard interior structures
- Side collisions: Pre-crash sensing / intersection assistant activation / optimal restraint of occupants with high performance belt tensioners and a 3+2-point seat belt system and activation of a lateral occupant displacement / active increase of the side stiffness of the vehicle through deployment of a structure-airbag / prevention of intrusions through sturdy CFRP monocoque / deployment of airbags for early restraint and prevention of contact with hard interior structures, penetrating structures / deployment of airbags to prevent crash-related interactions between vehicle occupants
- Rear impact: Pre-crash sensing / activation of automatic evasion toward the front / positioning and optimal restraint of passengers with high performance belt tensioners and a 3+2-point seat belt system / energy absorption through crash structure / prevention of intrusions into the passenger compartment through sturdy CFRP monocoque

An additional requirement in electric ultra-compact vehicles is that the high-voltage system must be electrically disconnected from the battery as soon as a heavy impact is detected to prevent electric shock and the risk of fire. A detailed description of the components and functions and their design is provided in the following chapters.

SAFETY COMPONENTS AND SYSTEMS

Assistance systems/environment sensing electronics

A complex sensor and control system was designed for the Visio.M vehicle with respect to the needs-oriented control of restraint components. A combination of radar and camera sensors creates a "virtual 360° safety cocoon" around the vehicle. The principle of sensor redundancy was applied for the planned pre-crash deployments. The sensors are designed for a comprehensive vehicle assistance package (e.g. Euro NCAP 2020). They help to prevent critical driving situations as well as accidents and were used to trigger pre-crash systems. The evaluation of the integral functions of the individual components was conducted in a simulation using selected urban intersection scenarios.

Restraint systems

The core element of the restraint system is a highly adaptive belt system consisting of a three-point seat belt with an additional two-point seat belt. This 3+2 seat belt design (See Figure 3, left) provides for optimal occupant restraint and largely prevents uncontrolled occupant movement during frontal and side impacts and rollovers. The forces on the occupants during a crash are controlled by optimally coordinated actions of electrically controlled, adaptive belt tensioner and force limiter systems. The electrically controlled high performance belt tensioner achieves a restraint force of up to 900 N. In connection with the pre-crash sensing of frontal and rear collisions, this makes is possible to keep occupants in their optimal seating position, or even to pull them back from an unfavorable position, even in the case of an autonomous full brake application. Airbag systems in passenger compartments are consistently only used where an impact with a hard vehicle structure or an interaction between the passengers must be prevented. A conventional driver airbag module is used in the steering wheel. Adaptive components such as multistage deployment or active venting can be added if required. Lateral protection is afforded by the combination of a head airbag mounted on the roof frame and a thorax-pelvis airbag attached to the body shell. Because of the specific seating design of the Visio.M vehicle in which there is no seat adjustment along the vehicle longitudinal axis (fixed-eye-point design), it is impossible for a belted front passenger to make contact with the dashboard. For this reason, standard installations of a front passenger airbag and knee airbag are not required. The fixed-eye-point design additionally makes it possible to precisely define the area in which protection must be provided and helps in designing compact modules. A special feature is the protection system against interaction between the driver and front passenger. In the event of a crash, an airbag is deployed between the shoulders and heads of the vehicle occupants to prevent them from being thrown against each other. The airbag is mounted at shoulder height on the driver's seat in the vehicle interior.

Active lateral occupant displacement

Another innovation is the active lateral displacement of the vehicle occupant (See Figure 3, left) on the impact side in the event of side collisions. Investigations have shown that it is possible to displace the seat and the occupant by approx. 100 mm toward the center of the vehicle through a pre-crash triggering that occurs approx. 150 ms before a collision. Simulations demonstrate that the load reduction averages 22.3 %. In addition, the boundary conditions for designing the side airbags are improved. The occupant displacement mechanism is implemented using a pyrotechnical actuator in the seat. The seat also houses the unlocking mechanism, the shock absorption at the end of the movement and the seat fixation after displacement. Use of

this function requires the space in the center of the vehicle, which exists in the Visio.M (missing center console/tunnel), and an interaction protection mechanism between the occupants.

Figure3. Active lateral occupant displacement, 3+2 seat belt design and sidebag (early design phase) and Frontal structure-airbag.

Structure-airbags

Another innovative feature is the structure-airbag concept (See Figure 3, right) for actively influencing the crash pulse during frontal and side collisions. Triggered before a collision, a hose fabric is filled with gas (approx. 16 bar) and supports the composite structure of the vehicle as a load-absorbing element. For frontal protection, this structure airbag is mounted on the cross member behind the bumper covering. When activated, the covering is pushed forward by approx. 12 cm directly prior to the crash (approx. 50 ms) and the structure-airbag behind it contributes to an effective extension of the useable crumble zone. To fill the structure airbag, a gas generator technology is used which largely operates without pyrotechnics and whose performance is therefore minimally dependent on temperature and which is especially aging resistant. Operating pressures up to 30 bar achieve support forces of up to 300 N/cm². Burst membranes are used to specifically release pressure in the structure airbag by means of controlled venting of the stored energy. The same technology is used to provide protection during side collisions. Integrated in the door module, this structure-airbag pushes the lower area of the door outward immediately prior to a collision, establishes a stiffening connection between the A and B-pillars and counteracts overriding of the door sill. The design of the structure airbag and the occupant protection components is closely coordinated with the performance of the vehicle structure.

VEHICLE STRUCTURE

Structure concept

The structure concept of the Visio.M vehicle is based on the requirement for lightweight design on the one hand, and on the safety requirements for ultra-compact vehicles on the other. The hybrid structure (See Figure 4) enables a stiff vehicle passenger compartment for securing the survival space in the presence of a sufficient deformation path for specific energy dissipation through the use of different materials in different areas of the vehicle. To secure the survival space, the passenger compartment is built with an extremely stiff, multi-part monocoque in a shell design. The low seating position in the vehicle permits an almost complete protection of the occupants while material use through the monocoque is kept to a minimum. The monocoque consists of CFRP materials. With the "tub-like" shape of the monocoque, the lightweight construction material – which is still expensive at this time – is used to preserve the passenger compartment in the event of a crash. All other crash-related areas in the structure are made of the less-expensive standard aluminum profiles to achieve the greatest possible energy absorption levels with sufficient strength and stiffness.

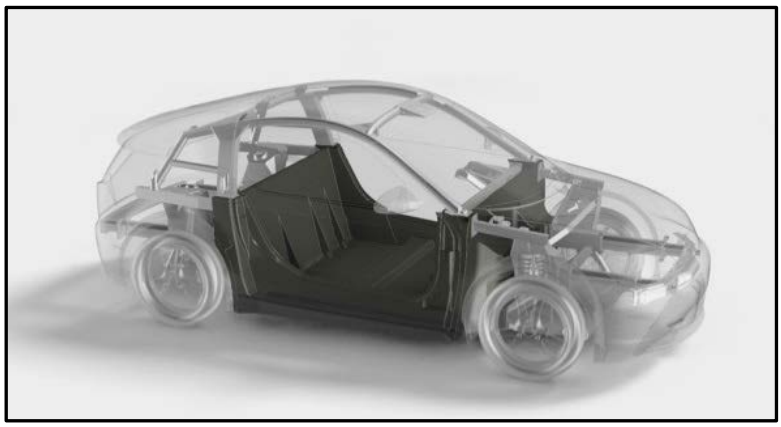

Figure4. Hybrid structure of the Visio.M vehicle.

Monocoque

The structural design of the monocoque consists of 11 single parts which were manufactured from CFRP using prepreg as semi-finished material with CFRP tools. The low number of components made it necessary to develop single parts in such a manner that their package, design and structure are multi-functional and optimally designed in terms of production and joining. In light of the possibility of a small series production, CFRP tools were selected because they achieve a considerably higher number of pieces while reaching smaller production tolerances than epoxy tools. The prepreg semi-finished products used were both woven and unidirectional mats, which were used in various areas of the monocoque depending on the load and design. By means of the local use of lightweight cores, such as Rohacell and aluminum honeycombs, the single parts were joined in a device with structure adhesive and then hardened using the autoclave process to form the component. By designing the adhesive flanges according to the applied load, it was possible to eliminate the need for other joining methods. After completion of the monocoque, all joints were analyzed for uniform thickness distribution and voids using ultrasound technology to rule out the possibility of errors in the joining process. To ensure the integrity of the structure, multiple quasi-static pressure tests were conducted. The monocoque was clamped into a device and forces derived from the crash simulation were applied to the points of load application in the front, rear and side wall areas. To perform an acoustic analysis, measurement heads were attached to the surface of the monocoque. The evaluation and analysis of the acoustic signals are used to detect and localize situations critical to the fiber composite. By steadily increasing the load, the load limit of the component is slowly approached without destroying the component, and in this way the computational design of the component can be validated. In addition, the ultrasound test and noise emission test are used for component analysis after the conduction of the crash tests to identify inside or outside damage to the fiber matrix composite and joints that may not be visible.

Doors

The multi-part door design consisting of an inner and outer part with an integrated shaft reinforcement and side collision brackets is also made of CFRP and closes off the passenger compartment on the side. The small installation space between the driver and the outer part make a very stiff door structure necessary. Because of the broad overlap with the door, the monocoque also contributes to the safety of the occupants with its especially high sill in the transition area to the B-pillar. With a total of only 4 structure-related components, the doors contribute to a reduction in the production costs thanks to the integration of functions as well. In addition to the usual components such as the door lock, window lift, loudspeaker, sensors and electrics, the door also incorporates the structure-airbag (see above).

Crash structure

The crash structure in the front section of the vehicle, roof frame and rear section of the vehicle consists of a wide variety of conventional standard aluminum profiles and sheets. Aluminum alloys of the 6000 series were used, which were produced specifically for prototypes using WIG manual welding on a welding device and which then obtained their final strength through T6 heat treatment.

LAYOUT AND VALIDATION

The following paragraphs will give some examples of the different methods which were used during the development phase of the integrated safety concept of the Visio.M vehicle.

Simulations of the integrated safety concept

Many of the components of the integrated safety concept are activated before an accident occurs. The data required for deployment are provided by the environment sensors. Because deployment of irreversible safety components such as the structure-airbag or the active lateral occupant displacement must be absolutely reliable, their validation is closely linked to that of the sensor system. In addition, the safety components only develop their full potential if they are activated in a defined time period prior to the accident. Typical sensor characteristics such as the latency periods, as well as the run times of the associated algorithms, can have a considerable impact on the performance of the safety components (See Figure5). Consequently, the expense of validating these system is high, but can be moderated through the use of simulations. Another advantage is the fact that it is possible to begin with the simulation-based validation very early in the development process since it does not rely on the availability of the components. The simulation of traffic scenarios has the big advantage that they are reproducible, unlike tests on the vehicle testing site. Thus it is possible to focus on a range of different aspects of the safety concept, since the input data are always the same. Based on the use characteristics of the Visio.M vehicle, an entire catalog of urban scenarios was developed and the interplay of the integrated safety concept was designed accordingly. In this way, it was possible to specify the safety concept at a very early stage of development without a prototype. The definition of an accident situation and non-accident situation for these scenarios makes it possible to easily and fully classify the simulation space. Moreover, the following tests and validations of the synthetic sensor system can be performed based on this material. Thus, a procedure was used that can specify, test and validate the sensor and safety features being used for a large number of specific traffic scenarios.

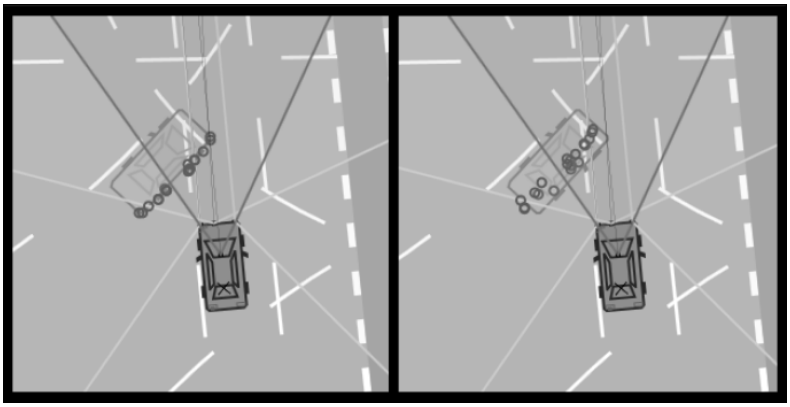

Figure5. Comparison of an ideal sensor and a sensor considering latency period and noise.

Based on this, the installation position, angle of view and range of the environment sensors were defined so that especially critical intersection scenarios can be detected almost as early as necessary. A variety of sensor technologies were used for the integrated safety concept to ensure redundant coverage of critical areas around the vehicle and to make use of the advantages of the different technologies in an optimal fashion. Based on a synthetic sensor concept, the environment sensor system is simulated independently of the technology. For the individual sensors, specific properties such as the cycle rates, ranges, detection probabilities, occlusion probabilities and overlap signals are modeled. Using this principle, the safety concept can be initially validated for a 100% sensor to identify limitations early on and to counter these effectively. In the next step, the influences of the sensors on the performance of the safety concept were examined to determine if the individual components can be triggered reliably. In particular, the simulation of the cycle rates, the latency periods during sensing and the estimates of the run times of the underlying algorithms are coordinated so that the components can develop their full potential in protecting passengers.

Simulations and tests regarding the vehicle structure

The monocoque, doors and aluminum structure packages were subjected to multiple optimization loops overall. To develop a lightweight structure that is appropriate for the load path, one of the techniques applied was the topology optimization method. This optimization method is used to identify load paths within the available installation space. Based on structural mechanical requirements, a static load spectrum was derived for the finite element model, which contained chassis loads, stiffnesses and impact loads. The identified optimal load paths were used in the course of the project as a basis for developing the body shell. To be able to perform design calculations for the specific materials, precise material models are required. The aluminum alloys EN AW-6060 T6 and EN AW-6082 T6 are used in the front and rear sections of the vehicle and in the roof frame. Because the characteristic material parameters vary with heat treatment, for example, the samples of the materials used were characterized. The characteristic material parameters are critical for simulating the impact behavior because they have a highly sensitive response to the material modeling. Based on various tests, these materials were characterized and the corresponding material models were derived from the findings. Although the material EN AW-6082 T6 has a higher yield point than EN AW-6060 T6 (230 MPa compared to 200 MPa), the elongation after fracture is considerably lower (approx. 12% compared to approx. 17%). The material EN AW-6082 T6 is more suitable for structural areas with static loads. However, if high energy absorptions are required that are associated with high plastic deformations, material EN AW-6060 T6 is used. Furthermore, the calculation was validated using component tests (quasistatic pressure tests) with the longitudinal members from the aluminum front section structure. The goal was to determine the deformation behavior and the force level of the longitudinal members using the previously established characteristic material parameters and to compare these results with the calculation results. The findings from the component test and simulations were used to adapt the aluminum crash structure to the design load cases. The design began with a “0° rigid wall“ test with full-width impacts. The overlap of the structural deformation values obtained from the calculation and from the test showed very good agreement and confirmed the calculated design of the aluminum structure. For the design of the CFRP monocoque as the central component of the structural concept, a "zero intrusion cell" for frontal and rear impacts was defined as a requirement on account of the small size of the passenger compartment. It was based on static and dynamic calculations. The dynamic calculations involved implementation of the characteristic material parameters of the various CFRP materials into the calculation model. For this purpose, component tests were performed to establish the corresponding damage parameters for the constitutive laws in use. The material models determined in this way were used to identify areas in the monocoque that are subject to high loads.

RESULTS OF FULL SCALE CRASH TESTS

According to the load cases which were defined as requirements on the integrated safety concept of the Visio.M vehicle at the beginning of the development phase three full scale crash tests using a Visio.M prototype were conducted to prove the efficiency of the concept:

1. Frontal impact: 40% offset, ODB, 64 km/h; Euro-NCAP, without deployment of structure-airbag

2. Frontal impact: 40% offset, ODB, 64 km/h; Euro-NCAP, with deployment of structure-airbag

3. Side impact: MDB, 50 km/h, ECE R95

The two frontal impact tests differed in the deployment of the structure-airbag with the objective of figuring out its benefit.

Frontal and side impact

The tests were conducted with a total mass of the Visio.M prototype (See Figure 6, left) including measurement instrumentation, Dummies etc. of 700 kg. The vehicle structure and the occupant restraint systems were acting in accordance with their design. The monocoque kept stable and avoided the intrusion of components into the passenger compartment. The analysis of the occupant load values according to the Euro-NCAP [1] test protocol for the adult occupant protection box and the offset frontal impact show a result with 15,74 (driver) and 16 (passenger) of 16 possible points. The side impact (See Figure 6, right) was conducted with just one dummy located on the driver's seat. Its load has also a respectable value of 13,704 of 16 possible points.

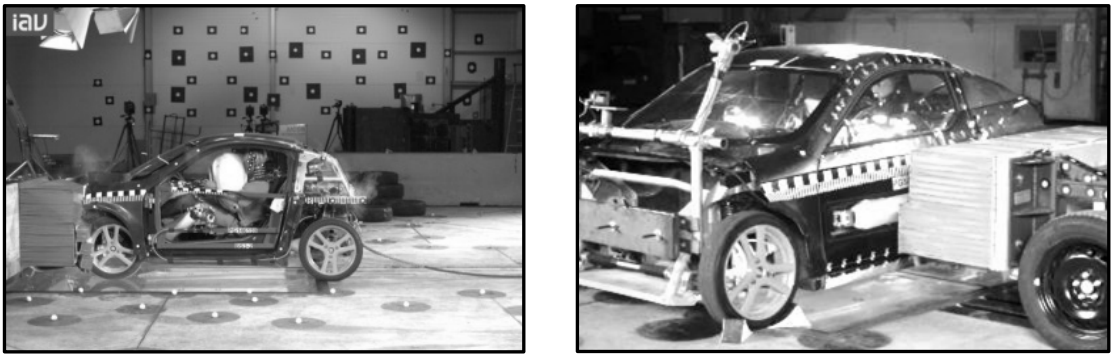

Figure6. Frontal impact: 40% offset, ODB, 64 km/h, Euro-NCAP and Side impact: MDB, 50 km/h, ECE R95.

CONCLUSION

The work and the results of the Safety workgroup of the Visio.M project indicate that, by the use of innovative safety systems and methods, it seems to be possible to reach an acceptable level of occupant safety for ultra-compact vehicles which is comparable to those of compact cars. Even if most of the specified systems and components have just reached a prototype status, the integrated safety concept of the Visio.M vehicle could be beneficial to push the acceptance and thus the market penetration of electrically powered small motorized vehicles in recent years. On the other hand it is questioned if the safety requirements of the L7E vehicle class are sufficient for ultra-compact

[1] Just one test scenario of the Euro-NCAP test protocol was part of the Visio.M load cases – Thus, prediction of a star rating and is not feasible and even was not goal of the working group

vehicles with the character of the Visio.M or a separate homologation class for such vehicles is reasonable. However, this paper shows that higher levels of safety are achievable.

ACKNOWLEDGEMENT

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OCCUPANT PROTECTION IN REAR-END COLLISIONS PRECEDED BY AUTONOMOUS EMERGENCY BRAKING DEPLOYMENT

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ABSTRACT

The safety of vehicle occupants has evolved recently due to the market implementations of new sensing technologies that enable predicting and identifying hazardous road traffic situations and thus actively prevent or mitigate collisions. The obvious benefits of the active safety systems has also been recognized and acknowledged by the regulatory and consumer bodies responsible for transportation, and as a result, the new standards, regulations and public rewards are being introduced.
The active safety systems can prevent or mitigate collisions by controlling the motion of the vehicles through autonomous actuation of either: braking, steering or both simultaneously. The autonomous control of the vehicle inevitably affects the motion of the travelling occupants with respect to the vehicle interior. Depending on the severity of the maneuver, the occupant motion may lead to non-optimal postures for the in-crash phase if the collision is unavoidable. This consideration creates the direct need for developing the active systems together with passive systems with the ultimate objective to best protect the occupants. This paper presents a simulation methodology for developing new automotive safety systems in an integrated manner that ensures optimal exploitation of benefits of predictive sensing and occupant restraints. It also demonstrates the application of the above methods, to investigate and optimize the occupant whiplash protection in rear-end collisions occurring during the autonomous emergency braking of the collided vehicle.

The investigation was performed using simulation techniques (MADYMO software). The driver occupant is initially exposed to the low-g longitudinal acceleration resulting from emergency braking, during which the rear-end acceleration pulse is applied, representing the collision conditions (following the High Severity Sled Pulse of Euro NCAP Whiplash testing protocol). Two different models of anthropometric test devices are used and compared: BioRID-II facet Q model and Active Human Model (AHM) to predict occupant motion while braking and assess injury risk as a result of the rear-end collision.

The results obtained showed the severity of the out-of-position occupant posture created by the autonomous braking maneuver, and its effect on injury risk in the consecutive collision. It was observed that the occupant motion resulting from braking is more pronounced in case of AHM than BioRID-II. Increased occupant travel during pre-braking impairs significantly the effectiveness of occupant rear-end protection restraint systems, thus increasing the whiplash injury risk. Further study demonstrates conceptual, pre-crash deployed safety solutions that alleviate the negative effects of the out-of-position postures created by pre-braking.

The study shows the need for developing the new safety systems in an integrated manner. It was performed based on the numerical simulations and some of the model components were not fully validated. The simulation methods and techniques will play a significant role in the integrated safety systems development processes, allowing testing the conditions of high complexity in order to represent the real life scenarios and thus ensuring better occupant protection.

INTRODUCTION

The introduction of Advanced Driver Assistance Systems (ADA systems or ADAS) generates new opportunities to mitigate the damage caused by traffic accidents or, in many cases, prevents them from happening. ADA systems such as Autonomous Emergency Braking System (AEBS) or lane change assist (LCA) support the driver in hazardous traffic situations by controlling longitudinal (by braking) and lateral (by steer torque) motion of the vehicle in case of collision risk. These systems, though relatively new to the market, have proved their significance for vehicle safety and are recognized already by legislative authorities and consumer bodies. The European Commission has introduced legislation for AEB and Lane Departure Warning (LDW) systems in commercial vehicles [1], and consumer testing protocols are currently available for AEB systems in the standard Euro NCAP protocol dedicated for city and interurban traffic.

Previous studies have shown that autonomous systems, such as AEB or autonomous steering, can lead to a non-optimal occupant posture and position resulting in reduced performance of the occupant restraint systems in case of a collision [2]. At the same time, the increasing presence of surround sensors allows for an improved performance of the passive safety systems by using information from before the crash. This information can be used to trigger restraint systems during the pre-crash phase e.g. pre-pretentioning of safety belts to reduce the occupant misalignments during pre-crash lateral or longitudinal loadings.

Previous studies [2], [3] have shown that the on-board restraint systems can be optimized in an integrated manner for a specific load case, i.e. frontal or side. The wide range of ADA systems available in the new vehicles can provide information about the vehicle's surrounding and can therefore be used to estimate the interaction with other vehicles resulting from the activation of a single ADA system. This plays an important role not only on the level of controllers implementation, but also on the occupants' protection: given a certain flow of actions initiated by the ADA controllers, the injuries suffered in an imminent collision might depend on the occupant Out Of Position (OOP) resulting from the avoidance of a preceding potential collision. With the more and more extensive implementation of AEB systems the urban areas have become a potential scenario for the combination of AEB actuations followed by a rear-end collision.

A first attempt of correlating the performance of an AEB system with the performance of the vehicle's restraint system in protecting the occupants in a rear collision has been done and described within this paper. The performance of the AEB system and the vehicle's restraint potential in limiting the whiplash injuries are awarded separately in the Euro NCAP protocol, with the only requirement of a minimum whiplash score for the vehicle to be eligible for the AEB City award.

This study presents a new application of the integrated safety method described in [2] with the analysis of the out of position resulting from the actuation of an AEB system before a rear collision. In line with the methodology, the advantage of predictive sensing for the optimization of the on-board restraint systems is confirmed, along with the difference in the injuries estimation between the BioRID-II dummy model and the active human model. The analysis is performed on a simulation level and extended with the activation of a selection of on-board restraint systems prior to the rear collision with the main objective of showing the different risk of high whiplash injuries with and without the preceding actuation of the AEB system.

METHODOLOGY

Currently, no experimental methods or simulation tools exist for evaluating the effects of pre-crash dynamics on the occupant injury risk during the crash phase. In this paper, the use of two software packages that together provide the potential to cover all critical aspects of the design of an integrated safety system is shown. One of the software packages (PreScan) focuses on the sensing and active control systems of a vehicle, and the other package (MADYMO) predicts an occupant response and injury risk throughout the whole pre- and potential in-crash event.

The methodology used in this study has been previously presented [2] when applied for the investigation into the frontal collision load case with pre-crash autonomous braking and the side collision load case with pre-crash triggered restrained systems [3]. In the current study, the methodology was appropriately adjusted to best represent

the phenomena characteristic for the problem of out-of-position while emergency braking, followed by a rear-end impact load case (See Figure 1).
The real world traffic situation is represented in PreScan in which the vehicle model under investigation, equipped with predictive sensors, is exposed to the collision risk situation. A control system based on the predictive sensors provides detection and initial classification of collidable objects (here referred to as targets), with respect to which the Time To Collision (TTC) information is estimated. Once the crash detection system model classifies the collision risk, the occupant's injury analysis is initiated in MADYMO with the initial conditions imported from PreScan. Based on the estimated TTC information sent to MADYMO, on-board restraint systems (e.g. belt pre-pretensioners) are triggered in case of an unavoidable collision with the target. MADYMO uses the above listed information to calculate the deployment of restraints and compute the resultant occupant's posture. The outputs from MADYMO analysis is used to quantify the significance of active restraint systems in the rear-end collision.

The presented approach assumes that the pre-crash control system for rear-end collision placed on the struck vehicle does not affect the vehicle motion itself. Therefore, the collision conditions remain unchanged with and without the system. The pre-crash control system affects only the motion of the occupants by deploying the on-board restraint system before the crash in order to mitigate the injuries.

In the current study the methodology has been further extended to investigate the effects of AEBS actuations (vehicle pitching and braking) prior to the predicted rear collision. The origin of the pre-crash vehicle motion is not investigated in this study, but simply adopted as input to the MADYMO simulation to quantify the significance of occupant's misalignments and thus the out of position posture in the rear-end collision. The AEBS-induced vehicle motion is prescribed in MADYMO and synchronized with the rear-end crash pulse. The AEBS controller principle, its application and effects on the vehicle motion have been studied and described in [2].

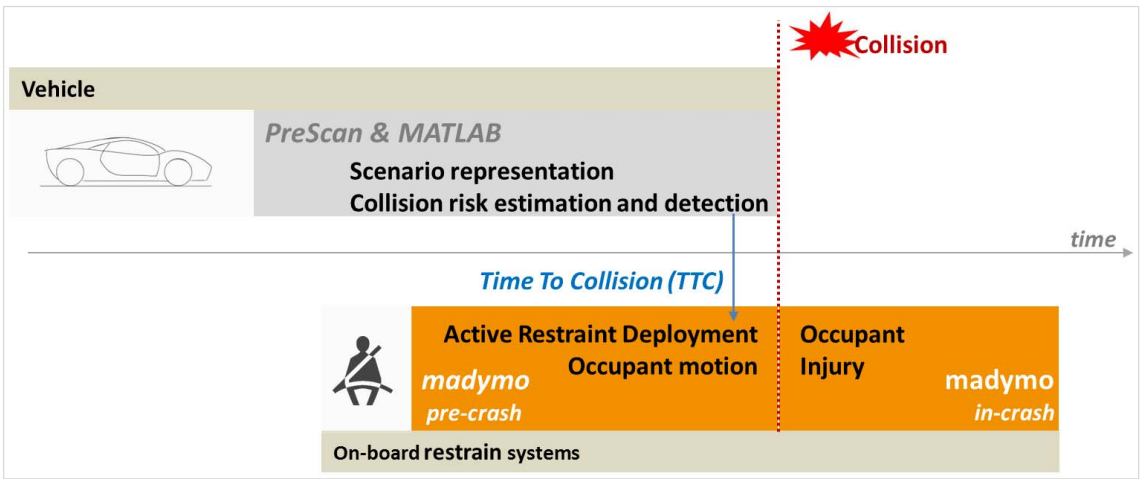

Figure1. Method.

Traffic scenario identification

Recent studies [4] confirm that in Germany rear-end collisions represent the third most common impact scenario after frontal and side impacts, and amount to 15% of all car accidents. Most of the car-to-car single rear-end collisions occur on urban roads [5] and 80% of rear-end collisions include accidents in longitudinal traffic conditions in which vehicles are stuck in a traffic jam or queuing at the traffic light [4].
Two traffic scenarios have been selected for this study and developed in the PreScan software, each representing a rear-end collision caused by a car (striking vehicle) failing to brake in the vicinity of a red traffic light and impacting the preceding car (struck vehicle) at the speed of 48 km/h. Two scenarios conditions for the struck vehicle are investigated:

1. The struck vehicle is stationary queuing at the traffic light
2. The struck vehicle drives at 56 km/h and comes to a full stop after the intervention of an AEB system to avoid a collision with the preceding stationary vehicle queueing at the traffic light.

The simulations of both traffic scenarios are shown in the Figure 2.

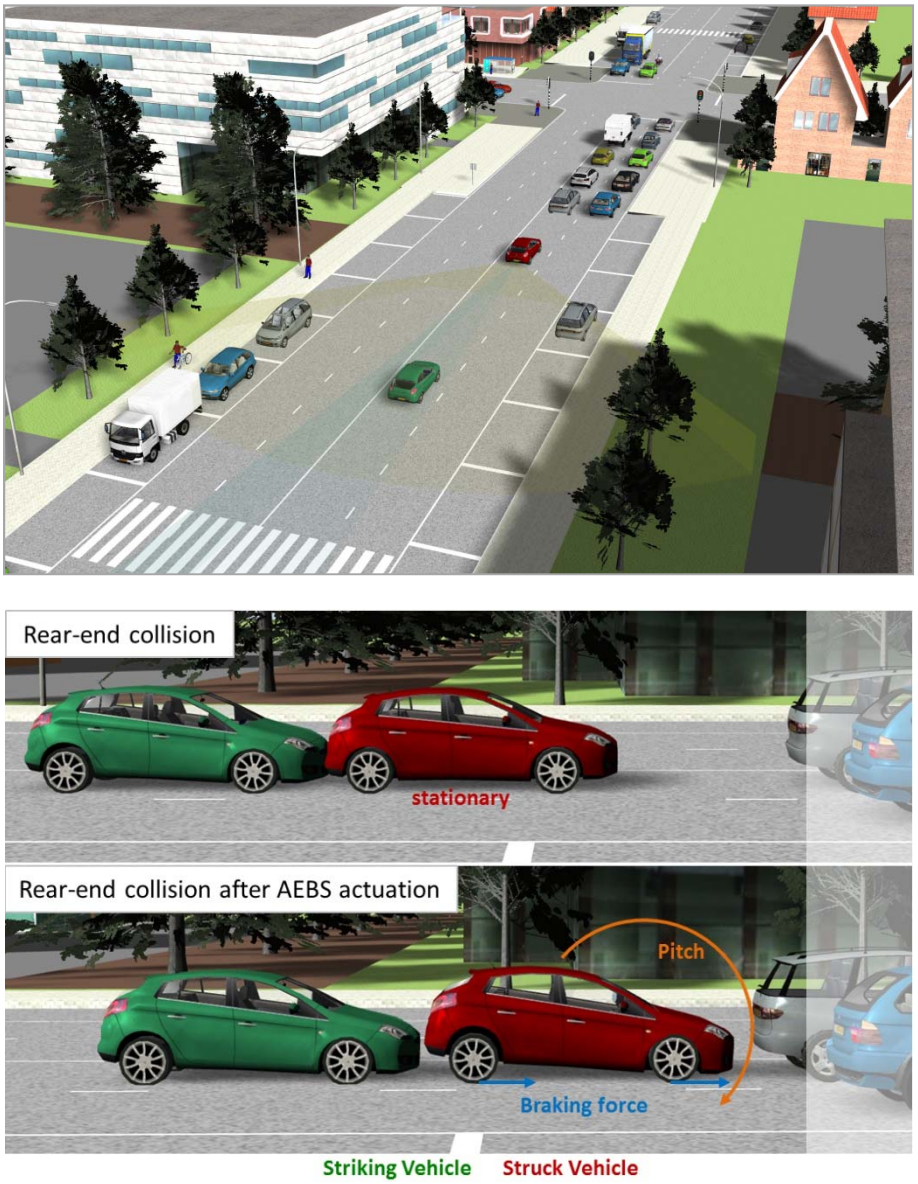

Figure2. Traffic Scenarios - Overview (top), details (bottom).

Maneuver dynamics of the struck vehicle model due to AEBS intervention

The deceleration and pitching profiles resulting from the activation of the AEB system have been computed by means of the PreScan embedded vehicle dynamics model [6]. A mid-class vehicle has been used for this study and it has been assumed that the maximum longitudinal braking force can be generated (dry asphalt, high friction). Supposing that the collision between the two vehicles is fully inelastic and both vehicles are of the same mass, the velocity change of 24.45 ±1.2 km/h required by the Euro NCAP protocol (See section "Collision condition and investigated injuries") implies a striking vehicle driving at the speed of 48 km/h.
In line with the controller principles described in [2] due to the AEB intervention the struck vehicle undergoes a maximum longitudinal deceleration of 0.79 [g] and a maximum pitch angle of 1.4 [deg].

Collision condition and investigated injuries

In order to assess the occupant whiplash injury risk, the High Severity crash pulse of the Euro NCAP Whiplash protocol has been used [7]. The adopted crash pulse has been registered in a laboratory and complies with the Euro NCAP protocol requirements (not shown in this paper).
The same crash pulse has been used also in the traffic scenario involving the actuation of the AEB system. Although the initial conditions of the struck vehicle (pitching) do not fully comply with the sled test requirements (horizontally placed sled), it can be assumed that the small pitch angle does not compromise the validity of the crash pulse.

In line with the Euro NCAP dynamic test protocol, the injuries on the neck and thoracic spine are registered by means of a Bio-RID-II dummy, and quantified in terms of:

1. NIC peak
2. Maximum Nkm
3. Peak of Head rebound velocity
4. Maximum vertical and shear force on the Upper Neck
5. Peak of T1 acceleration
6. Time to first contact between the Head and the headrest

According to the protocol, all parameters except the rebound velocity are calculated up to the end of head to headrest contact.
The Euro NCAP parameters are calculated for both occupant models and it is therefore assumed that the limits (See Table 1) defined by the protocol are applicable also to outputs of the human model.

Table1.
Euro NCAP High Severity Pulse limits.

	Higher Performance Limit	**Lower Performance Limit**	**Capping Limit**
NIC [-]	13.00	23.00	25.50
Nkm [-]	0.22	0.47	0.78
Head Rebound Velocity [m/s]	4.10	5.50	6.00
Upper Neck Shear Force [kN]	30.00	210.00	364.00
Upper Neck Tension Force [kN]	470.00	770.00	1024.00
T1 acceleration [g]	12.50	15.90	17.80
Time to head- headrest contact [ms]	53.00	80.00	92.00

Rear collision detection principles

A controller algorithm and two radar sensors have been modelled to estimate the risk for the vehicle (host/struck vehicle) of being rear-struck by the vehicle coming from the back (striking vehicle). By means of a Long Range Radar (LRR, with one beam 150 [m] long and 8 [deg] wide) and a Short Range Radar (SRR, with one beam 30 [m] long and 80 [deg] wide) the area behind the host vehicle is scanned for targets. The sensors' readings are processed by the controller algorithm that computes the Time To Collision (TTC) based on which the on-board restraint systems can be triggered before the collision. The system (controller and sensors) acts in four steps to produce the TTC information with respect to the identified target vehicle (striking vehicle):

1. The LRR scans the surrounding of the host vehicle and identifies approaching objects. The TTC is calculated for each of them
2. Based on TTC $\leq$ 1.6 [s] the target type identification process (object vs vehicle) is initiated
3. The SRR scans the surrounding of the host vehicle and identifies targets
4. If the same target is detected by both sensors and has been classified as a vehicle, the related TTC information is made available for the on board restraint systems to be triggered

The controller and the sensors have been implemented in PreScan, using Matlab/Simulink for the sensors' readings processing and for the computation of the TTC information.

Test sled and restraint systems models

The Euro NCAP Whiplash sled test has been reproduced in MADYMO with a seat including headrest, cushions and structure, a safety belt and a foot rest. The seat geometry is represented using facet surface technique and its compliance is expressed in terms of stress-strain characteristics representative of a generic middle-class vehicle seat. The model represents a generalized mid-size class passenger car and is validated for the three Euro NCAP whiplash sled pulses. The characteristics and properties of the seat are not shown in this paper. The belt is modelled with FE technique and represents the functionality of a belt system without locking mechanism and retraction functionality. To investigate the effectiveness of pre-crash deployed injury countermeasures the model is additionally equipped with the retractor pre-pretensioner (here referred to as pretensioner) and the active headrest prior to collision. The actuation of the active headrest aims at reducing the gap between the occupant's head and the seat and is implemented by prescribing the angular motion to a maximum angular displacement of 10 [deg]. The active headrest is actuated before the crash and can be triggered at the desired TTC based on the pre-crash vehicle sensors (i.e. radar sensor models). The actuation of the active retractor pretensioner to reduce the gap between the occupant and the backrest can be triggered with a pre-defined load at the desired TTC based on the pre-crash vehicle sensors (i.e. radar sensor models).
The design and optimization of the restraint systems actuation has been performed by means of simulations and has not been validated. The optimization enabled to define the triggering time (TTC) and the type of actuation (amount of angular headrest displacement and pretensioner loading force), and is not described in this study. The active restraint systems under investigation have been optimized for both load-cases and are listed in Table 2 together with the reference model (seat and seat-belt with no pre-crash activation).

Table2.
Restraint systems under investigation.

	Headrest forward rotation [deg]	**Pretensioning load [kN]**	***Reference in the paper***
Reference model	*n.a.*	*n.a.*	*Ref*
Active Headrest rotated forward	10	*n.a.*	*AH_10deg*
Retractor Pretensioner (1)	*n.a.*	0.15	*RPT_0.15kN*
Retractor Pretensioner (2)	*n.a.*	0.50	*RPT_0.50kN*
Combination of Active Headrest and Retractor Pretensioner (1)	10	0.15	*AH+RPT_0.15kN*
Combination of Active Headrest and Retractor Pretensioner (2)	10	0.50	*AH+RPT_0.50kN*

INVESTIGATION APPROACH

The paper describes the investigation into the effect of OOP induced by the (autonomous) actuation of an AEB system prior to a rear-end collision. The intervention of an AEB system alters the occupant's position with respect to the seat, thus affecting the restraining capabilities of the safety system. In the specific case, the AEB system actuation increases the relative distance between the occupant's head and the headrest, thus compromising the Euro NCAP Geometry assessment. As a consequence, the advantage of the restraint systems optimized according to (static) in-position requirements might be compromised.
In addition, the potential of triggering the on-board whiplash protection system prior to the rear-end collision is investigated. Based on the analysis of the whiplash injuries as required by Euro NCAP, the actuation and combination of active restraint systems is eventually analyzed.

Two occupant models are selected for the investigation, the MADYMO Active Human Model 50th percentile (here referred to as AHM) and the MADYMO BioRID-II Q facet dummy. The BioRID-II facet dummy is a well-

established ATD (Anthropometric Test Device), typically used in rear crash test protocols. It is extensively validated in numerous component, full scale and full system tests for in-plane rear loading [8].
The active human model has an improved biofidelity and includes muscle activity and posture maintenance activation: the neck, spine, elbows and hips can be controlled in order to try to maintain the initial position under the influence of external loading. The active human model is validated against volunteer and PMHS (Post Mortem Human Subject) test data for occupant pre-crash simulation of low-g frontal, as well as high- and low-g rear load-cases [9], [10], [11].
In the study, the neck, spine, elbows and hips of the human model are activated. The muscle activation settings used in the investigation represent an occupant that is aware about the upcoming collision and his muscles are initially braced (isometrically pre-tensed due to the psychological stress resulting from being in a dangerous situation). Occupant awareness/unawareness and bracing/relaxation are represented on the modeling level with two parameters: Muscle reaction time – time from 0 to 30ms represent an aware occupant Co-contraction – values above 0.5 represent braced occupant.

For both occupant models the same seat model is adopted, with the same initial orientation of both backrest and headrest. The BioRID-II has been placed into the seat making sure that the vertical and horizontal distances of the head with respect to the headrest are within the Euro NCAP corridors. The human model has been positioned assuring that the head-to-headrest position is as close as possible to the one of the BioRID-II (a maximum difference of 16 mm in the longitudinal direction). The seating procedure for both occupant models has been implemented by means of pre-simulations and is not described in this paper. The Figure 3 compares the position of both occupant models at the end of the AEBS intervention (before the rear-end collision) when placed on the same seat model. Due to the vehicle's deceleration and pitching, the occupant is displaced out of his initial position and the distances to the headrest and backrest increase. The Bio-RID-II shows a more significant out of position, with a longitudinal distance to the headrest five times higher than the initial value (41 [cm] versus 7.5 [cm]).

Figure3. Reference Model - Occupant models posture before the crash with and without previous AEB activation.

The sequence of events in case of a regular rear-end collision and a rear-end collision following the activation of an AEB system is shown in the Figure 4. In the regular rear-end collision all the active restraint systems are actuated based on the estimated risk of rear-end collision. With the AEBS intervention the retractor pretensioner is controlled by the AEB controller and triggered when the braking phase is initiated, while the headrest deployment is triggered based on the estimated rear-end collision.

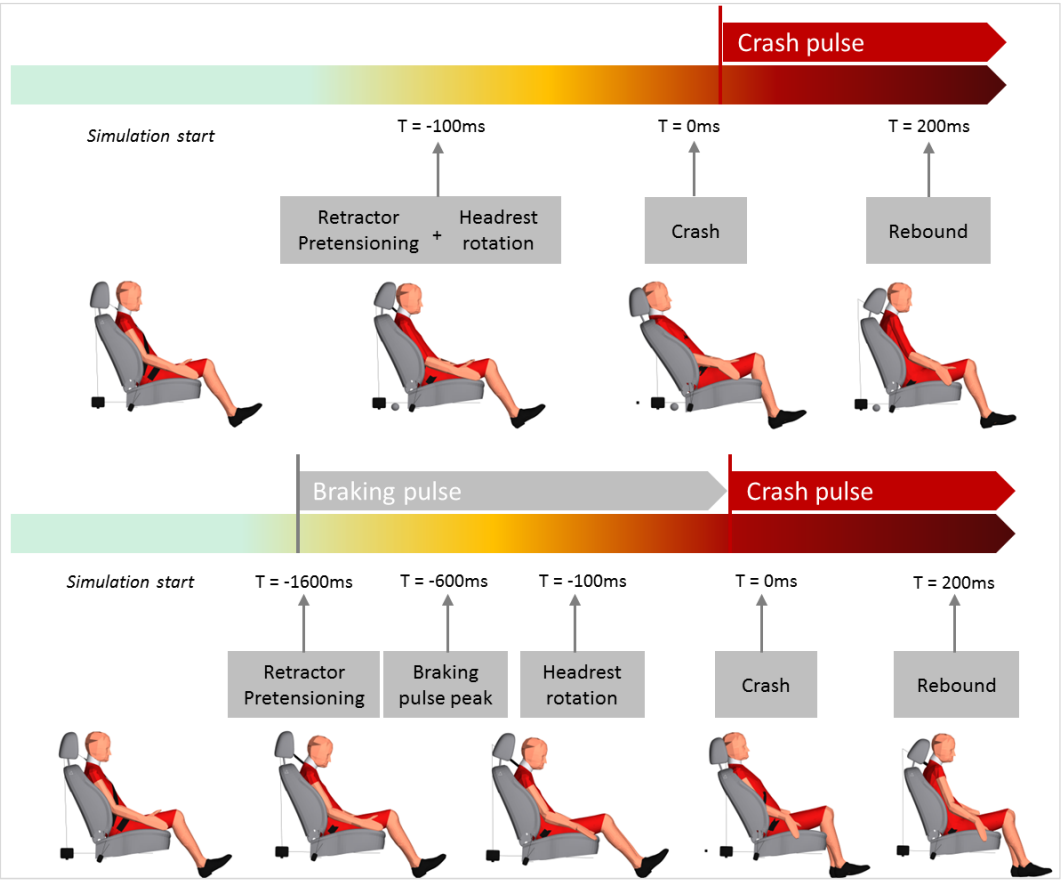

Figure4. Sequence of events - Regular rear-end collision (top), rear-end collision after AEBS intervention (bottom).

In order to quantify the overall risk of high whiplash injuries, the Euro NCAP Lower Performance limits are assumed to be the maximum value (100%) with respect to the ideal situation of no injuries (0%): according to the Euro NCAP Whiplash test protocol, a criterion is awarded a "null score" if its value exceeds the Lower Performance Limit. The ratios (here referred to as Injury Ratios) between the in-simulation-observed injury values and the corresponding Lower Performance limits have been calculated and expressed in terms of percentages (100% corresponds to injury values equal to the Lower Performance limits). The injury ratios have been calculated for each of the seven injury criteria required by the Euro NCAP Whiplash test protocol and eventually averaged for each simulation (one simulation corresponds to one occupant model, one restraints configuration and one load case).
It should be noted that the results evaluation has been carried out only with the Euro NCAP injury parameters and no analysis of the neck in jury mechanisms has been performed.

WHIPLASH INJURY ANALYSIS RESULTS

The sensitivity of the reference restraint system to the load-case and to the occupant model is shown in the Figure5. The activation of an AEBS always increases the risk of high whiplash injuries in a consequent rear-end collision, but the effect is differently quantified by the two occupant models: for the BioRID-II model the average injury ratio of 111% increases to 194%; a similar trend, though less pronounced, can be observed for the Active Human Model registering an average injury ratio increasing from 74% to 107%. The intervention of the AEBS amplifies also the difference between the occupant models: in a regular rear-end collision the BioRID-II produces whiplash injuries around 37% higher than the AHM, with the intervention of the AEBS the whiplash injuries are almost 90% higher for the BioRID-II.

The results with the reference models show a significant decrease in occupant protection resulting from the AEB-induced OOP, and thus create the need for the pre-crash intervention to correct the position of the occupant before entering the rear-end in-crash phase.

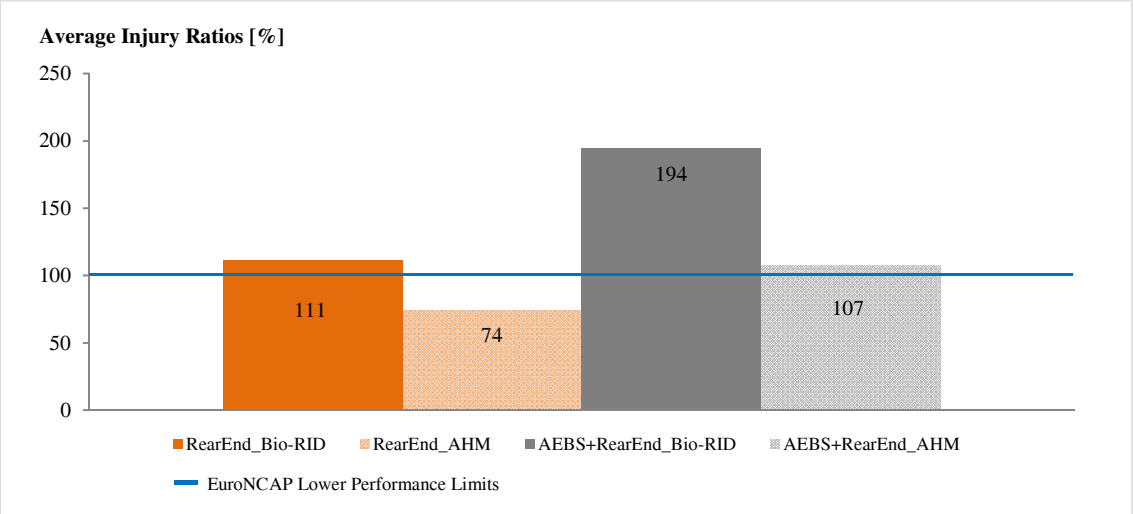

Figure5. Whiplash injuries in the reference models.

The effectiveness of different active restraint systems in reducing occupant injury values in rear-end load case with respect to the reference system is presented in the Figure 6. The two bar plots show the results for different ATD models: BioRID-II and AHM.

In case of the BioRID-II the 83% increase in the risk of high whiplash injuries caused by the AEBS (grey vs. orange bar) could be limited to a minimum of 74% by combining the active headrest and belt pretensioning. However, unlike the rear-end-only load case, triggering active systems in the pre-crash phase after an emergency braking always showed injury values still higher than the Euro NCAP Lower Performance limits.
The potential of actuating the restraint systems before the rear-end collision proved always beneficial and similar trends in the injuries reduction after the AEBS actuation are observed. Depending on the applied system configuration the injuries are reduced by 18% - 55%.

In case of the AHM the 33% increase in the risk of high whiplash injuries caused by the AEBS (grey vs. orange bar) could be limited to a minimum of 5% by combining the active headrest and the belt pretensioning. Besides, triggering active systems in the pre-crash phase after an emergency braking always resulted in whiplash injuries equal to or lower than the Euro NCAP Lower Performance limits.
The potential of actuating the restraint systems before the rear-end collision proved beneficial only after the AEBS deployment, with 8% - 25% lower injuries. In the rear-end-only load case the active restraint systems did not significantly affect the performance of the reference system: although no benefits have been found, a 5% increment has been observed.

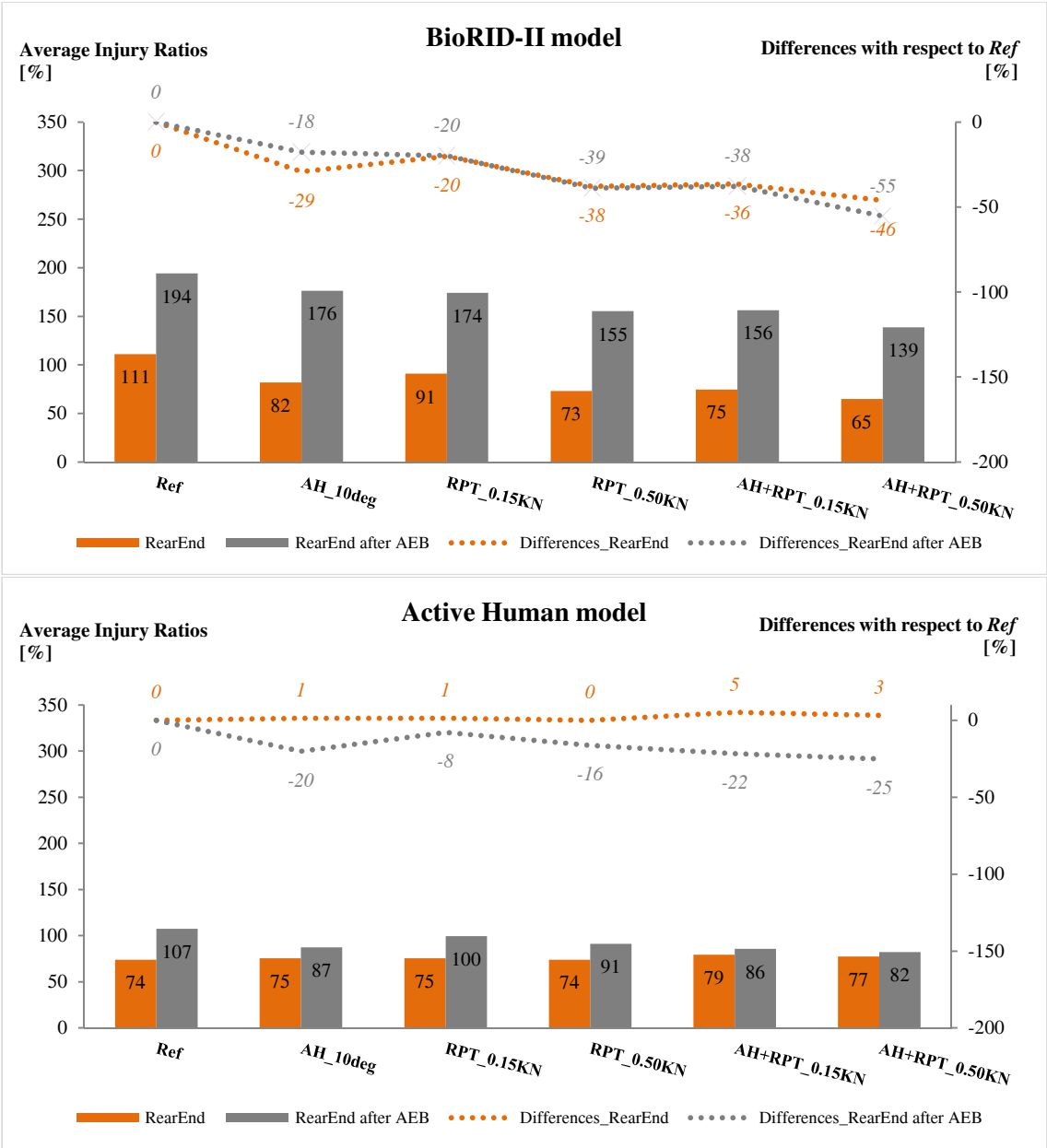

Figure6. Average Injury Ratios with and without the intervention of the AEBS - BioRID-II (top) and Active Human Model (bottom).

The direct comparison between the injury results obtained with two ATD models (BioRID-II and AHM) throughout the active restraint systems under investigation is presented in the Figure 7.
The AEBS-induced OOP has differently affected the injury prediction of the occupant models. The difference in the injury values varies between 57% and 87% depending on the applied system configuration. In contrast with the simulations with the BioRID-II, triggering active systems in the pre-crash phase always showed average whiplash injuries lower than or equal to the Euro NCAP Lower Performance limits when simulating with the AHM: with the BioRID-II the risk of high whiplash injuries is in the range of 139% - 194%, while a much lower range of 82% - 107% has been observed with the human model.
The potential of actuating the restraint systems before the rear-end collision proved always beneficial and showed similar trends in the injuries reduction. However, with the AHM, the observed reduction of whiplash injuries is less than with the BioRID-II.

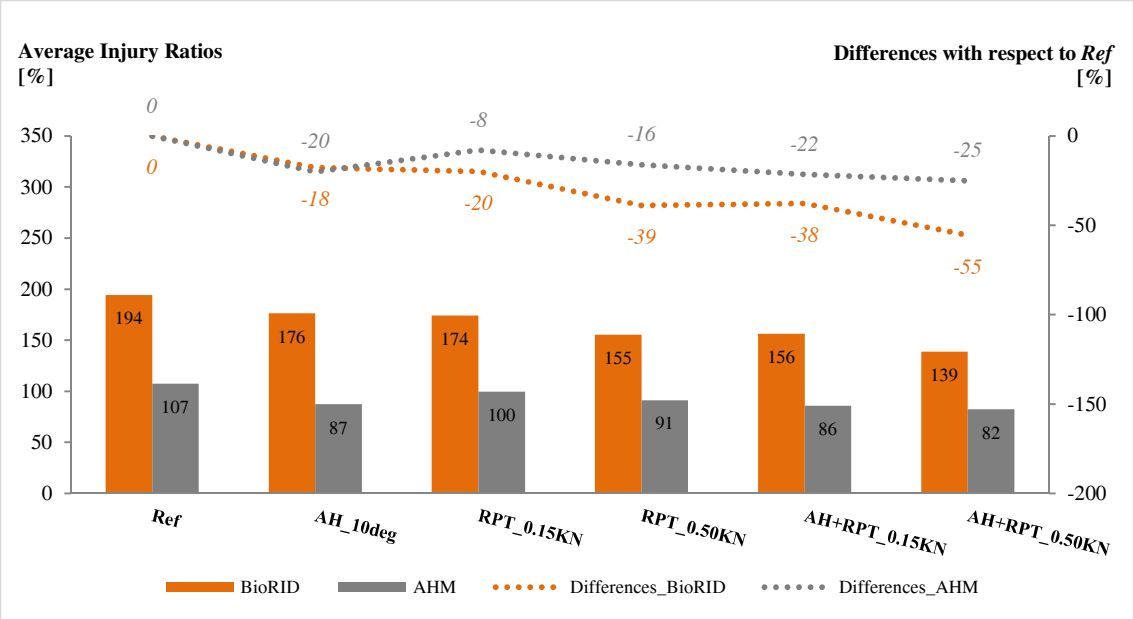

Figure7. Average Injury Ratios in the Rear-end collision after the AEBS intervention - Comparison between the occupant models.

Previous studies [11] prove that the initial seating posture and the head restraint position strongly influence the model response. In the study, the ratio between the head distance to the headrest and resulting injury values was found to be non-linear. In a regular rear-end collision reducing the initial gap between the head and the headrest reduces the risk of high whiplash injuries as long as the BioRID-II is used; with the human model no significant effect in the whiplash injuries has been observed when reducing the head to headrest gap (maximum increment of 5% in the injuries). In the Figure 8 the injury ratios observed with both occupant models are plotted with respect to the head-headrest distances (for clarity reasons, the results of the BioRID-II in the AEB scenarios are not entirely plotted). The reduction of the gap reduces the difference between the whiplash injuries of the BioRID-II and the AHM from 37% to 14%. In case of AEB-induced OOP, reducing the initial gap reduces the risk of high whiplash injuries. However, the gap reduction does not bring the risk of high whiplash injuries of the BioRID-II close to the ones of AHM, with differences in the range of 32% to 87%.

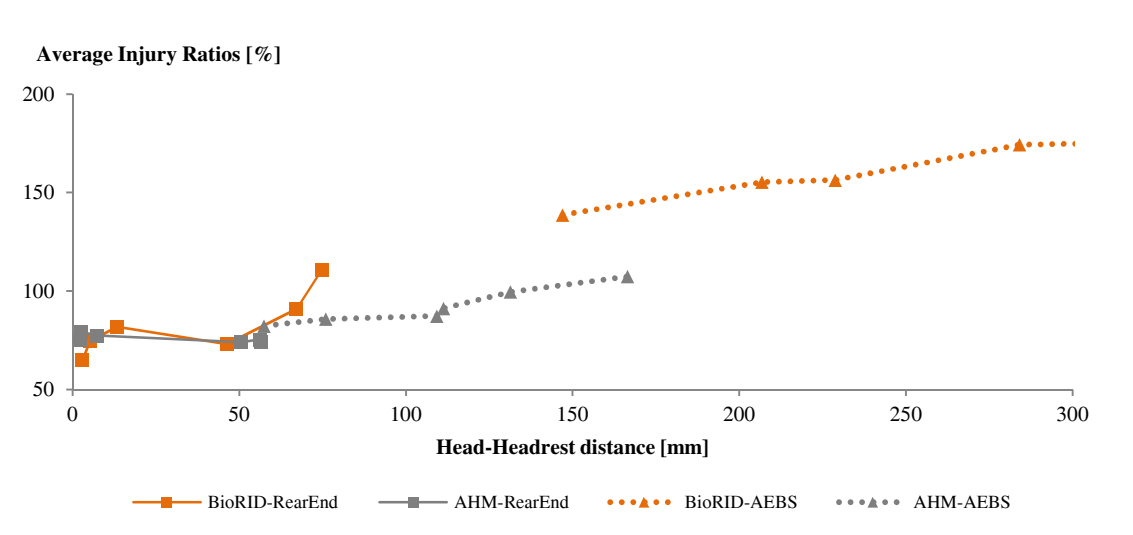

Figure8. Average Injury Ratios vs Head-Headrest distance

Results summary

With the intervention of an AEB system prior to a rear-end collision the risk of high whiplash injuries as a result of an altered seating position for the occupant (OOP) increases. The risks predicted by the BioRID-II increase by 83%, while in case of the AHM, the risks increase by 37%. For both occupant models the adoption of the active restraint systems cannot fully compensate the higher risk of high whiplash injuries caused by AEB-induced OOP, thus offering an overall protection level lower than in the regular rear-end collision (with no OOP).

The difference in the whiplash injury prediction between the occupant models changes radically between a regular rear-end collision and a rear-end collision after the actuation of an AEBS. Even though used with the same restraint systems and under the same loading conditions, in a rear-end collision the difference is in the range of 1% - 37%, while after the activation of the AEBS the difference can be as high as 57% - 89%.

The study shows that the intervention of active systems prior to a rear-end-only collision reduces the injuries to values lower than the Euro NCAP Lower Performance limits for both occupant models. The adoption of active restraint systems during the actuation of an emergency braking may result in an improvement with respect to the passive-only systems for both occupant models, but the whiplash injuries estimated by the BioRID-II remain above the Euro NCAP higher limits.

The BioRID-II model showed a consistent behavior in the prediction of the whiplash injury values with or without the intervention of the AEB system: in terms of risk reduction with respect to the reference model, the actuation of each active system has proved equally beneficial in both cases. On the other hand, with the AHM, only the AEBS-induced pre-collision loading shows the need for additional active restraint systems (which proved to be able to reduce the injury risk with a trend similar to the BioRID-II), while in a regular rear-end collision the level of protection of the reference system is neither improved, nor significantly worsened with the addition of active systems.

Reducing the head to headrest gap reduces the difference in the whiplash injuries estimation between the two occupant models for the regular rear-end collision. In case of AEB-induced OOP, the distances observed with the BioRID-II are significantly higher than the ones of the human model (150 – 400 [mm] range for the first, 55 – 180 [mm] range for the latter).

CONCLUSIONS

A methodology for the development of passive and active safety systems in an integrated manner has been drafted and motivated in this paper. Due to the increased implementation of autonomous functions in the new vehicles (e.g AEBS), there is also an increased need for investigating and testing the consequences of operation of such systems on occupant safety. The protocols assessing the whiplash injury risk in a rear-struck vehicle adopt a BioRID-II dummy in the dynamic tests for which a crash pulse is applied to an initially stationary sled, thus assuming no prior AEBS actions. With the analysis of an altered initial state of the vehicle (due to AEBS) the established protocols and the occupant model (dummy) may become obsolete or less applicable

The study shows that the AEB-induced OOP results in an increased risk of whiplash injuries in the follow-up rear-end collision. The increase of injury risk depends on the type of occupant model used in the simulation and has been done for only one collision severity case, one braking pulse and one vehicle. However, the initial results of this study indicate already that the whiplash assessment protocols for cars equipped with AEB systems should include the effect of AEB-induced OOP. Addressing the above problem would require, though, a robust method to identify the position of the occupant (including dynamic effects) at which he or she enters the in-crash phase.

The negative effect of AEB-induced OOP in the rear-end collision can be alleviated effectively by applying different occupant motion control measures deployed in the pre-crash phase. The main mechanical principle of the investigated system configurations is the reduction of the distance between the occupant and the backrest and headrest. The highest effectiveness in reducing the negative effect of AEB-induced OOP was obtained for the system with active headrest and motorized belt pretensioner.

Both investigated occupant models showed significant differences in predicting the pre-crash occupant motion resulting from AEB deployment, and thus also in the injury results in the follow-up rear-end collision. The severe OOP recorded with the BioRID-II model can be explained with the fact that the dummy is not validated for frontal loading, neither is it mechanically designed for use outside the in-plane rear loading and rebound phase. No mechanism in the BioRID-II can provide thoracic stiffness in flexion, thus resulting in an excessive (when compared to testing with volunteers in similar testing configuration [12]) forward motion of the upper torso under a braking loading.

It can be concluded that the BioRID-II and its model cannot represent the forward motion of the occupant during the pre-crash phase and cannot be used for these purposes. Further studies should include feasibility and effectiveness of using AHM to predict the forward OOP induced by AEBS and then swap the BioRID-II model at the moment of rear-end crash start (T=0.0 [s]). This approach ensures that in both pre- and in-crash phases the adopted ATDs are adequate and validated for the loading conditions of pre- and in-crash phases.

Further studies into this problem should increase the confidence in the conclusive statements of this paper by:

- broadening the scope of the investigation (different rear-end crash severity, braking pulse)
- sensitivity study into testing condition parameters: seat geometry, seat characteristic compliance, seating position of the occupant

In conclusion, given the significant injury risk typically accompanying rear impact collisions also at very low relative speeds [4] and the yet limited understanding of the potential for integrated safety to address this issue, this paper intends to initiate the interest in further research that can exploit new predictive technologies to reduce the harm caused by rear-end impact.

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ECALL – DEFINING ACCIDENT CONDITIONS FOR MANDATORY TRIGGERING OF AUTOMATIC EMERGENCY CALLS

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ABSTRACT

eCall, the pan-European automatic crash notification system, will facilitate road vehicles to contact emergency services autonomously when a potentially injurious crash has been detected by vehicle sensors. Type-approval requirements will set out conditions for assessing systems under which automatic triggering of eCalls will be mandatory. Research is needed to specify the accident typologies and severities represented by these conditions.

This paper analyses what definition of accident conditions would ensure that a high number of casualties benefit from automatic eCalls. The conditions should also allow cost-effective type-approval testing, avoid excessive numbers of superfluous eCalls, and not restrict manufacturer's design freedom.

Two conditions were considered as being particularly suitable for the European type-approval system:

- Condition A: Trigger in accident conditions similar to, and at least as severe as, a mandatory frontal or lateral full-scale crash test.
- Condition B: Trigger in conjunction with deployment of any airbag.

In-depth accident data from the Road Accident In-Depth Studies (RAIDS) database, collected between 2000 and 2010 for the Co-operative Crash Injury Study (CCIS), was analysed to produce an estimate of the proportion of car occupant casualties captured by each of these conditions and subsequently scaled to a national level for Great Britain.

The analysis found that Condition A captured only 34.7% of fatally and seriously injured casualties whereas Condition B would apply to 81.0%. For Great Britain, with about 9,335 fatally or seriously injured car occupants annually, this is a difference of 4,330 fatal or serious casualties which could benefit from automatic eCall triggering each year. However, if Condition B was applied, automatic eCalls would be triggered for 74,390 slight casualties per annum in GB (and for an additional unknown number of damage-only accidents).

The sensitivity of Condition B, i.e. the proportion of casualties successfully selected, is considerably higher compared to Condition A. Nevertheless, accident types where airbags are deliberately not deployed would not be captured. Condition B exhibited an almost unvaryingly high sensitivity in selecting fatal casualties and serious casualties respectively.

The higher sensitivity of Condition B is achieved at the expense of specificity in selecting fatal or severe casualties, i.e. more of the collisions for which an eCall is triggered would be slight casualties. There are indications, however, that the negative consequences of superfluous eCalls could be mitigated.

The results are based on British data and cannot be transferred in detail to other countries. The general trends identified would be expected to also appear in reproductions of this analysis using data from other European countries.

The most preferable mandatory automatic eCall triggering condition for type-approval legislation appears to be triggering in conjunction with deployment of any airbag. Nevertheless, up to 19.0% of fatal and serious car occupant casualties might not be captured by this condition. To allow this problem to be overcome using advanced triggering algorithms, a non-restrictive approach could be taken with regard to the triggering requirement, i.e. require triggering in the presence of the condition yet not prohibit triggering in its absence.

INTRODUCTION

eCall and the Associated Regulatory Process in the European Union

eCall, the pan-European accident emergency call system (AECS), will facilitate road vehicles to contact emergency services autonomously when a potentially injurious crash has been detected by vehicle sensors. The in-vehicle system (IVS) will contact a public safety answering point (PSAP) via the pan-European emergency number 112. Once the connection is established, it will transmit a minimum set of data (MSD), containing information such as the exact location of the accident and the vehicle involved, and open a duplex voice channel to allow communication between vehicle occupants and PSAP operators. Shortly after the accident, emergency services therefore know that there has been an accident, and where exactly it occurred and can request additional detail, if needed, from the occupants. The safety benefit of eCall arises through the potential reduction in response times for emergency services attending to the accident, thus helping to treat injuries more rapidly which can contribute to a reduced probability of death in road accidents (Sánchez-Mangas et al. 2010).

The European Commission (EC) has adopted a proposal in June 2013 to make eCall mandatory for passenger cars in the near future (European Commission 2013). This was followed in February 2014 by the European Parliament's Legislative Resolution (European Parliament 2014). The subsequent Council's General Approach from May 2014 sets out the high level expectation with regard to the automatic triggering of eCall systems in Article 5.2 (Council of the European Union 2014): An eCall shall be triggered automatically "*in the event of a severe accident, detected by activation of one or more sensors or processors within the vehicle*". This expectation awaits translation into specific requirements for minimum triggering conditions that ensure effective system performance in passenger cars.

The objective of this study is, therefore, to assess the suitability of different accident condition definitions as minimum triggering conditions for type-approval requirements to ensure a high number of casualties benefit from automatic eCalls, while avoiding excessive numbers of superfluous eCalls and fulfilling constraints for implementation in type-approval legislation.

Review of Accident Conditions in Discussion for Automatic Triggering

As reported in (Carroll et al. 2014), a review of international legislation, technical standards, cost-benefit studies and international voluntary system implementations provided a selection of different accident conditions for automatic triggering.

The set of European technical standards with regard to eCall does not set out specific mandatory triggering conditions. prEN 16454 Sections 9.4.9 and 9.4.10 refer to full-scale crash tests according to UN Regulation No. 94 (UN R94; frontal impact protection) and UN Regulation No. 95 (UN R95; lateral impact protection) to define shock resistance requirements. Section 9.4.11 defines a test to demonstrate that the automatic trigger is activated by different crash types. However, these sections do not provide any stipulation as to whether triggering should activate the automatic eCall during UN R94 or UN R95 crash tests or any other crash types, but simply that it performs in accordance with the manufacturer's intention.

Studies have been performed by McClure & Graham (2006), Stevens & Hopkin (2010), the European Commission (2011) and Hayden (2014) to determine the costs and benefits of a mandatory implementation of pan-European eCall. These studies did not report the specific triggering conditions used for the underlying benefit calculations and do therefore not constitute a source of accident conditions to assess for the present study.

The European Union (EU) is also involved in the legislative process at the UN level through the Informal Working Group on Automatic Emergency Call Systems (IWG AECS) under the Working Party on General Safety Provisions (GRSG) within WP.29 (1958 Agreement). The draft UN Regulation on AECD/AECS sets out the expectations with regard to automatic triggering in Part III, Section 24.2.2: An automatic call shall be triggered at least by the "*occurrence of a frontal collision according to Regulation No. 94 (frontal collision); or occurrence of a lateral collision according to Regulation No. 95 (lateral collision)*". In order to simplify type-approval, the EU is aiming to keep the European legislation closely aligned with Regulations under the 1958 Agreement (CARS21, 2012). Therefore, the triggering conditions proposed at the UN level are considered in this study as a possible option for EU legislation.

The upcoming mandatory AECS implementation of the Russian Federation, ERA-GLONASS, will reference the technical standard GOST R 54620, which sets out that automatic triggering must occur "*in the event of an accident in which there is a substantial likelihood of threat to life and health of people in the vehicle*". This is further detailed to include front-, side- and rear-impacts. The exact triggering conditions are left to the manufacturer's discretion; however, it is recommended to trigger an automatic call if the acceleration severity index (ASI) of a collision event exceeds a certain score. The ASI algorithm is commonly used as a vehicle-based way to predict the likelihood of injuries in full-scale roadside barrier tests because these are performed without crash test dummies. It is not deemed a suitable mandatory triggering condition for the present study: Given the development effort and complexities surrounding modern crash sensors in vehicles, the prescription of a specific algorithm in not considered suitable for European type-approval legislation with regard to the design freedom of vehicle manufacturers.

Voluntary implementations of AECSs exist in many world regions, including Japan, the United States of America (USA) and the EU. The Japanese implementation, HELPNET, links the automatic triggering of emergency calls to accidents where an airbag was deployed (IWG AECS-Representation of Japan 2014). The American voluntary AECSs are expected to also rely mainly on deployment of an airbag (Kononen et al. 2011). As to the voluntary systems in the EU, it was inferred from communications with vehicle manufacturers that, again, airbag deployment was an important condition for automatic triggering. Therefore, the condition of airbag deployment for automatic triggering forms the second option investigated as legislative triggering condition.

METHODS

Data Sources

Two sources of road casualty data were used, the UK's detailed Road Accident In-Depth Studies (RAIDS) database and the British road casualty database, referred to as STATS19. The in-depth accident data were used to identify the proportion of casualties where automatic eCalls were likely to have been initiated under certain definitions of accident conditions for automatic triggering. The RAIDS data were scaled to British national casualties with respect to injury severity using STATS19 data.

RAIDS RAIDS is one of the most comprehensive in-depth accident studies in the world; it is funded by the UK Department for Transport (DfT) to provide an evidence source to help prevent future road collisions and mitigate the injuries suffered. RAIDS pulls together four separate historical studies that ran from 1982 to 2010 into one database, including the Co-operative Crash Injury Study (CCIS). RAIDS currently collects information on approximately 500 accidents per year.

The CCIS project collected in-depth real world car occupant injury data from 1983 to 2010. Vehicle examinations were undertaken at recovery garages several days after the collision. Car occupant injury information was collected from hospitals and HM Coroners and questionnaires were sent to survivors. All injuries were coded using the Abbreviated Injury Scale (AIS) 1990 Revision (AAAM 1990). Accidents were investigated according to a stratified sampling procedure, which favoured cars containing fatal or seriously injured occupants as defined by the British Government definitions of fatal, serious and slight. Fatal injury includes only casualties who died less than 30 days after the accident, not including suicides or death from natural causes. Serious injury includes casualties who were admitted to hospital as an in-patient. Slight injury includes minor cuts, bruises, and whiplash. The CCIS project also favoured newer vehicles.

STATS19 STATS19 is the database of all police reported injury accidents on public roads in Great Britain (GB). About 50 fields are recorded for each accident, including details of the accident circumstances, any vehicles involved and the resulting casualties. Driver and passenger casualties are linked to the vehicle that they were in or on at the time of the accident and pedestrian casualties are linked to the vehicle which hit them.

The injury severity of the casualties involved in the accident is assessed by the investigating police officer. Each casualty is recorded as being either slightly, seriously, or fatally injured. Further details of what is recorded are given in STATS20 (Department for Transport 2011).

Analysis

CCIS data from phases 6, 7 and 8, which encompasses accidents collected from 2000 to 2010, were used for this analysis. The primary selection criteria for the CCIS in-depth accident cases were:

- Cars registered between 2000 and 2009 and involved in an accident occurring between 2000 and 2010
- Cars towed from the scene
- Cars fitted with front and side airbags (to represent modern vehicle fleet)
- Car occupants with known injuries

This formed the base sample of car users (drivers and passengers). Two principle automated eCall triggering options were considered:

- Condition A: Trigger in accident conditions similar to, and at least as severe as, a mandatory frontal or lateral full-scale crash test according to UN R94 or UN R95 respectively.

  CCIS car occupants were differentiated, with those who experienced collisions similar to UN R94:
  - The car did not roll over
  - Experienced a frontal impact according to Collision Deformation Classification (CDC) SAE J224b (CDC side = 'F')
  - With a Principal Direction of Force (PDF) of $\pm$ 30° (CDC PDF of 11, 12 or 01)
  - With significant residual frontal crush (CDC extent $\geq$ 3)

  And those who experienced collisions similar to UN R95:
  - The car did not roll over
  - Experienced a side impact according to CDC SAE J224b
  - For CDC side = 'R', PDF between 60° to 120° (CDC PDF of 02, 03 or 04)
  - For CDC side = 'L', PDF between 240° to 300° (CDC PDF of 08, 09 or 10)
  - With significant residual frontal crush (CDC extent $\geq$ 3)

- Condition B: Trigger in conjunction with deployment of any airbag.

This sets a lower deployment threshold than the first option and may include more accident modes.

The CCIS car users were classified by those who experienced an airbag deployment and those who did not.

The resulting numbers from the CCIS analysis were scaled to match those of GB national casualty numbers. STATS19 data for accidents of the years 2010, 2011 and 2012, involving car users only, were used (Department for Transport 2013).

RESULTS

Results of the Analysis

There are an estimated 125,945 vehicle occupant casualties in road collisions per annum in GB, with 9,335 of these being fatally or seriously injured (KSI). Considering all injury severity levels, automatic triggering Condition A was found to capture 24,913 casualties, whereas Condition B captured 81,955 casualties. Limiting the analysis to KSI casualties, Condition A captured 3,235 casualties compared to Condition B capturing 7,565 casualties (see *Table 1*).

***Table 1*. Annual GB casualty numbers and number of casualties selected by automatic triggering Conditions A and B respectively; reported for different injury severity levels and different positions**

		All severities	KSI	Fatal	Serious	Slight
Annual GB casualties	All occupants	125,945	9,335	839	8,496	116,610
	Drivers	84,989	6,247	576	5,671	78,742
	Passengers	40,956	3,088	263	2,825	37,868
Selected by Condition A	All occupants	24,913	3,235	394	2,841	21,678
	Drivers	16,641	2,243	283	1,960	14,398
	Passengers	8,271	992	111	881	7,279
Selected by Condition B	All occupants	81,955	7,565	703	6,862	74,390
	Drivers	55,246	5,017	475	4,542	50,229
	Passengers	26,709	2,548	228	2,320	24,161

This means the sensitivity of the assessed automatic triggering conditions, i.e. the proportion of casualties successfully selected from all casualties of the corresponding severity level, compares as follows: The sensitivity in capturing casualties of any injury severity level was found to be 19.8% for Condition A and 65.1% for Condition B. When focussing on KSI casualties only, the sensitivities were 34.7% for Condition A compared to 81.0% for Condition B.

Conversely, this means if Condition A was applied, up to 6,100 KSI casualties per annum in GB (65.3%) might not be covered by automatic eCalls. For Condition B this number would reduce to 1,770 (19.0%).

The sensitivity of Condition B is elevated by the factor 3.3 for all injury severity levels and by the factor 2.3 for KSI compared to Condition A. Sensitivities split by injury severity and between drivers and passengers are given in *Table 2*; a comparison is visualised in *Figure 1*.

Table 2. **Sensitivity of automatic triggering Conditions A and B, i.e. proportion of casualties successfully selected from all casualties of the corresponding severity level; reported for different injury severity levels and different positions**

		All severities	KSI	Fatal	Serious	Slight
Condition A	All occupants	19.8%	34.7%	47.0%	33.4%	18.6%
	Drivers	19.6%	35.9%	49.1%	34.6%	18.3%
	Passengers	20.2%	32.1%	42.2%	31.2%	19.2%
Condition B	All occupants	65.1%	81.0%	83.8%	80.8%	63.8%
	Drivers	65.0%	80.3%	82.5%	80.1%	63.8%
	Passengers	65.2%	82.5%	86.7%	82.1%	63.8%

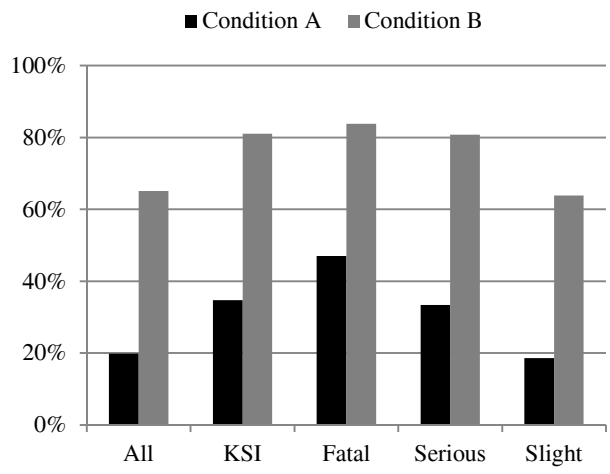

Figure 1. **Comparison of the sensitivity of automatic triggering Conditions A and B for different injury severity levels (all vehicle occupants)**

It can be seen for both conditions that the sensitivity is decreasing with decreasing injury severity level. This trend is more obvious for Condition A with a particularly marked drop in the sensitivity in selecting serious casualties compared to fatal casualties. The sensitivity of Condition B in selecting fatal and serious casualties is at a comparable level.

The sensitivity of both conditions does not vary markedly between drivers and passengers. For KSI casualties the variation is 3.8 percentage points for Condition A and 2.2 percentage points for Condition B.

The specificity of the assessed conditions, i.e. the proportion of non-KSI casualties (that is, slightly injured casualties) that were successfully not selected, compares as follows: Condition A provides a specificity 81.4% for all vehicle occupants compared to 36.2% for Condition B (see *Table 3* and *Figure 2*). Note that the reported specificity is based on recorded injury collisions only, because no data is available for damage-only collisions.

***Table 3*. Specificity of automatic triggering Conditions A and B, i.e. proportion of non-KSI casualties (that is, slightly injured casualties) not selected; reported for different positions**

		KSI
Condition A	All occupants	81.4%
	Drivers	81.7%
	Passengers	80.8%
Condition B	All occupants	36.2%
	Drivers	36.2%
	Passengers	36.2%

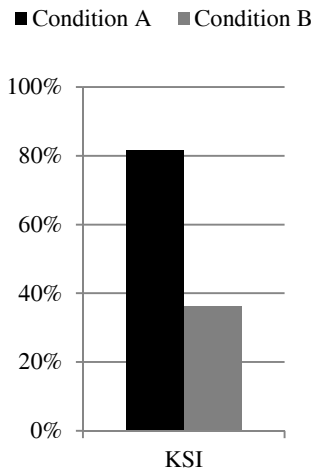

***Figure 2*. Comparison of the specificity of automatic triggering Conditions A and B in selecting KSI casualties (all vehicle occupants)**

The specificity of Condition B is markedly lower than that of Condition A. This means if Condition A was applied, automatic eCalls would be triggered for 21,678 slight casualties per annum in GB (18.6% of all slightly injured casualties). For Condition B this number would increase to 74,390 (63.8%).

The specificity of both conditions varies only slightly between drivers and passengers.

Limitations of the Analysis

The present analysis was performed based on in-depth accident data from GB. The analysis cannot be transferred in detail to the whole EU because impact typology varies across the member states. The authors have, however, no reason to believe that the general trends observed will differ or that the magnitude of the results would be of a different order. *Table 4* details the collision type distribution of the underlying GB in-depth accident data, i.e. the 3,351 CCIS cases identified by applying the primary selection criteria.

***Table 4*. Collision typology of cases selected for analysis from the in-depth CCIS accident database; absolute numbers and proportion of collision types; reported for different injury severity levels**

	All severities	KSI	Fatal	Serious	Slight
Front	1,406 (42.0%)	500 (41.9%)	64 (28.1%)	436 (45.1%)	906 (42.0%)
Side	783 (23.4%)	252 (21.1%)	68 (29.8%)	184 (19.0%)	531 (24.6%)
Rear	201 (6.0%)	28 (2.3%)	5 (2.2%)	23 (2.4%)	173 (8.0%)
Multi	343 (10.2%)	133 (11.1%)	28 (12.3%)	105 (10.9%)	210 (9.7%)
Rollover	597 (17.8%)	267 (22.4%)	57 (25.0%)	210 (21.7%)	330 (15.3%)
Other	21 (0.6%)	14 (1.2%)	6 (2.6%)	8 (0.8%)	7 (0.3%)
Total	3,351 (100%)	1,194 (100%)	228 (100%)	966 (100%)	2,157 (100%)

In-depth CCIS accident data was scaled up because the STATS19 database itself does not provide enough detail to estimate whether the assessed triggering conditions would have been met. It is assumed that, accounting for deliberate case selection strategies, the CCIS data is broadly representative of national crashes. However, the CCIS data collection followed a tow-away model, which means that less damaged cars are underrepresented because these are less likely to be towed away from the scene. Compared to STATS19 the cases within each severity level will be biased towards the more severe collisions of the respective level. This might lead to an overestimate of the sensitivity of both conditions.

The analysis was limited to vehicles fitted with front and side airbags which is expected to be the case for the vast majority of passenger cars sold in Europe after mandatory introduction of eCall. However, a smaller proportion of the vehicles in the database than is to be expected in future vehicles are fitted with side-curtain airbags that are prepared to be deployed in rollover accidents. This means that some rollovers will not see airbag triggering in the database, which is why the sensitivity of Condition B might be somewhat underestimated.

Further, for the analysis of Condition A only those casualties whose car principally experienced a front- or side-impact were included. This might lead to a certain underestimate of the real-world sensitivity of Condition A, because an unknown proportion of the oblique, multi-impacts and rollover events may have involved dynamic loading conditions similar to those experienced in the UN R94 and UN R95 tests and therefore triggered an automatic eCall during the course of the real event.

Lastly, the results of this study are not intended to be absolute measures of likely automatic eCall numbers; rather they provide a comparison between the two options. Absolute numbers of expected superfluous eCalls could not be estimated because the accident data does not include damage-only collisions, for which no data was available that would allow an analysis of the specific accident conditions.

DISCUSSION

Sensitivity of the Assessed Triggering Conditions

A suitable triggering condition has to provide a high level of sensitivity to ensure that a high proportion of the relevant casualties benefits from the automatic eCalls. The assessment focussed on KSI casualties because the prevalence of incapacitating injuries (preventing a manual emergency call) as well as the prevalence of conditions resulting in long term disabilities (or death) without rapid medical treatment in this group is higher than among the slightly injured casualties.

The results of the accident analysis confirmed that Condition B is more sensitive than Condition A, i.e. successfully captures a higher proportion of all KSI casualties. This result confirmed expectations based on the fact that the accidents selected by A can be considered a sub-set of those selected by B: A captures crashes whose impact angle resembles UN R94 or UN R95 tests and which are of comparable or higher severity. Because vehicles always deploy the respective airbags in these tests, all of these cases are, among others, included in B.

However, the difference in sensitivity was found to be large: Condition A captures only 34.7% of KSI casualties, whereas B captures 81.0%. This would result in a difference of up to 4,330 KSI casualties per annum in GB. Even in light of the fact that the formal interpretation of Condition A applied for this analysis represents a worst case that might be somewhat unrealistic from a practical real-world implementation perspective, this difference appears high.

Condition B also exhibited an almost unvarying sensitivity in selecting fatal casualties and serious casualties respectively, whereas the sensitivity of Condition A already dropped considerably at the serious casualty level. Further, Condition B is slightly superior in equally selecting drivers as well as passengers, however the difference to Condition A is small. Considering the marked difference in sensitivity and the low level of Condition A in absolute terms, clear preference should be given to Condition B based on sensitivity.

Nevertheless, 19.0% of KSI casualties would not be captured by this condition, which is 1,770 KSI casualties per annum in GB. Although the sensitivity is expected to be higher among more recent vehicles due to the higher fitment rate of side-curtain airbags prepared for rollover protection, there will remain a proportion of collisions not captured: Airbag systems are deliberately not deployed in certain accident types (such as rear shunt accidents where the vehicle is accelerated forwards) or are not deployed because of insufficient detection capabilities (such as certain cases of under-run accidents with low deceleration levels yet high injury risk due to large intrusion).

This shortcoming of Condition B could be addressed by pursuing a non-restrictive approach when implementing the triggering condition in type-approval legislation, i.e. require triggering in the presence of the condition yet not prohibit triggering in its absence. This would ensure, via regulation, that a reasonable minimum proportion of casualties are captured, while allowing vehicle manufacturers to apply more advanced algorithms tuned to the specific vehicle characteristics and making use of the full available sensor infrastructure to cover additional KSI casualties.

Specificity of the Assessed Triggering Conditions

Besides sensitivity, the triggering condition also needs to provide a high level of specificity to avoid a high number of superfluous eCalls. These two targets are of somewhat conflicting nature because the severity of injuries sustained in accidents varies not only with external accident conditions or characteristics of the vehicles involved, but also with factors which are unknown to the vehicle's triggering logic, such as the occupants' individual physiology (size and mass), injury resistance or pre-impact posture.

The specificity in selecting KSI casualties of Condition B (36.2%) was found to be markedly reduced compared to Condition A (81.4%). This means for Condition B, which is preferable based on sensitivity, approximately 74,390 of the 81,955 annually reported casualties via automatic eCalls in GB will only be slightly injured. This is also an indicator of the protection afforded by airbags where a high deceleration crash can result only in slight injuries. The overall number of automatic eCalls will be even higher and include an unknown number of additional calls from damage-only accidents (which are not quantified in this analysis). While superfluous automatic eCalls do not create dis-benefits for the road users concerned, the work of PSAPs and the correct targeting of those persons most in need of emergency medical treatment might be hampered if the number of eCalls is excessive.

It can be expected that a certain proportion of the slightly injured casualties would also call emergency services manually and there might be certain benefits from automatic eCalls, although the major part of this group will not be reliant upon the automatic triggering. The number of additional eCalls from damage-only accidents is unknown. However, there are indications that PSAPs and emergency services would be able to mitigate the negative consequences of superfluous eCalls from Condition B:

- Even among conventional emergency calls approximately 60% are reported to be non-emergencies (European Commission 2011);
- PSAPs receive ample information for triage via the MSD and the voice communication channel with the occupants. Advanced injury prediction algorithms can be applied as suggested by Bahouth *et al.* (2014) and Kusano & Gabler (2014);
- Emergency services already attend most injury collisions, even with only slightly injured occupants. Experience from the RAIDS programme also shows, that many ambulances attend collisions and treat casualties who do not appear in the STATS19 statistics (either because their injuries are relatively minor or because not every case is reported by the police); and
- The already existent implementation of Condition B in certain voluntary AECSs in the EU, Japan and USA is not known to have led to major disruptions of third party service providers (TPSPs). Furthermore, TPSPs having a system in coexistence with the mandatory eCall could help by filtering minor calls and only transferring the more severe cases.

Suitability for Implementation in Type-Approval Legislation

Airbags are not mandatory equipment for any vehicle sold in the EU. Nevertheless, to pass the performance criteria of the regulatory full-scale crash tests UN R94 and UN R95 and to score sufficiently in Euro NCAP, including the pole-impact test where a head-protecting airbag is a prerequisite, virtually all passenger cars are

equipped with frontal airbags and a high and increasing proportion is also equipped with side-torso and side-curtain airbags. Hence, Condition B can be applied to virtually all passenger cars. The specific implementation of the triggering requirement could cater for the theoretically remaining vehicles that are not equipped with any airbag; for example, via implementation as an 'if fitted' requirement.

A feasible and low-cost means of demonstrating adherence to the triggering requirement for type-approval would be a paper-based process. The vehicle manufacturer or IVS supplier could, for example, hand in a dossier of documents that assures the type-approval authority of the non-restrictive link between airbag deployment and automatic eCall triggering.

To prevent undue restriction of design freedom, the triggering algorithm should be left to the vehicle manufacturer's discretion within certain boundaries. This is also due to the fact that only vehicle manufacturers have advanced knowledge of the vehicle models and should therefore be enabled to tune the eCall triggering to the properties and sensors of the specific model. Implementing Condition B for mandatory triggering in a non-restrictive way does comply with these aims: Firstly, the algorithm under which conditions to trigger an airbag (and hence also trigger a mandatory eCall) is fully at the vehicle manufacturer's discretion. The automatic eCall requirement would just ensure that emergency services are notified after collisions which the vehicle manufacturer considered severe enough to deploy non-reusable restraint systems that need to be replaced. Secondly, an implementation of the requirement that allows triggering also under different accident conditions ensures that vehicle manufacturers can apply their expertise to also cover the remaining proportion of casualties in non-airbag deployment collisions.

Conclusions

This study found that mandatory triggering of automatic eCalls under accident conditions similar to, and at least as severe as, the frontal and lateral full-scale crash tests defined in UN R94 and UN R95 respectively cannot successfully ensure via regulation that a high proportion of casualties will benefit from automatic eCalls. In contrast, a non-restrictive requirement to trigger automatic eCalls after collisions where an airbag deployed was found to cover up to 4,330 fatally or seriously injured casualties more per annum in GB (57,042 casualties when considering all injury severity levels) and is, therefore, considered a more suitable candidate for implementation in type-approval legislation.

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Utilization of crash scene photos of vehicle damage and intrusion to improve trauma care preparedness

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ABSTRACT

Objective

To design, develop, and field test a smartphone app (called TraumaHawk) that would transmit photographic vehicle crush information to a trauma center in advance of patient arrival, then determine whether such information increases the amount of lead time the trauma center has to activate and prepare for treating crash injured patients.

Methods

TraumaHawk, a smartphone app for law enforcement and first responders, was designed by the University of Iowa to send photographs showing extent of intrusion and vehicle damage in a vehicle's occupant compartment to the receiving trauma center. With some basic training, first-responders and law enforcement personnel were taught how to photograph vehicles at a crash scene; trauma staff similarly received training regarding crash injury biomechanics and traumatology. For TraumaHawk cases received October 2013–August 2014, electronic medical records and trauma team notification pages were examined. Time of notification and actual time of patient arrival were noted. Time of TraumaHawk alert for these cases was also recorded. Traditional paging and TraumaHawk lead-times (minutes) were calculated. A paired *t*-test was used to determine if the mean lead-times for the Paging and TraumaHawk alerts differed significantly.

Results

During the study period, 35 TraumaHawk cases were identified, and 32 met trauma team activation criteria. For these 32, actual mean time between the trauma team page and patient arrival was 12 min; for TraumaHawk, advance notice was received at the trauma center 26 minutes before patient arrival, more than doubling notification time ($p<0.001$).

Conclusions

Utiltizing TraumaHawk to identify serious crashes remotely allowed the trauma team significantly more time to prepare for incoming trauma patients than the conventional ambulance crew notification. This allotted time allowed trauma staff to assemble a more complete and appropriate level of care by specialists, as well as to arrange other vital aspects of care—such as scheduling operating rooms.

Keywords: Motor vehicle crashes, traumatic injury, injury mechanism, prehospital

INTRODUCTION

Photographic documentation of crashed vehicles at the scene can be used to improve triage of crash victims. A U.S. expert panel developed field triage rules to determine the likelihood of occupants sustaining serious injuries based on vehicle damage that would require transport to a trauma center (Sasser et al., 2011). The use of photographs for assessing vehicle damage and occupant compartment intrusion as it correlates to increased injury severity has been validated (Davidson et al., 2014). Providing trauma staff with crash scene photos remotely could assist them in predicting injuries, or in the least, determine when a crashed vehicle damage indicates severe forces to the occupants. This would allow trauma care providers to easily assess when a more traumatic crash occurred, determine the appropriate transport mode, as well as develop mental models of treatment options prior to patient arrival at the emergency department (ED).

Crash-scene medical response has improved tremendously in the past 20-30 years. This is in part due to the increasing number of paramedics who now have advanced life support (ALS) training that allows independence in the field. By adopting more advanced procedures involving a more streamlined and efficient field treatment, the paramedics are more focused on treating crash victims and may have less time, or the need, to communicate with trauma centers regarding the crash severity and potential injury mechanisms. As a result, trauma centers may not learn about severe trauma patients until just a few minutes before they arrive. If the damaged vehicle photos could be electronically transmitted from the scene to the trauma center, this would allow an advanced remote interpretation of the crash severity prior to ED arrival and provide clues about the type and severity of injury.

With strategic crash scene photo documentation, trauma professionals have been trained to assess the severity and patterns of injury based on exterior crush and occupant intrusion. In past years, training was conducted during surgery grand rounds and to ED staff at the pilot trauma center as well as at paramedic training in the region. This training focused on the principles to assess occupant compartment intrusion that increases the force that translates into injury severity and also assess the amount of exterior crush that determines the severity of force all the occupants experienced. (Tencer et al., 2005; Assal et al., 2002; Mandell et al., 2010). Again, first responders have the unique opportunity to assess and visualize the severity of damaged vehicles at the crash scene, but often the information regarding the mechanism of injury and crash severity is limited due to time constrains in the field and may not be relayed to ED trauma staff.

To integrate photographic and scene information, an app called “TraumaHawk” was created to capture images of crash vehicles and send them electronically to the trauma center. If efficiently implemented, the crash scene photos would provide the potential advantage of increasing the lead-time for ED arrival of known severely injured crash patients. Ideally, this advanced interpretation could result in better treatment and outcomes for crash victims by determining a need for airlift versus ground transport, allow more lead times for trauma preparedness for arrival, and possibly prioritize treatment plans that focus on potential injury mechanisms. In addition advanced notice can make the overall operation more efficient. Trauma staff is frequently utilized during non-emergent periods to do other

inpatient operative and bedside procedures that once started cannot be interrupted. Having some advanced lead-time for patient arrival could allow time to finish the procedure, or postpone and reschedule.

The objective of this paper is to describe the design, development, and field testing of a smartphone app (called TraumaHawk) that transmits photographic vehicle crush information to a trauma center in advance of patient arrival. We then determine whether such information increases the amount of lead time the trauma center has to activate and prepare for treating crash injured patients.

METHODS

Background and TraumaHawk Development

Development of the TraumaHawk app was a team collaboration that included law enforcement from the Iowa State Patrol, first responders, ALS paramedics, trauma doctors, nurses and app developers. Involving all parties was crucial in ensuring that both the app and reporting process would be intuitive and practical for all users. Figure A1 displays several screen shots from the TraumaHawk app. The design allows on-scene personnel to create a report in about one minute and transmit it electronically to the ED. The app alerts trauma staff to the exact location of the crash, and its distance from the trauma center. The report displays a series of relevant photos of the vehicles involved in the crash, and allows for added contextual information. Icons help first responders easily select specific photos to document the exterior and interior of the crashed vehicles. The few images captured allow assessment of steering wheel deformation, A-pillar compromise, roof crush and other intrusions into the occupant compartment of the vehicle that are correlated with increased injury severity (Tencer et al., 2005; Assal et al., 2002; Mandell et al., 2010).

TraumaHawk User Procedures

TraumaHawk is currently implemented on Apple iPhone® 5s smart phones supplied by the state. To create a report, law enforcement or a first responder clicks on the App (Figure A1A) and then clicks “New Report” on the first screen (Figure A1B). Within the new report, the user is asked to state the type of crash (frontal, side, rollover, or rear-end); meanwhile, GPS location is also automatically logged, and calculates the distance the crash is from the Level 1 Trauma Center (Figure A1C). As can be seen in Figure A1D, the user is then guided as to what areas of the automobile should be photographed. The six areas chosen by the research team were selected based on the work by Davidson et al. (2014) that demonstrated these particular regions are most predictive of injury severity. Figure A1E shows the screen that pops up when the “Driver’s Side” option is selected in Figure A1D. The user is asked to provide three pictures of the driver’s side that together create a full side view of the vehicle, as well as 45º angled views at both corners of the damaged plane. If the user is unclear as to where the pictures should be taken, he/she can click on “Help” and view example photos of how to capture or frame the damaged side of the vehicle. Figure A1e is an example of photos taken at a TraumaHawk alert crash that illustrate the result of a high-speed near-side impact that met the intrusion rule for transport of the front right passenger to the trauma center. The field users are also allowed to include additional textual information on the crash. Nighttime photos have been successfully taken

utilizing the iPhone 5s internal flash. Additional lighting can also be provided from the high intensity flashlights that are used by law enforcement.

Finally, users have the ability to 'sanitize' each image by using their fingers to 'smudge' out crash victim faces (if present) and vehicle license plates to ensure confidentiality and protect the privacy of crash victims.

TraumaHawk in the Emergency Department

Once a report has been submitted, it is electronically transmitted to the ED trauma center where the patient will be transported and displayed as an iPad® text alert; a signature auditory alarm alerts staff at the charge nurse's station that a report has been delivered. A copy of the report is also sent to the research team via secure e-mail. The iPad report is then viewed by the ED charge nurse, who alerts the ED staff physician of the TraumaHawk notification. The ED physician reviews the TraumaHawk report and shares the photos with the Trauma team to assess crash severity, the potential for traumatic injuries, and how best to activate the trauma team most efficiently. A flow diagram of the overall process is presented in Figure 1. After the images have been received, a member of the research/trauma team communicates with the field users, mainly State troopers, who sent the photos to give them feedback on the image quality and contents. This promoted better personal communication from the field users and also provided an opportunity to discuss any factors influencing the ability or inability to capture the required photos.

TraumaHawk cases are received at the University of Iowa Hospital, which is an American College of Surgeons Committee on Trauma accredited Level 1 Trauma Center with over 600 adult and pediatric trauma beds. At this Trauma Center, in order for a trauma notification to be sent, a patient must meet certain CDC Field Triage criteria. Paramedics utilize these triage rules, examining the physiological and anatomic criteria to assess whether a patient qualifies for notification (Sasser, et al., 2011). A patient may also be considered a trauma notification for certain levels of crush and intrusion for a high-risk automobile crash. Some of the indicators of a high-risk automobile crash are defined as:

1. Component intrusion greater than 12 inches at the occupant's site that includes the roof; or greater than 18 inches of crush at any location.
2. Patient is ejected (partial or complete) from the automobile, or
3. A death occurred in same passenger compartment, or
4. Vehicle telemetry data are consistent with a high risk of injury

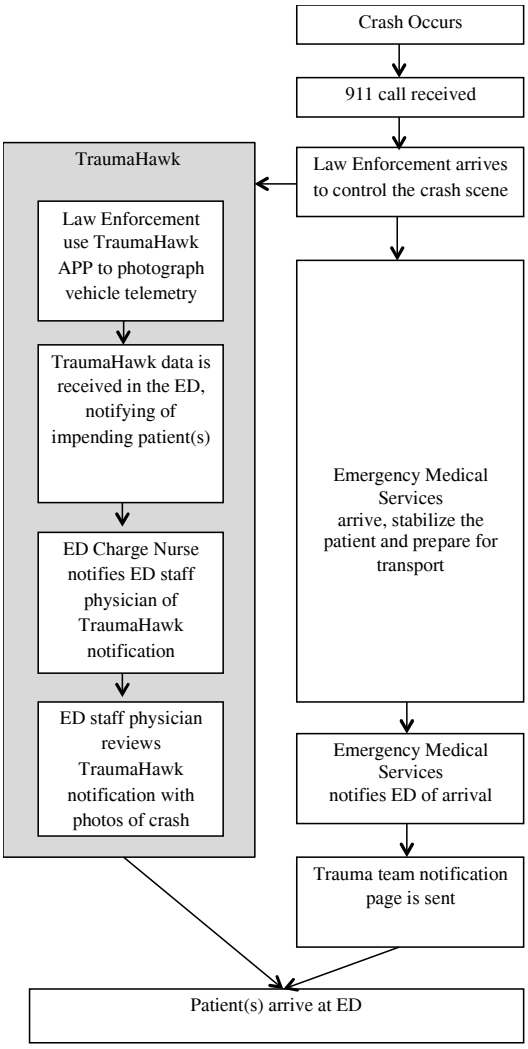

Figure 1. TraumaHawk flow diagram from crash to ED arrival

In October 2013, 15 phones with the TraumaHawk App were distributed to a convenience sample of prehospital providers, mainly to law enforcement (Iowa State Patrol), along with local county and city-based ALS ambulance services. In the first few months of deployment, we observed that the State Patrol and/or law enforcement were generally in the best position to complete and transmit the TraumaHawk reports at the crash scene. After providing first aid and traffic control, the on-scene law enforcement officer has a short window in which to capture a report once the paramedics arrive to help manage the scene. Having the on-scene photo documentation done by law enforcement does not impede on any emergency activities or delay extrication, or any patient care. The paramedics were frequently too busy with patient care priorities to pause and document the scene. However, on ambulances that carried a three-member crew, the designated driver was able to take pictures and submit a report. It should be noted, however, that each crash can have a different order of first responders to a crash scene. Depending on the crash location, particular in rural areas, law enforcement may be one of the last parties to arrive. However, they were still able to document the scene prior to patient transport, or ED arrival.

After the photos are received in to the secure email inbox and utilized in the trauma bay, they are then entered in to the patient's permanent medical record as photo attachments by hospital staff. Privacy concerns and compliance with the Health Insurance Portability and Privacy Act (HIPPA) were discussed with hospital legal counsel and the hospital compliance office. It was determined that photos that were taken by law enforcement did not constitute protected health information until they were viewed by the trauma team. However, it was felt that photos taken by EMS crews would constitute protected health information because they are using the photos as part of a medical evaluation. In these cases, any photos that contained identifiable information would need to be 'sanitized' as described above. The photos can only be sent to a password protected email inbox so that they are secure and only accessible by attending medical staff and the research team. Additional security is built into the app itself. Crash scene photos can only be accessed through the TraumaHawk app, not through the phone's camera or other photographic software. Finally, photos taken by the TraumaHawk app are perishable and are automatically deleted from the iPhone two hours after they are taken and the reports were submitted.

Trauma Alert Times and Trauma Registry Data Collection

For TraumaHawk cases received from October 2013–August 2014, electronic medical records and trauma notification pages were examined to document the time and content of trauma notification pages, and the actual time of patient arrival. Time of the TraumaHawk alert cases were identified and recorded. The difference between traditional paging and TraumaHawk lead-times was calculated in minutes. A paired *t*-test was used to determine if the mean lead-times for the Paging and TraumaHawk alerts differed significantly.

To examine how TraumaHawk motor vehicle crashes (MVC) differed from all MVCs seen at the Trauma Center over the study period, hospital-based trauma registry data were abstracted for all MVCs (ICD-9 CM E-codes =E810.0-E825.7) from October 2013 through June 2014, and then analyzed. Trauma notifications were excluded if the crash involved a motorcycle or moped, all-terrain vehicle, or snowmobile that did not include a collision with a passenger vehicle; if patients were not brought directly to the Trauma Center (transferred from an outside hospital to trauma center); or if they were not brought via ground or air ambulance. Differences in proportions of TraumaHawk versus other MVCs were compared using Pearson chi-square test and differences in means were examined using a Student's *t*-test

RESULTS

From October 2013 through August 2014, 35 TraumaHawk reports were received, of which 32 met the criteria for a trauma team notification. During this time, 319 eligible MVC were seen at the Trauma Center, of which 10.0% (n=32) had TraumaHawk reports.

TraumaHawk-reported patients had an average injury severity score (ISS) of 6.4 (standard deviation=11.4), 50% (n=16) were male, their mean length of hospital stay was 5.6 days (standard deviation=7.9), and the majority

(93.8%, n=30) arrived by ground ambulance. These characteristics did not differ between TraumaHawk and Non-TraumaHawk patients (see Table 1). TraumaHawk patients were less likely to be admitted (25.0% vs. 44.8%, p=0.0325) and were, on average, younger than non-TraumaHawk patients (30.8 vs. 38.6 years, p=0.0365).

Table 1. Patient, Emergency Dept. and Hospital Stay Characteristics by Presence of TraumaHawk Photos

	TraumaHawk		
	Yes (%)	No (%)	p-value
Age, years (mean, std)	30.8 (19.4)	38.6 (20.0)	0.0365
Male	16 (50.0)	153 (53.5)	0.7070
Arrival Mode			
Air ambulance	2 (6.3)	55 (19.2)	0.1797[1]
Ground ambulance	30 (93.8)	230 (80.4)	
Police	0	1 (0.4)	
Injury Characteristics			
ISS	6.4 (11.4)	8.0 (10.5)	0.5020
Max AIS	1.7 (1.3)	2.0 (1.2)	0.1721
ED GCS	14.6 (1.3)	14.3 (2.7)	0.2256
TRISS	0.97 (0.07)	0.95 (0.16)	0.2383
Admitted to Hospital	8 (25.0)	128 (44.8)	0.0325
Length of stay, days (mean, std)	5.6 (7.9)	5.2 (8.3)	0.8811
Died	0	7 (2.5)	0.9999[1]

[1] Fisher's exact test

Of the 32 TraumaHawk cases who were also trauma notifications, the actual mean time between the trauma team page and patient arrival was 12 minutes; with TraumaHawk, the advanced notice was received at the trauma center 26 minutes before patient arrival, more than doubling notification time (p<0.001). On average, the ED doctor saw patients 69 minutes after they sustained their injury. These times were significantly lower for TraumaHawk patients (56.7 minutes, standard deviation=23.3) than for non-TraumaHawk patients (70.2 minutes, standard deviation=43.8) (p=0.03). In addition, the trauma surgeon responded, on average, 66 minutes after the injury. TraumaHawk patients saw the trauma surgeon, on average, 58.1 minutes (standard deviation=22.1) after their injury vs. 67.3 minutes (standard deviation= 36.0) for non-TraumaHawk patients (p=0.07).

The TraumaHawk reports averaged six (range 1-14) photos per report. In the 35 TraumaHawk reports, 88.6% included interior images of the driver area with a view of the steering column, and 80% showed a view of the driver floorboard. In all cases, the damage planes were documented.

DISCUSSION

Advanced warning and trauma page activation regarding an incoming crash allows ED personnel to allocate resources more efficiently. They are able to order the disposition of patients and allocate adequate staff to receive incoming crash victims. The increased time afforded by a trauma alert also allows trauma surgeons and specialty services to adjust schedules accordingly (i.e., they might delay the start of a non-urgent scheduled procedure to provide time to assess the incoming trauma victim).

While all trauma staff receive a standardized page with a report from the field, this often includes only the most basic information about the manner of collision such as frontal crash, rollover; some vital sign information and potential body region injury may also be described. It is said that, "a picture is worth a thousand words". Some of the feedback from trauma staff indicated that the viewing of the TraumaHawk report images prior to a patient's arrival allowed a much better assessment of potential injury than a brief radio report would. This assessment did enable the trauma team to prepare and plan for specific key treatment and specialties services (orthopedics, neurosurgeon, etc.) such was the case in identifying the potential for a pelvic fracture for the patient in Figure A1E.

TraumaHawk is a useful tool to teach the basics of automotive traumatology. This is a complex science that involves an understanding of restraint systems, physics, occupant factors, and crash dynamics. Having a basic understanding of traumatology, one can correlated the damage crush and intrusion into the vehicle to potential severe injury patterns, as well as measure the extent of force in which the passengers may have sustained. This then can help shape the mental model of treatment by EMS and trauma care providers. A crash injury mechanism curriculum had been created by the team and delivered to all users by an in-person presentation during this pilot phase. The course has been certified to provide continuing medical education (CME) credits. The course illustrates the basic methods on how to interpret the Step 3 CDC rule examining damage planar crush and the potential injury patterns from intrusion. Currently several short topic modules are being created from this curriculum that can be reviewed electronically by law enforcement, prehospital personnel, nursing, and trauma staff. This curriculum will be a required component of the using the information generated from the app and the modules would also be available to the users on the iPhone. We see that such a series of courses would become standard training for all personnel involved in the treatment of crash victims.

Improving the mental model of crash dynamics and potential injury has several potential advantages on patient care. In the prehospital setting, when used in conjunction with the CDC trauma guidelines it can help to determine whether to take the patient to a level II or III trauma center for treatment or whether to bypass one of these closer

hospitals in favor of going directly to a level I trauma center. TraumaHawk reports can help to make determinations about which patients should be transported by air ambulance versus the standard ground transport. The research did not evaluate if TraumaHawk impacted these decisions or transport modes. Further research is planned to evaluate after the pilot with TruamaHawk procedures are in place.

Once in the hospital, all patients undergo a standardized and very thorough exam. The photos generated by the TraumaHawk app can help the team focus on particular parts of the exam where the data would indicate there is a high risk for injury. Conversely, if a patient appears to be uninjured or has very mild injuries after a full and thorough exam, having an understanding of the crush patterns of the vehicle (or lack thereof) can provide the treating team with reassurance that the patient is safe for discharge and could reduce the need for invasive procedures and radiological images. Current prehospital treatment protocols are always in place to examine patients, and even in low speed crashes occupants can still be severely injured and not have significant crush. As this was an implementation pilot, trauma staff feedback and communication regarding it use was conducted. This generated some positive responses from ED staff, especially the additional time to prepare trauma bays and schedule the potential need for operating rooms and some pre diagnosis of potential mechanism of injury.

There are limitations to this study. First, TraumaHawk crashes tended to occur in closer proximity to the ED than did non-TraumaHawk crashes; therefore we cannot say if the shorter time between patient injury and the ED/Trauma physician was perhaps due to the shorter distance traveled. Second, because there are only a small proportion of MVCs seen at the ED with TraumaHawk reports, the generalizability of the current results are limited, although, the characteristics of TraumaHawk patients and their injuries did not differ greatly from non-TraumaHawk patients.

From these pilot data, TraumaHawk was shown to increase the advance time for trauma notification and preparedness at a trauma center for identified trauma patients. Because of the added context, patients were seen more quickly than non-TraumaHawk cases. Since the initial 15-phone deployment, we have increased the number of phones to 35 in state trooper vehicles, and more data will be available soon. With the success in the implementation of TraumaHawk, further research and evaluations are planned to examine the benefits in the triage, transport and treatment of crash victims.

CONCLUSIONS

Utilizing TraumaHawk to identify serious crashes and potential injury mechanisms allowed the trauma team significantly more time to prepare for incoming trauma patients than the conventional ambulance crew notification. This allotted time allowed trauma staff to assemble a more complete and appropriate level of care by specialists, as well as to arrange other vital aspects of care—such as scheduling operating rooms.

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FIGURE A1

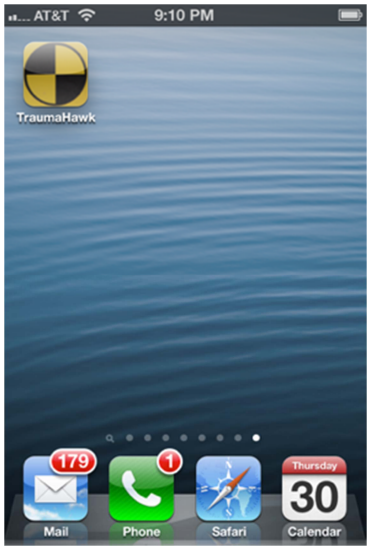


Figure A1a

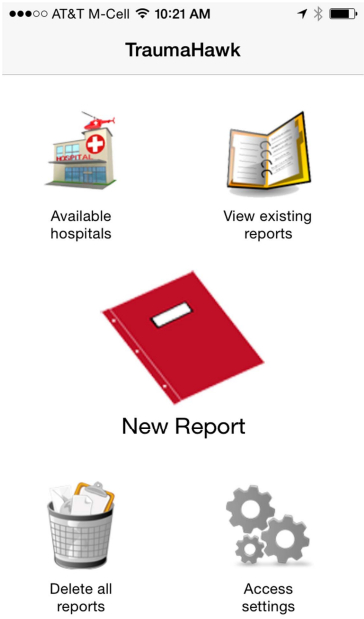
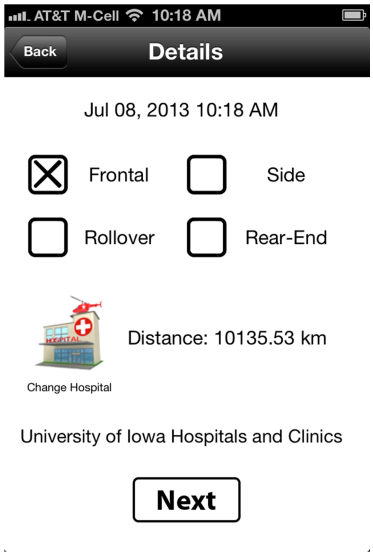
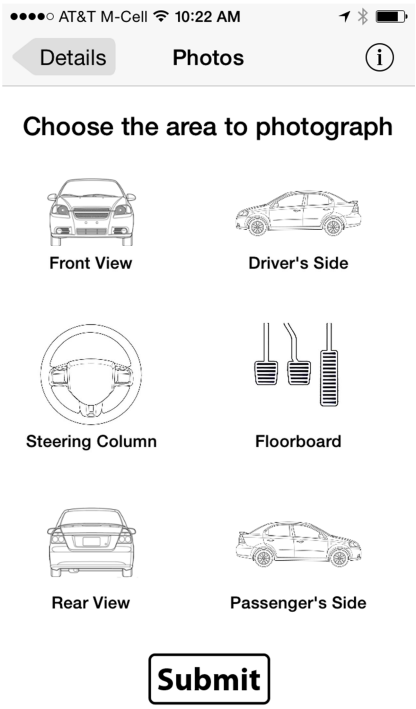


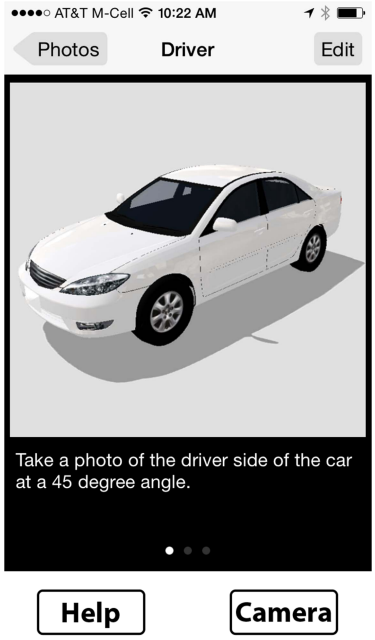
Figure A1b


AT&T M-Cell 10:18 AM
Back
Details
Jul 08, 2013 10:18 AM
Frontal
Side
Rollover
Rear-End
Distance: 10135.53 km
Change Hospital
University of Iowa Hospitals and Clinics
Next

A1c


AT&T M-Cell 10:22 AM
Details
Photos
Choose the area to photograph
Front View
Driver's Side
Steering Column
Floorboard
Rear View
Passenger's Side
Submit

A1d



A1e

Figure A1. TraumaHawk iPhone 5S interface and screen shots

FIGURE A2

Figure A2. Example images from a TraumaHawk crash file

OCCUPANT TRANSPORTATION DECISION ALGORITHM: AN ADVANCED AUTOMATIC CRASH NOTIFICATION ALGORITHM DEVELOPED AND EVALUATED FOR MOTOR VEHICLE CRASH OCCUPANT TRIAGE

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ABSTRACT

The objective was to develop an Advanced Automatic Crash Notification (AACN) algorithm and evaluate its performance in making optimal occupant triage decisions. The developed AACN algorithm known as the Occupant Transportation Decision Algorithm (OTDA) uses measurements obtainable from vehicle telemetry to predict risk of overall occupant injury and recommend a transportation decision for the occupant following a motor vehicle crash (MVC), particularly whether transport to a Level I/II trauma center is recommended. A list of injuries necessitating treatment at a Level I/II trauma center (TC) was determined using an injury-based approach based on three facets (severity, time sensitivity, and predictability). These three facets were quantified for each injury from expert physician and emergency medical services (EMS) professional opinion and database analyses of the National Trauma Data Bank and National Inpatient Sample. Severity, Time Sensitivity, and Predictability Scores were summed for each injury to compute an Injury Score. Injuries with an Injury Score exceeding a particular threshold were included on the Master Target Injury List, which is a list of injuries more likely to require Level I/II TC treatment. OTDA inputs for development include the Master Target Injury List and 38,970 National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) 2000-2011 occupants. The OTDA uses multivariate logistic regression to predict an occupant's risk of sustaining an injury on the Master Target Injury List from the following model variables: longitudinal/lateral delta-v, number of quarter turns (in rollover only), belt status, multiple impacts, and airbag deployment.

A parametric OTDA was developed with five tunable parameters allowing for extensive optimization. The OTDA was optimized with a genetic algorithm that compared the OTDA transportation decision for each NASS-CDS occupant to a dichotomous representation of their Injury Severity Score (ISS). Occupants with ISS 16+ should be transported to a Level I/II TC. OTDA optimization minimized under triage (UT) and over triage (OT) rates with the goal of producing UT rates < 5% and OT rates < 50% as recommended by the American College of Surgeons (ACS). For the optimized OTDA, UT rates by crash mode were 5.9% (frontal), 4.6% (near side), 2.9% (far side), 7.0% (rear), and 16.0% (rollover). OT rates by crash mode for the optimized OTDA were 49.7% (frontal), 47.9% (near side), 49.7% (far side), 44.0% (rear), and 49.7% (rollover).

The OTDA was developed with an injury-based approach that examined three injury facets to identify injuries necessitating treatment at a Level I/II TC. Large hospital and survey datasets containing information on injuries, mortality risk, treatment urgency, and hospital transfers were used in conjunction with large crash datasets with crash, vehicle, occupant, and injury data. The OTDA has been rigorously optimized and has demonstrated improved UT rates compared to other AACN algorithms in the literature and OT rates meeting ACS recommendations. Since the OTDA uses only vehicle telemetry measurements specified in Part 563 regulation, this AACN algorithm could be readily incorporated into new vehicles to inform emergency personnel of recommended triage decisions for MVC occupants. The overall societal purpose of this AACN algorithm is to reduce response times, increase triage efficiency, and improve overall patient outcome.

INTRODUCTION

There are approximately 6.4 million motor vehicle crashes (MVCs) annually in the United States (US) [1]. These crashes killed 33,000 people and injured 3.9 million people in 2010 [2]. Many crashes leave a heavy burden of

morbidity that can affect victims throughout the rest of their lives. While the advent of passive safety standards (seat belts, airbags, etc.) has lowered the morbidity and mortality of motor vehicle crash victims, there are significant barriers to further improvements. Most experts believe that an important future avenue for progress is to improve the trauma triage process, that is, the process whereby patients are given the "right care" at the "right place" at the "right time." Optimizing this process is difficult due to timing, decision making, resources, and access to care.

Advanced Automatic Crash Notification (AACN) has shown promise in improving the trauma triage process by predicting occupant injury severity using vehicle telemetry data to recommend a transportation decision. Event data recorders (EDRs) use electronic sensors in the car to collect crash data and AACN systems can transmit this data to the proper authorities. The 49 CFR Part 563 regulation for EDRs released by NHTSA specifies the data elements required for all vehicles equipped with an EDR [3]. Required data elements include longitudinal delta-v, seat belt status, frontal airbag deployment, and multiple events. The regulation also includes data elements required for vehicles under specified conditions. Data elements for these include lateral delta-v, vehicle roll angle, and side airbag deployment. Using the information collected from a vehicle, the risk of an occupant sustaining an injury can be calculated, and a decision process for determining the level of care for the occupant can be presented to emergency medical personnel. The National Study on the Costs and Outcomes of Trauma (NSCOT) identified a 25% reduction in mortality for severely injured patients who received care at a Level I trauma center rather than at a non-trauma center [4]. AACN technology can provide data on the vehicle location, delta-v, principal direction of force (PDOF), airbag deployment, and the occurrence of rollover or multiple event collisions which may be valuable in estimating the occupant's injury risk following a MVC.

Current AACN algorithms include OnStar and URGENCY which incorporate model variables such as crash direction, delta-v, multiple impacts, belt use, vehicle type, age, and sex [5-11]. Both of these algorithms use Abbreviated Injury Scale (AIS) metrics to define severely injured patients. Although AIS-based metrics are most commonly used, other methods of injury scoring have been developed to better discriminate severely injured patients.

The objective of this study was to develop an AACN algorithm and evaluate its performance in making optimal occupant triage decisions using an injury-based approach. The developed AACN algorithm, known as the Occupant Transportation Decision Algorithm (OTDA), uses measurements obtainable from vehicle telemetry to predict risk of overall occupant injury and recommend a transportation decision for the occupant following a MVC.

METHODS

An injury-based approach quantifying three facets of individual injuries was developed to improve upon the severity scoring systems and better evaluate the risk of occupant injury. This approach focused on 240 injuries comprising the top 95% most frequently occurring AIS 2+ injuries in the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) 2000-2011. The injury-based approach identifies injuries requiring Level I/II trauma center (TC) level treatment by quantifying three facets of injury: severity, time-sensitivity, and predictability. Severity is associated with injuries which have a high mortality and high threat-to-life. Severity was scored based on mortality risk ratios (MRRs) obtained from the National Trauma Data Bank (NTDB) [12]. Time Sensitivity is associated with the urgency with which a particular injury requires treatment. Time Sensitivity was scored using expert physician survey data which incorporated the recommended treatment location and a rank of urgency [13]. Predictability is associated with injuries with a propensity to be missed on evaluation at the scene. Predictability was scored using two components: an Occult Score and a Transfer Score. The Occult Score is a measure of the likelihood that an injury is missed using expert survey data from physicians and emergency medical services (EMS) professionals. The Transfer Score is a measure of the likelihood that an injury is present in patients that require transfer from a non-trauma center to a Level I/II TC using the National Inpatient Sample (NIS) database [14]. The scores of each of these facets (Severity, Time Sensitivity, and Predictability) were computed for each of the 240 injuries on the top 95% most frequently occurring AIS 2+ MVC injuries list. Each score was normalized on a zero to one scale in which scores closer to one were more severe, more time sensitive, and less predictable.

The inputs to the OTDA include a Master Target Injury List and NASS-CDS 2000-2011 cases. The Master Target Injury List is determined by multiplying the Severity, Time Sensitivity, and Predictability Scores by a weighting coefficient and then summing these values to produce a Target Injury Score. Injuries exceeding a defined Injury Score Cutoff are then included on the Master Target Injury List. The Master Target Injury List is not a static list and

is capable of being varied in order to optimize the algorithm. An example computation of the Target Injury Score is provided in Figure 1 for an AIS 3 vault fracture. The injury had Severity, Time Sensitivity, and Predictability Scores of 0.73, 0.93, and 0.48, respectively. These scores indicated a severe and time sensitive injury that has moderately high predictability and the Target Injury Score was 2.14. For this example, the weighting coefficients were set to one. However, optimization of the algorithm allows the weighting coefficients to vary as will be explained later.

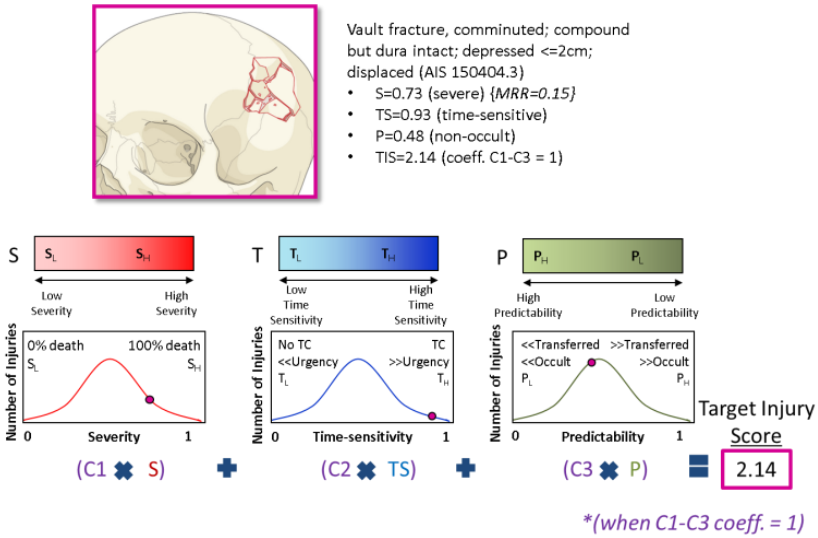

Figure 1. Example computation of a Target Injury Score for an AIS 3 vault fracture.

NASS-CDS 2000-2011 cases were used to train and evaluate the OTDA. Cases from NASS-CDS 2009-2011 with a model year greater than 10 years were excluded due to missing injury and occupant information (11,814 distinct occupant IDs excluded). After applying the exclusion criteria, the resulting NASS-CDS 2000–2011 dataset contained 54,703 cases, 94,283 vehicles, 115,159 occupants, and 303,230 injuries.

The OTDA uses multivariate logistic regression to predict the risk of an occupant sustaining an injury on the Master Target Injury List for specified crash conditions. Weighted NASS-CDS 2000-2011 data was used to select frontal, near side, far side, rear, and rollover crashes for driver and front right passengers 16 years and older. Five separate multivariate logistic regression models were created according to crash type: frontal, near side, far side, rear, and rollover crash. For determining the outcome measure, each occupant's injuries were assessed to determine if any one of the injuries was on the Master Target Injury List. If at least one injury appeared on the Master Target Injury List that occupant was coded as sustaining a Target Injury; if none of the occupant's injuries were on the Master Target Injury List, that occupant was coded as not sustaining a Target Injury.

Longitudinal delta-v was used for the frontal and rear models. Lateral delta-v was used in the near side and far side models. EDR correction factors for delta-v were implemented to adjust for differences in the delta-v estimated by WinSMASH in NASS and the delta-v obtained directly from the EDR [15-18]. For the rollover crash type, the number of quarter turns was binned into six categories: 1, 2, 3-4, 5-6, 7-8, 9-17. Any MVC with a quarter turn greater than 1 was categorized as rollover even if it met other crash mode criteria. Models for frontal, rear, and far side were adjusted for belt status, multiple impacts, and frontal airbag deployment. Models for near side and rollover were adjusted for belt status, multiple impacts, frontal and side airbag deployment. The majority of the variables included in the OTDA (longitudinal delta-v, belt status, multiple impacts, and frontal airbag deployment) were selected because they are EDR variables required for all vehicles in the EDR regulation, 49 CFR Part 563 [3]. Lateral delta-v and side airbag deployment were included because of their importance in defining crash severity for side impacts and they are EDR variables required for vehicles under specified conditions in 49 CFR Part 563. Occupants with any missing data for variables of interest were not included in the analysis. The Risk of any Target Injury is calculated with the cumulative distribution function for frontal, rear, and far side in Equation 1 and for near side and rollover in Equation 2. Logistic regression analyses were performed using SAS 9.4 (SAS Institute, Cary, NC) and R 3.0.2 (R Foundation for Statistical Computing, Vienna, Austria).

$$\frac{e^{(\alpha + \beta_1 DV + \beta_2 Belt + \beta_3 AB + \beta_4 MI)}}{1 + e^{(\alpha + \beta_1 DV + \beta_2 Belt + \beta_3 AB + \beta_4 MI)}} \quad \textbf{(1).}$$

where α= intercept, β_1, β_2, β_3, β_4=parameter coefficients for DV= longitudinal delta-v/lateral delta-v; Belt= belt status (0=no, 1= yes); AB= frontal airbag deployment (0= no, 1=yes); MI= multiple impacts (0= no, 1= yes).

$$\frac{e^{(\alpha + \beta_1 DV + \beta_2 Belt + \beta_3 AB + \beta_4 MI + \beta_5 SAB)}}{1 + e^{(\alpha + \beta_1 DV + \beta_2 Belt + \beta_3 AB + \beta_4 MI + \beta_5 SAB)}} \quad \textbf{(2).}$$

where α= intercept, β_1, β_2, β_3, β_4=parameter coefficients for DV= lateral delta-v/number of quarter turns; Belt= belt status (0=no, 1= yes); AB= frontal airbag deployment (0= no, 1=yes); MI= multiple impacts (0= no, 1= yes); SAB= side airbag deployment (0=no, 1=yes).

The OTDA features five tunable parameters (termed "Variable Parameters") allowing for extensive optimization. The five Variable Parameters include the Severity Multiplier, Time Sensitivity Multiplier, Predictability Multiplier, Injury Score Cutoff, and a Risk Cutoff. The Severity Multiplier, Time Sensitivity Multiplier, and Predictability Multiplier are the weighted coefficients used to produce the Target Injury Score. The Injury Score Cutoff is the threshold at which an injury is deemed to be included on the Master Target Injury List. The Risk Cutoff is the threshold above which a case is deemed recommended to be sent to a Level I/II TC.

The OTDA was optimized with a Covariance Matrix Adaptation- Evolution Strategy (CMA-ES) genetic algorithm that compared the OTDA transportation decision for each NASS-CDS occupant to a dichotomous representation of their Injury Severity Score (ISS). Occupants with ISS 16+ should be transported to a Level I/II TC. OTDA optimization minimized under triage (UT) and over triage (OT) rates with the goal of producing UT rates < 5% and OT rates < 50% as recommended by the American College of Surgeons (ACS) [19]. OT was assessed using the False Positive Rate (FPR) metric, also known as 1-Specificity [20-22]. This represents the proportion of mildly injured patients that went to a Level I/II TC. UT was assessed using the False Negative Rate (FNR) metric, also known as 1-Sensitivity [20-23]. This represents the proportion of seriously injured patients that did not go to a Level I/II TC. A graphical representation of the OTDA is provided in Figure 2.

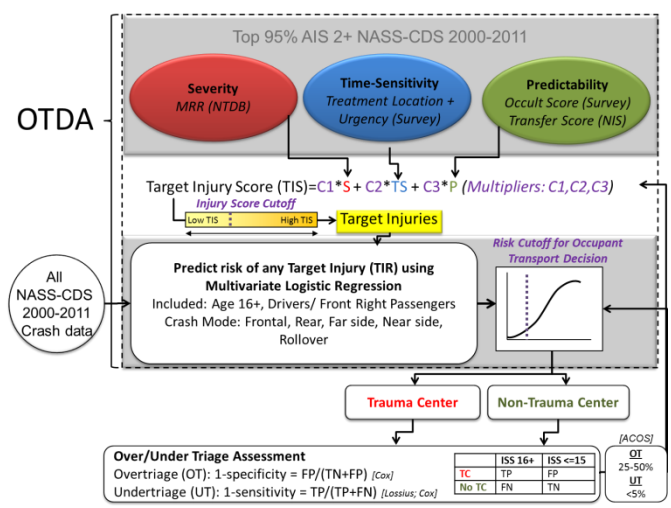

Figure 2. Overview of OTDA.

RESULTS

A total of 38,970 NASS-CDS 2000-2011 cases met the inclusion criteria and the number of cases by crash mode is summarized in Table 1.

Table 1.
Cases meeting inclusion criteria by crash mode.

Crash Mode	# of Cases
Frontal	21,273
Rear	2,667
Far side	3,608
Near side	3,890
Rollover	7,082
Total	38,970

The resulting OT and UT metrics for the optimal Variable Parameters are listed in Table 2.

For the optimized OTDA, UT rates by crash mode were 5.9% (frontal), 7.0% (rear), 2.9% (far side), 4.6% (near side), and 16.0% (rollover). OT rates by crash mode for the optimized OTDA were 49.7% (frontal), 44.0% (rear), 49.7% (far side), 47.9% (near side), and 49.7% (rollover). The UT rates for far side and near side met the 5% ACS recommendation. The OT rates for frontal, rear, far side, near side, and rollover all met the 50% ACS recommendation.

Table 2.
OT/UT metrics by crash mode for the optimal Variable Parameters.

Crash Mode	OT Metric (FPR)	UT Metric (FNR)	TP	FP	TN	FN
Frontal	49.7%	5.9%	903	10451	10312	57
Rear	44.0%	7.0%	40	1470	1154	3
Far side	48.7%	2.9%	232	1727	1642	7
Near side	47.9%	4.6%	559	1723	1581	27
Rollover	49.7%	16.0%	871	3040	3005	166

DISCUSSION

The OTDA was developed with an injury-based approach that examined three injury facets to identify injuries necessitating treatment at a Level I/II TC. Large hospital and survey datasets containing information on injuries, mortality risk, treatment urgency, and hospital transfers were used in conjunction with large crash datasets with crash, vehicle, occupant, and injury data. The OTDA has been rigorously optimized and has demonstrated improved UT rates compared to other AACN algorithms in the literature and OT rates meeting ACS recommendations. For studies using URGENCY where separate models were created by crash mode, the UT rates ranged from 29-49% for frontal crashes, 6-33% for near side crashes, and 19-46% for far side crashes [8-11, 24]. For the OT rates, the values ranged from 3-18% for frontal crashes, 5-46 % for near side crashes, and 10-15% for far side crashes.

Traditionally, priority has been given to the reduction of UT to prevent mortality & morbidity with the understanding that some elevation in OT is necessary to prevent seriously injured patients from being under triaged. The OTDA significantly reduced UT for all crash modes without elevating OT beyond the ACS guidelines. These results are very encouraging as the OTDA uses only crash characteristics that are obtainable from vehicle sensors, whereas the majority of AACN algorithms in the literature use variables such as occupant age or gender that are not obtainable directly from the vehicle. In short, the OTDA appears to be doing “more with less” than several algorithms to which it has been compared and shows great promise as an improved approach for triaging patients.

Additional reduction in UT and OT would be expected if additional variables such as occupant age and gender were included in the OTDA. There is some room for improvement in UT for rollover crashes. Rollover crashes are complex events and determining the severity of the event is difficult due to many factors. These factors include vehicle geometry, vehicle deformation, and subsequent impacts which can alter the number of quarter turns a vehicle experiences. Several studies have taken different approaches to determine rollover severity by using the number of quarter turns [25], the number of ground to roof impacts [25], the extent of roof crush [26], pre-roll speed [6], and primary area of damage [26]. The NASS rollover variable which designates the number of quarter turns has

been previously used in URGENCY and other studies involving rollover research [8, 11, 27-31]. Additional data elements could be incorporated in the future to better quantify the severity as well as a better differentiation of the types of rollovers.

Overall, side airbag deployment resulted in little difference in the OT/UT rates for near side and rollover crashes. However, for the cases that involved vehicles that deployed a side airbag, the UT rates were improved, but this is less evident when looking at the entire NASS-CDS sample since only 5-10% of the vehicles were equipped with side airbags. Therefore, with the inclusion of the side airbag variable there would be a benefit for the occupant in vehicles where a side airbag is equipped.

Since the OTDA uses only vehicle telemetry measurements specified in Part 563 regulation, this AACN algorithm could be readily incorporated into new vehicles to inform emergency personnel of recommended triage decisions for MVC occupants. The overall societal purpose of this AACN algorithm is to reduce response times, increase triage efficiency, and improve overall patient outcome.

CONCLUSION

An AACN algorithm, known as the OTDA, was developed that utilizes MVC characteristics obtainable from vehicle telemetry data and estimates the risk of serious injury for occupants. This risk for injury is used to recommend a transportation decision for the occupant (Level I/II TC versus non-trauma center). A parametric algorithm was developed with tunable parameters to allow for extensive optimization. Adjusting the Severity, Time Sensitivity, and Predictability Multipliers changes the taxonomy of injuries on the Master Target Injury List. The Injury Score Cutoff changes the number of Target Injuries that are included on the Master Target Injury List. The Risk Cutoff adjusts the level of risk that defines whether an occupant should be treated at a Level I/II TC versus a non-trauma center. The rigorous optimization of the OTDA produced improved UT rates compared to other AACN algorithms in the literature and OT/UT rates that met the ACS recommendations.

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RESULTS OF FIRST FIELD TEST OF TELEMETRY BASED INJURY SEVERITY PREDICTION

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ABSTRACT

Identification of severely injured occupants is of utmost urgency following a crash event. Advanced automatic collision notification (AACN) has great potential to improve post-crash care if the risk of severe injury to a vehicle's occupants can be accurately predicted. The National Expert Panel for Field Triage set a 20% risk of Injury Severity Score (ISS) 15+ injury [1] as the threshold for urgent transport to a trauma center. The objective of this study was to field test real world performance of the published injury severity prediction (ISP) algorithm in collisions involving recent model GM vehicles equipped with OnStar.

This study was approved by the IRB of the Michigan Department of Community Health. There were 924 occupants in 836 crash events, involving vehicles equipped with AACN capabilities, in the state of Michigan which were identified from the OnStar records. The police crash report corresponding to the event was identified in the State of Michigan database and used to confirm data sent by telemetry from the vehicle. The injury status of all occupants in the case vehicles was determined. Occupants not transported for medical evaluation were assumed to have ISS<15. For occupants transported from the scene for evaluation and treatment, medical records and imaging data were obtained from the treating facility. Case reviews were conducted to jointly analyze crash, vehicle telemetry, and injury outcome data. The algorithm was used to calculate the predicted risk of injury based on transmitted telemetry data and this prediction was compared to the observed injury outcome for each vehicle as well as each occupant.

In this field study, the ISP algorithm's ability to predict whether a vehicle had a seriously injured (ISS>15) occupant was, in terms of sensitivity, at 63.64% compared to the model sensitivity of 39.6% and it also came very close to expectations of specificity at 96.12% compared to the model specificity of 98.3% with use of age and gender data. Without use of age and gender, for ISP calculation, the sensitivity performance was 45.45% while the specificity improved slightly to 97.58%. Detailed analysis of cases suggests that further performance gains could be obtained with more detailed definition of crash direction, seating position, and occupant age.

There were 184 candidate crash occupants in 167 vehicles not included in the study analysis due to: A) missing Police accident reports, n=77 in 75 crashes; B) inability to retrieve medical records, n = 71 in 61 crashes; or C) rollover event, n=36 in 31 crashes. Analysis of these excluded cases did not reveal any bias in crash severity or injury that would confound the current study findings.

This study confirms for the first time under real-world field conditions that occupant injury severity can be predicted using vehicle telemetry data. The ISP algorithm's ability to predict a 20% or greater risk of severe (ISS15+) injury was better than anticipated and confirms ISP's utility for the field triage of crash subjects. This analysis suggests that AACN technology can greatly facilitate the collection of field data with ISP also serving as a baseline for potential monitoring of the benefits resulting from vehicle safety design changes.

INTRODUCTION

Over 1.2 million people died worldwide as a result of road traffic accidents in 2009. While many countries do not have data for injuries sustained in motor vehicle crashes (MVC), estimates from the WHO indicate the total number of non-fatal injuries sustained in a MVC is between 20 and 50 million. [2]

In 2013, the most recent year for which US data is currently available, there were 32,719 road traffic fatalities in the United States alone. Additionally, 2,313,000 people were injured (732 per 100,000). [3]

While some vehicle occupants sustain immediately fatal injuries, a substantial portion expire subsequently during transport or in the emergency department as a result of traumatic shock from injuries that compromise oxygenation and ventilation or cause bleeding. Minimizing the time between injury and treatment is absolutely critical to reducing mortality and morbidity. [4] It is therefore crucial to get first responders to the scene quickly – with the appropriate equipment to initially treat the injuries sustained and then to triage and transport the occupants to the appropriate medical center for further care. Level 1 trauma centers are resourced and staffed to provide definitive trauma care. Severely injured patients have a 25% reduction in mortality if transferred to a Level I trauma center versus if they are transported to a non-Trauma center [5]

At the injury scene, EMS providers determine the severity of injury, initiate medical management and identify the most appropriate medical facility destination through a process called "field triage." [6] In 2009, the Centers for Disease Control and Prevention (CDC) convened the National Expert Panel on Field Triage to review and make recommendations for improving the American College of Surgeons Field Triage Decision Scheme which served as the basis for triage protocols used by state and local EMS systems across the United States. [4] The goal of the field triage process is to get the right person to the right place in the right time. Not every MVC victim needs to be transported to a level I trauma center, but for those who do, it is vital that the first responders on the scene recognize this and move quickly. The first two steps of the Field Triage Decision scheme use anatomic (Step 1) and physiologic criteria (Step 2) to identify the most severely injured patients. Step 3 uses mechanism of injury, for which the National Expert Panel targeted a 20% risk of ISS>15 injury. MVCs were the most significant mechanism of injury addressed in Step 3 and the Panel recommended the inclusion of "vehicle telemetry consistent with high risk of injury". This criterion was included in the 2006 revision as a placeholder in anticipation of more widespread adoption of AACN equipped vehicles. [4].

The CDC subsequently convened a subcommittee of the National Expert Panel over 2007-2008 to coordinate the use of vehicle telemetry. [4] This Expert Panel on the Advanced Automatic Collision Notification and Triage of the Injured Patient concluded that AACN showed promise in improving outcomes to severely injured crash patients by a) predicting the likelihood of serious injury in vehicle occupants, b) decreasing response times by pre-hospital care providers, c) assisting with field triage destination and transportation decisions, d) decreasing time to definite trauma care and e) decreasing death and disability from MVCs. This panel recommended that pilot studies be conducted using vehicle telemetry data including

- Delta V (crash severity)
- Principal direction of force (PDOF)
- Seatbelt usage
- Crash with multiple impacts
- Vehicle type.

Additionally, it recommended that voice communication be established with the vehicle occupants to determine the presence of injuries and also to collect additional information such as age and gender that might affect injury risk. The panel also recommended that injury risk should be calculated with all available data and that if the occupant is at 20% or greater risk of ISS>15 injury, the relevant Public Safety Answering Point (PSAP) should be notified that the occupant meets the Field Triage Decision Scheme's Step 3 criterion for "vehicle telemetry consistent with high risk of injury" and appropriate resources dispatched. [4]

Based on these recommendations an ISP algorithm was developed using a logistic regression model of nationally representative crash data (NASS-CDS from calendar years 1999-2008). [7] Vehicle safety systems are constantly evolving, including changes to the vehicle structure and the restraint systems; as such the risk of injury may also evolve as the vehicle fleet changes. Since AACN equipped vehicles are newer and NASS-CDS contains crash data from many model years, NASS-CDS was filtered to include model year 2000 and newer cars, light trucks, and vans. Only planar non-rollover crash events were used as the ISP algorithm is not designed for rollover crashes. Delta-V is calculated within the current generation of Event Data Recorders (EDRs) and is utilized in the ISP algorithm because delta-V has been shown to be predictive of injury within planar crashes; this same relationship has not been demonstrated in rollover crashes. [6]. For the logistic regression model, crash PDOF was binned into four crash directions (front, left, right and rear). Frontal crashes were defined as those with PDOF of 11, 12 or 1 o'clock, right side as those from 2 to 4 o'clock, rear from 5 to 7 o'clock, and left from 8 to 10 o'clock. The ISP algorithm was

designed to predict the probability that a crash-involved vehicle will contain one or more occupants with severe injury (ISS>15). Analysis of the logistic regression model and resultant ISP algorithm targeting 20% or greater risk of ISS>15 injury showed that crash direction, seat belt use and Delta-V were the most important predictors of serious injury. The NASS-CDS dataset estimates delta-V on an energy-based calculation using post-crash vehicle deformation.

The ISP model sensitivity, based on the NASS-CDS dataset, was 40% and specificity was 98% using an injury probability cutoff of 20% risk of ISS >15.

The current study was undertaken as a pilot to analyze the field performance of the ISP algorithm for newer AACN-equipped GM vehicles involved in crashes. Study objectives also included assessment of the effects of 1) limiting data collection to a single vehicle manufacturer (GM); 2) substitution of transmitted Delta-V from crash sensors in place of vehicle deformation based crash severity; and 3) substitution of transmitted PDOF from crash sensors in place of vehicle deformation based crash direction.

Methods

Any vehicle involved in a MVC, which had a current subscription to the OnStar telematics program, was eligible for inclusion. The ICAM team received permission from the Michigan Department of Community Health (MDCH) to access medical records for any patient involved in one of these crashes. Both vehicle and occupant identification remained anonymous to GM and OnStar.

For this pilot study, ICAM received a convenience sample of 1,003 OnStar crash cases that took place in the state of Michigan from January 2008 through August 2011. These data included information provided by the SDM to the PSAP. Also included is the latitude and longitude of the scene, delta direction, delta velocity, whether and which airbags deployed, whether multiple impacts occurred, whether a rollover event occurred, vehicle category and type.

As a research institution, ICAM requested and was granted access to the Michigan Department of Transportation User website. With the time and location data from the OnStar, staff members were able to pinpoint each crash and retrieve the Police Accident Report (PAR). The PAR provides extensive detail about the vehicle, crash, and occupants. In order to request medical records, it was necessary to gather the occupants' names and birthdates as well as where they were transported if they needed further care. Matching the vehicle identification number (VIN) from the OnStar data to the PAR, the ICAM team ensured they were looking at the report for the correct vehicle and crash. 1,108 candidate crash occupants were identified using this process.

With names and birthdates, the treating hospitals were contacted to request medical records (EMS transport sheets, Emergency Department notes, operative notes, radiology reports, and discharge notes) as well as radiological data – specifically any computed tomography scans performed on the occupants. ICAM nursing staff then abstracted injury information from the medical records and created a list of injuries sustained for each transported occupant. If occupants were not transported, it was assumed that their injury severity score (ISS) was <15.

Of the 1,003 candidate crash cases, there were 184 occupants in 167 vehicles that were not included in the study analysis due to: A) missing police accident reports, n=77 in 75 crashes; B) inability to retrieve medical records, n = 71 in 61 crashes; or C) rollover event, n=36 occupants in 31 crashes. Analysis of these excluded cases did not reveal any bias in crash severity or injury that would confound the current study findings. In the end 836 crash vehicles with 924 occupants were available for analysis.

The implementation of the ISP Algorithm for seatbelt usage uses a base case of 0 if the seat belt is not used or its use is unknown, for any occupied seat. In this study approximately 40% of the crash incidents did not have complete seat belt information so the base case was applied in these cases in the same way that the OnStar application would process these cases. See Appendix B for relative weights of NASS sample to the convenience sample for key variables.

Concurrently, ICAM's crash investigator with more than 30 years of experience in the crash industry crosschecked the OnStar telemetry data against the PARs for each case. He confirmed that the SDM data matched the PAR data. Any incongruous data was marked for further review.

Study subject confidentiality was protected by having all records and medical data tagged with an anonymous study ID by ICAM medical staff before crash review of GM/OnStar engineers. No subject identifiable data collected by ICAM was made available to GM/OnStar.

A multidisciplinary review panel including ICAM medical and research personnel as well as automotive engineers with previous medical training from GM and OnStar was convened to review all cases where an occupant was transported to a medical center. Furthermore, cases with incongruities between predicted ISP and observed outcomes were reviewed in depth with consideration of all the following factors:

Crash Factors

1. Configuration
    a. PDOF
    b. Angled
    c. Offset (Vehicle Overlap)
    d. Narrow object
2. Compatibility
    a. Mass
    b. Geometry
    c. Stiffness
3. Multiple impacts
4. Rollover
5. Occupant seating position
6. Ejection
7. Entrapment

Vehicle factors

1. Deployment of Airbags
    a. Curtain
    b. Thorax
    c. Pelvic/thorax
    d. Knee
    e. Second stage co-deploy
2. Safety belt restraint
    a. Use
    b. Loading locations on occupant
3. Deployment of Pre-tensioners
    a. Dual
    b. Single
    c. Location (on retractor, buckle, or outboard lap anchor)
4. Head rest configurations
5. SDM
    a. Supplier
    b. Generation

Occupant factors

1. Age
2. Gender
3. Morphomics
    a. Anthropometry
    b. BMD
    c. Muscle Quality/Mass
    d. Fat Distribution/Mass
4. Co-morbidities
5. Stature

RESULTS

As some telematics providers do not collect age and gender information, we examined ISP performance with and without inclusion of age and gender data.

ISP calculated with Known Age/Gender

SENSITIVITY – 63.64%

SPECIFICITY – 96%

	Low ISS	**High ISS**	
Low ISP	**792**	**4**	796
High ISP	**33**	**7**	40
	825	11	836

Table 1 ISP with Known Age & Gender

ISP TRUE NEGATIVES (ISP<.2, no occupant in vehicle with ISS>15): The majority of the vehicle cases were, as expected, those in the low ISP/low ISS category. In fact, there were 792 cases in this category using age and gender when calculating the ISP. The occupants in these vehicles were not transported to a hospital and were considered uninjured. The ICAM panel did not review these cases, as they were considered true negatives.

ISP TRUE POSITIVES (ISP >.2, at least one occupant in vehicle with ISS>15): The initial expectation that there would be few cases with a high ISP and high ISS (true positives) was confirmed. There were seven such cases when age and gender were included in the ISP calculation. (Table 2)

ID	(Age/ Gender)	Veh Occ	PDOF	ISP	ISS
721	(75 M)	Drive	Right	0.31	29
2541	(18 F)	2nd row right	Right	0.4	75
749	(48 F)	Driver	Front	0.58	43
772	(20 M)	Driver	Left	0.66	16
2030	(81 F)	RFP	Right	0.27	22
965	(46 F)	Driver	Front	0.29	29
1522	(55 F)	Driver	Right	0.61	17

Table 2 ISP True Positive Cases

ISP FALSE NEGATIVES: There were four cases in the low ISP/high ISS category. The average age of these case occupants was 46.75. The calculated ISP in this false negative group ranged from 0.03 to 0.19 (3% to 19% risk of ISS>15 injury). The average ISP was 0.12. The average ISS in this group was 24.5. All the cases in this group involved females.

We looked at each of these cases in depth to determine if we could discern potential reasons for the discrepancy between prediction and outcome. As stated previously severely injured patients with ISS>15 require the highest level of care and rapid identification of this group is essential. (Table 3)

ID	(Age/ Gender)	Veh Occ	PDOF	ISP	ISS
1430	(45 F)	RFP	Rear	0.15	26
964	(40 F)	Driver	Rear	0.19	34
1806	(52 F)	2d row right	Right	0.03	17
1403	(50 F)	Driver	Left	0.12	21

Table 3 ISP False Negative Cases

Case 1430

This case occupant was the 45-year-old, female, 3-point-belt restrained, right front passenger of a mid-size sport utility vehicle. The vehicle was involved in a severe rear impact from a semi-truck, followed by a minor frontal impact. The driver of the vehicle, a 50-year-old male, sustained lung injuries, an ISS of 10. The case occupant sustained severe head and chest injuries and had an ISS of 26. The telemetry did not report multiple impacts (it did not meet the 15 mph ΔV notification cutoff for a frontal impact). However, clearly there were multiple collisions (rear followed by front). A potential contributing factor is the incompatibility in terms of stiffness, mass, and geometry between the two vehicles.

Case 964

This case occupant was the 40-year-old, female, with unknown belt status, driver of mid-size sport utility vehicle. The case vehicle was struck in a rear-end fashion by a large semi-truck, which caused the case vehicle to travel diagonally through the intersection and over a curb. She sustained severe head, abdominal, and pelvic injuries and received an ISS of 34, with a calculated ISP of 0.19. The information from OnStar had 2 high ΔVs (>40 mph); the crash was not identified as a multiple impact, but was classified as a rollover. There was no indication on the PAR that a rollover had taken place; the vehicle was on its wheels at the time of the report, hence this case was included for consideration. A potential contributing factor is the large difference in terms of stiffness, mass, and geometry between the two vehicles.

Case 1806

The case occupant was the 52-year-old, female, 3-point-belt restrained, right rear passenger of a mid-size passenger car. The impact was a right sided, T-type impact, essentially occurring at her seating position. Her ISS was 17, due to chest injuries and pelvic fractures and the calculated ISP was 0.03. Both front-seat passengers were belted so the ISP was calculated utilizing their belted status. ISP correctly predicted the outcome for the front seat occupants, however, not correctly for this rear-seated occupant. The current algorithm was designed to predict the probability that a crash-involved vehicle will contain one or more occupants with severe injury (ISS>15) and therefore

underweights the injury risk of right sided impacts when there is an occupant located on the right side of the vehicle. Since most of the vehicles in the NASS-CDS dataset used in the previous study to develop the ISP algorithm did not have right front or rear seat passengers, the ISP may underweight the injury risk of passengers at those locations and could be evolved to include a right front passenger variable.

Case 1403

The case occupant was the 50-year-old, female, 3-point-belt restrained, driver of a mid-size passenger car. The case vehicle was struck on the left side, forward of the A-pillar by a school bus and was categorized as a left-side impact in the OnStar data. This very thin occupant sustained severe head injuries, an ISS of 21 and a calculated ISP of 0.12. A potential contributory factor is the case occupant's stature. In our past research, we have found that thin occupants often sustain more serious head injuries than heavier occupants. [8] Another potential contributing factor is the incompatibility in terms of stiffness, mass, and geometry between the two vehicles.

ISP FALSE POSITIVES: There were 33 cases in the high ISP/low ISS category. We analyzed these on a case-by-case basis to assess any potential trends. Twenty-two of these cases were determined to be single impacts and eleven of the cases sustained multiple impacts. Nineteen of the cases (57.6%) were transported to a medical center. The average age in this group was 39.56, which was younger than the 46.75 average age of the ISP false negative group. The average ISP for this group was 0.36, and the average ISS was 3.09. (Appendix A)

DISCUSSION

The results of this field study confirm the utility of vehicle telemetry data transmitted by AACN systems for identification of crash vehicles that contain seriously injured occupants. Multiple models have been developed in the past, but they have all relied on vehicle-deformation based measurement of crash severity and data obtained from the NASS-CDS dataset. This study is the first to utilize actual telemetry data transmitted from vehicles involved in wide variety of crashes to assess real world injury prediction.

The field performance of the Injury Severity Prediction algorithm utilizing the OnStar dataset using age and gender data showed 63.64% sensitivity and 96% specificity. Without age and gender data, sensitivity is 45.45%, while specificity improved slightly to 97.58%. Sensitivity is defined as the probability that a test result will be positive (ISP≥0.2) when the condition (ISS>15) is present. The observed sensitivity performance was better than the 40% performance that the ISP algorithm achieved when applied to the NASS-CDS dataset. There may be several reasons for this including more consistent and accurate measurement of crash severity, more accurate determination of restraint use and more consistent vehicle safety performance as all the crash vehicles were from a single manufacturer and were newer models.

The specificity performance of the ISP in this study was 96%. Specificity is defined as the probability that a test result will be negative (ISP<0.2) when the condition (ISS>15) is not present. The observed specificity performance was slightly less than the 98.3% performance that the algorithm achieved when applied to the NASS-CDS dataset. While the overall number of cases studied is relatively small, there were fewer ISS>15 injured cases observed than would have been expected based on the number of cases, configuration and crash-severity mix of the crashes included in this study. This trend might be the result of continuously improving vehicle safety performance in the study fleet versus the NASS-CDS fleet used to calibrate the algorithm. The average age of the study fleet was younger than the average age of the vehicles in NASS-CDS.

The results of this field study confirm the importance of age and gender data and also suggest that it may be important to utilize more granular age data than a single threshold at age 55. The sensitivity of the ISP algorithm improved from 45.45% to 63.64% with the inclusion of age and gender data and the false negative group was slightly older on average than the false positive group (46.75 vs. 39.56). It is well known that the increased crash injury risk accelerates with advancing age rather than plateauing at age 55. [5, 9-11] The current ISP algorithm includes age (>55) and gender (presence of a female in the vehicle) as variables. However, SDMs do not have the capability to capture these data. It has been suggested that when the telematics provider contacts the occupants in the crashed vehicle, they can ask questions about who is in the vehicle. In this way, they can obtain age and gender data to send to the PSAPs. The results of the current study confirm the importance of age and gender in injury risk calculation and highlight the importance of collecting this data. Several of the false negative (low ISP/high ISS) cases involving very elderly patients as well as the overall aging population trend suggest that sensitivity might be further improved by including more granular age parameters in the ISP than a single threshold of age 55. Similarly, the younger age in the false positive (high ISP/low ISS) cases suggest that decreasing the risk coefficients for young

occupants might also improve ISP performance. These potential benefits must be weighed against the increased time and potential confusion that may result in attempts to obtain this information.

The original algorithm was developed from data culled from the National Automotive Sampling System (NASS) and defined crash direction into only four categories (front, left, right, and rear). This study followed that convention. However, real world crashes do not always fit precisely into these categories, and frequently fall into offset or narrow configurations that may have a different impact on the occupant injury risk. The large number of offset frontal and sideswipe cases among our false positives suggests that improving telemetry data to better differentiate these crash configurations may help improve ISP performance.

Right oblique and right side impact crashes are underweighted in the original ISP algorithm. Our data with 1 of the false negative cases involving right side occupant suggest that it may be beneficial to adjust the right side impact coefficients to reflect a higher risk of severe injury if it is determined by telemetry or communication that right sided seats are occupied in a right oblique or side impact crash.

Telemetry data regarding possible occupant ejection would also be very useful if automotive grade sensors for this application are created.

While the study covered all types of vehicles, from compact car to large pickup, we limited the specific vehicle models in order to see injury patterns more clearly. The type of vehicle can affect the pattern and risk of injury, especially in two-vehicle crashes where there is vehicle incompatibility in terms of mass and geometry. The sensitivity of this study is better than originally predicted (40%) possibly in part due to the consistency of the vehicles from a single manufacturer with a consistent occupant protection strategy.

While the specificity of this study is a little less than expected, it is quite good for a preliminary study. This specificity performance may allow very large potential savings as technology becomes more comprehensive and reliable. The observed specificity performance in the field by the ISP suggests that it may become possible to decrease the dispatch of limited EMS resources to the scenes of low risk crashes. With new safety systems coming on line within the next few years as well as enhancements in the SDM systems, we anticipate continued improvements in ISP specificity performance.

Study Limitations

When selecting for convenience samples, it is important to recognize that there are limitations to the collection and reporting of the data.

One significant challenge for collection of telemetry crash data is that the SDMs can vary from vehicle to vehicle, depending on the vehicle model year and the evolution of module hardware/software upgrades. In order to build the sample, OnStar collected data on vehicles where the SDMs were known to have the capability needed to support the algorithm calculation. As such, the mix of vehicles in the study differs slightly from the NASS-CDS ISP development sample and has a higher percentage of sport utilities and a lower percentage of pickups and vans compared to the development sample. See Appendix B for the full weighting comparison.

Another limitation of the study relates to seat belt status. For any front occupied seat, the ISP algorithm assumes a base case if the seat belt is *unbelted* or its use is *unknown.* The probability of injury severity is lowered if the belt status is determined to have been buckled. Therefore, in the case of unknown belt status, the ISP will have a higher probability of injury severity than if the algorithm assumed the belt was used. In this study, approximately 40% of the crashes did not have complete seat belt information and for these cases the *unknown* base case was applied – as ISP algorithm would code them in a real-world situation. It should be understood that had seatbelt status been known and if the occupants in these cases were belted, the outcome of the study could have been slightly different. For the seven cases classified as High ISP/High ISS (true positive), it is possible that some of these cases would have had a lower ISP and been classified as a false negative, thereby reducing sensitivity. Similarly, for the 33 cases in the High ISP/Low ISS category (false positive), some of those cases would have possibly been classified as true negative, thereby increasing specificity. The cases with Low ISP/Low ISS (true negative) and Low ISP/High ISS (false negatives) would be unaffected as reducing the ISP would not change the categorization of these cases.

Another limitation is that the "multiple impacts indicator" is an element that varies fairly significantly from NASS-CDS to GM's telemetry protocols. In NASS-CDS, multiple impacts are flagged anytime a vehicle has two impacts regardless of their severity. For example, in NASS-CDS, if a vehicle hits a mailbox and subsequently hits a tree, both events are recorded and the multiple impacts indicator is turned on. At GM/OnStar multiple impacts is turned on if two or more qualifying events occur in the same ignition cycle. A qualifying event is an event that has a Delta V over a predefined level. In our example the impact with the mailbox would not have a Delta V significant enough to be a qualified event and the multiple event indicator would not be turned on. See Appendix B for the full weighting comparison.

Finally, due to IRB limitations, the study was conducted using only state of Michigan crashes. However the sample does include crashes from varying years, seasons, weather conditions, times of day, and days of the week.

CONCLUSION

The level of sensitivity for severe injury achieved by ISP in this field study was a remarkable 63.64%. This performance is impressive from a medical perspective, especially considering that it is achieved with only data or communication transmitted from the vehicle and before dispatch of EMS to the scene.

Since the consequence of missing a severe injury is immediately life-threatening, sensitivity has generally received the highest priority in trauma care. The longstanding Field Decision Scheme has been used as the basis for triage protocols in state and local EMS systems across the United States for many decades. The combined sensitivity of the first two steps (Physiologic and Anatomic) of the Decision Scheme has consistently remained around between 40-50% with field data collected first hand by EMS during the pre-hospital phase of care. [12-15] Newer crash sensors may also support improvements in the performance of the ISP algorithm. As the SDM systems in vehicles change and more detailed telemetry data collection is possible, ICAM anticipates improvements in risk prediction. The fleet is in constant flux with new safety systems as well as enhanced SDMs. [16, 17]

Michigan, parts of the United States, and the world all have many rural areas where reports of crash events to public safety may be delayed, leading to slow response by EMS. [18, 19] These same areas are also characterized by long transport distances that will delay the transfer of the severely injured to medical facilities. Automatic collisions notification alone, without additional vehicle telemetry for injury prediction, can save significant lives [20]. Time is of the essence in these cases and getting these occupants to the proper medical destination capable of definitive trauma care is essential. Transmitted telemetry data from AACN can not only provide notification that a crash has occurred, it can also alert the local first responders as to what type and how severe of crash they are responding to – they will know what equipment to bring in order to best triage and treat the occupants. There is potential also to immediately initiate air transport and get them to the scene quickly as well.

The resources utilized in the emergency care of crash injuries place a significant burden on local communities, especially rural ones. Over triaging patients without severe injuries to trauma centers or other medical centers for unnecessary evaluation is expensive and wasteful. The recent changes to Step 3 (mechanism of injury) of the Field Triage Decision Scheme is estimated to provide yearly US savings of over $500 million in medical costs alone. [21] With widespread use of AACN, those savings can be multiplied.

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Appendix A

UMID	Age	Gender	Veh Occ	PDOF	Veh Type	ISP	ISP A/G	ISS	Mult	Trans	Review Notes
633	37	F	Driver	Front	CAR	0.16	0.23	4	N	Y	near-side offset frontal
2105	21	F	Driver	Left	CAR	0.18	0.25	0	N	N	near-side sideswipe
2106	32	F	Driver	Left	CAR	0.14	0.20	0	N	N	full frontal
644	16	M	Driver	Left	CAR	0.71	0.71	1	Y	Y	near-side offset front corner hit, into a near-side sideswipe
716	49	F	Driver	Front	UTILITY	0.17	0.24	0	Y	Y	near-side offset frontal (tree)
1233	17	F	Driver	Left	UTILITY	0.27	0.36	1	N	Y	near-side L-type front
743	56	F	Driver	Left	CAR	0.21	0.52	2	N	Y	near-side T-type (21 mph delta V)
751	18	F	Driver	Front	CAR	0.18	0.26	10	N	Y	full frontal
837	80	F	Driver	Front	UTILITY	0.26	0.59	11	N	Y	full frontal
1248	99	M	Driver	Front	CAR	0.16	0.35	0	N	N	severe frontal into a guardrail/barrier
863	50	F	Driver	Right	CAR	0.29	0.39	0	N	N	full frontal
892	20	F	Driver	Right	CAR	0.14	0.21	0	N	N	minor near-side sideswipe followed by far-side offset frontal into tree
551	53	F	Driver	Front	CAR	0.41	0.52	11	Y	Y	near-side frontal into mailbox (minor) followed by center frontal into tree
919	40	M	Driver	Front	CAR	0.26	0.26	0	Y	Y	near-side offset frontal followed by a near-side offset frontal tree impact
938	17	M	Driver	Front	UTILITY	0.37	0.37	1	Y	Y	full frontal
946	48	F	Driver	Front	UTILITY	0.24	0.33	14	N	Y	near-side sideswipe, followed by offset near-side frontal
1253	18	M	Driver	Left	CAR	0.57	0.57	1	Y	Y	near-side sideswipe (minor), followed by offset near-side frontal
955	62	F	Driver	Front	CAR	0.12	0.36	5	Y	Y	3 impacts (front, left, and rear) with a ditch
957	43	F	Driver	Front	UTILITY	0.13	0.29	2	N	Y	frontal
997	26	F	Driver	Front	UTILITY	0.22	0.31	0	Y	N	near-side L-type rear followed by minor frontal into tree
1001	39	F	Driver	Right	UTILITY	0.28	0.38	9	N	Y	far-side T-type
1024	36	F	Driver	Front	UTILITY	0.33	0.43	1	N	Y	full frontal
1027	57	M	Driver	Left	CAR	0.12	0.27	14	N	Y	near side T-type
1040	58	F	Driver	Front	UTILITY	0.08	0.28	0	N	N	offset frontal
2533	59	F	Driver	Left	CAR	0.17	0.47	0	N	N	near-side T-type
1078	23	F	Driver	Front	CAR	0.27	0.36	0	N	N	full frontal

UMID	Age	Gender	Veh Occ	PDOF	Veh Type	ISP	ISP A/G	ISS	Mult	Trans	Review Notes
1172	22	F	Driver	Left	CAR	0.22	0.30	0	Y	N	near-side from pickup, followed by narrow frontal into pole/tree
1186	24	M	Driver	Front	CAR	0.53	0.53	10	N	Y	near-side offset frontal
1221	62	F	Driver	Right	CAR	0.08	0.26	5	Y	Y	far-side T-type, followed by near-side T-type
1291	22	F	Driver	Front	CAR	0.22	0.31	0	N	N	far-side offset frontal
1521	35	F	Driver	Left	UTILITY	0.22	0.31	0	N	N	near-side offset frontal
2107	43	F	Driver	Left	CAR	0.30	0.40	0	N	N	near-side L-type front
1768	24	M	Driver	Left	PICKUP	0.28	0.28	0	Y	N	near-side sideswipe followed by offset frontal

Appendix B

Seat Belt Usage
The implementation of the ISP Algorithm for seatbelt usage uses a base case of 0 if the seat belt is not used or its use is unknown, for any occupied seat. For seat belt usage by all occupants the belt usage coefficient is used in the ISP calculation. In this study approximately 40% of the crash incidents did not have complete seat belt information so the base case was applied in these cases in the same way that the OnStar application would process these cases. In those cases where seat belt information was unavailable and the Police report indicated belt use, or the injury patterns indicated belt use, then the belt usage coefficient was used in the ISP calculation.

Vehicle Models
The vehicle makeup in this study is influenced by the fact that all of the accidents were confined to the state of Michigan. The original study, by Kononen, Flannagan, and Wang, relied on a much larger source of information (NASS/CDS). It is important to understand the differences in vehicle types.

Multiple Impacts
Multiple impacts were determined by the availability of secondary delta V data. If the secondary delta v was null then the accident was a determined to be a single impact.

See following table for full comparison to NASS-CDS development data set.

		Average Values		
		All Cases	Complete Cases	Complete Cases
Variable		**NASS-CDS**	**NASS-CDS**	**ICAM Sample**
	ISS15+	0.124	0.108	0.012
	Median ln(Delta-V mph)	2.820	2.820	2.606
Direction	**Front**	0.800	0.780	0.695
	Left	0.082	0.088	0.100
	Right	0.074	0.080	0.122
	Rear	0.044	0.052	0.083
Vehicle_Type	**Car**	0.675	0.676	0.700
	Utility	0.168	0.174	0.2810
	Pickup	0.101	0.093	.0780
	Van	0.057	0.056	0.000
	Multiple Events	0.395	0.364	0.021
	RFP Present	0.274	0.278	0.318
	all_belted	0.774	0.793	0.345
	any_female	0.573	0.597	0.573
	maxvehage2	0.192	0.196	0.269

PILOT STUDY ON ADVANCED AUTOMATIC COLLISION NOTIFICATION AND HELICOPTER EMERGENCY MEDICAL SERVICE SYSTEM IN JAPAN

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ABSTRACT

This paper focuses on the pilot study on Advanced Automatic Collision Notification (AACN) and Helicopter Emergency Medical Service (HEMS) systems in Japan. The pilot study was carried out in Chiba prefecture by the AACN Committee in affiliation with Emergency Medical Network of Helicopter and Hospital (HEM-Net).

There were many opinions that Japanese accident data was preferable to develop a Japanese AACN algorithm. Then, the Occupant Injury Predict Algorithm newly developed by Nihon University was utilized for the study. About 2.8 million Japanese accident data (so called ITARDA Macro Data) were used to define logistic regression risk curves of fatal and severe injuries to car occupants. To validate this algorithm, the in-depth accident case study by Nihon University and Nihon Medical University at the Chiba Hokusoh Hospital was used. Moreover, to decide the threshold value, this in-depth accident study was also used.

Regarding the AACN prototype system, HELPNET infrastructures already developed for existing Japanese ACN service were used for sending vehicle data to the HELPNET center. In the simulated accident, Event Data Recorder (EDR) data was added on usual HELPNET data and transmitted from a car to a HELPNET server at the HELPNET center. The AACN server got vehicle data such as Delta V and seatbelt status as input to the algorithm.

The result was transmitted to a Tablet PC at the Fire Department Head Quarters and Chiba Hokusoh hospital simultaneously. An operator of HELPNET made an Emergency Call to both the Fire Department and Hokusoh hospital individually.

In case of severe injury, a Tablet PC indicated the situation and a doctor dispatched to the accident spot by a helicopter. After a helicopter with a doctor took off, verbal communications between the helicopter and Fire Department started to decide a rendezvous point nearby the crash spot. After landing, the doctor contacted the injured occupant who was carried by an ambulance there. The AACN prototype system for a limited area, only in Chiba prefecture, was developed.

AACN transmitting tests were carried out at some spots in Chiba prefecture within the jurisdiction of two headquarters individually. The prototype AACN system operated as intended. Within a minute from the airbag deployment signal, the algorithm result screen arrived simultaneously on AACN Tablet PCs at Chiba Hokusoh hospital, Chiba prefecture Fire Department H.Q. and also at the transmitting spot. The next step of AACN transmitting test should be that AACN activates HEMS of Chiba Hokusoh hospital. To expand cover area in Japan, collaborations of other HEMS base hospitals in other prefectures should be planed soon.

INTRODUCTION

In Japan, casualties of traffic accidents are recently decreasing. According to the National Police Agency, 573,824 traffic accidents occurred in Japan in 2014. Compairing with 2012, this was a decrease of 55,179. These crashes killed 4,113 peoples (decrease of 260) and injured 711,374 people (decrease of 70,120). Since 2004, the decreasing trend seems to continue, however, the situation is still serious [1].

Under continued conditions, it would be very difficult to achieve Japanese Gorverment Target, which was that the traffic accident fatalities in Japan should be 2,500 or less by 2018 and realize the safest road traffic society in the world by 2020, decided in the Cabinet in 2013.

Automatic collision notification (ACN)

To decrease casualties of motor vehicle crashes, many technologies such as pre-crash and post-crash seem to be effective. Beside such technologies, collision notification technologies are also helpful to decrease dispatch of emergency medical service (EMS). In Japan, an automatic collision notification (ACN) service called HELPNET started in 2005. The scheme of HELPNET is provided in Figure 1.

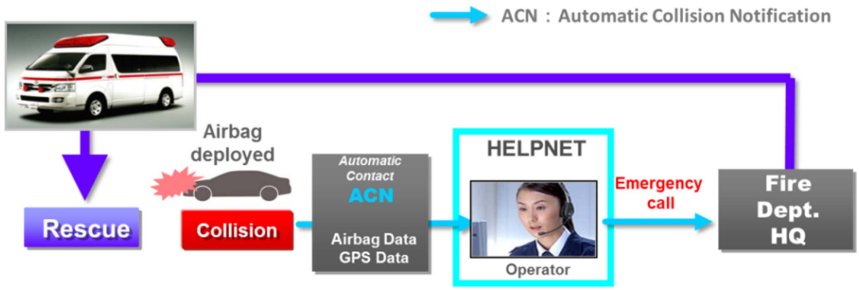

Figure 1. Existing ACN service in Japan

In case of a collision with airbag deployment, the ACN system automatically contacts the HELPNET center and collision information such as airbag deployment data and Global Positioning System (GPS) data are sent to HELPNET server. An operator of HELPNET calles drivers of vehicles with a deployed airbag using aDigital Comunication Module (DCM). If there is no answer from the driver, the operator calls the nearest Fire Depertment Head Quarter.

Advanced automatic collision notification (AACN)

Life saving potential of an advanced automatic collision notification (AACN) system is expexted in Japan[2,3].

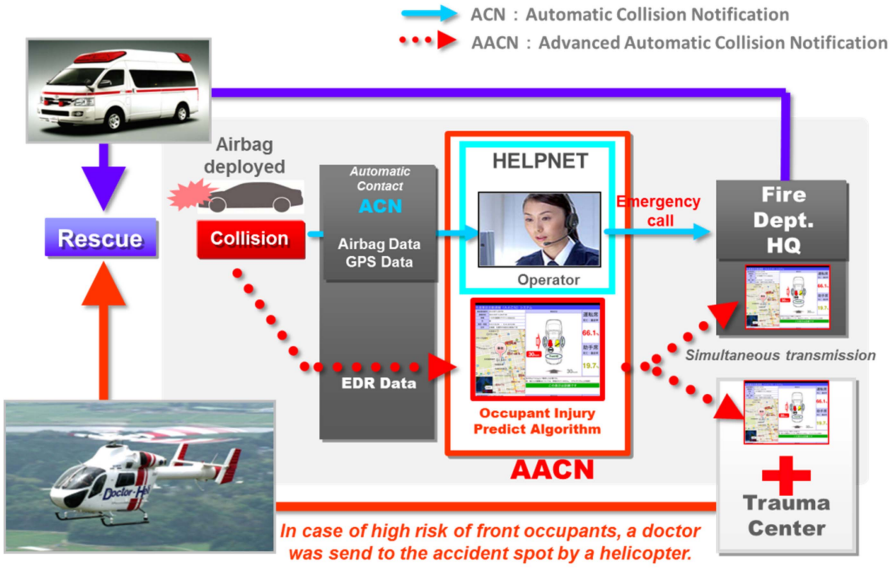

Figure 2. Developing AACN and HEMS system in Japan.

The scheme of AACN and HEMS system is provided in Figure 2. In December, 2011, the authors carried out a demonstration test of AACN and HEMS system at a test site of the Japan Automobile Research Institule (JARI). A crash test using a prototype vehicle with an AACN system was carried out. The vehicle with dummies struck a crash barrier at 50 kph. EDR's data was transmitted to the server. Occupant Transportation Decision Algorithm (OTDA) of Wake Forest University [4] used these data to determine the kind of hospital to which the injured driver is to be transffered. From Chiba Hokusoh hospital, a helicoper with a doctor took off and landed at a rendezvous spot next to the barrier. The doctor contacted the dummy representing an injured driver after 21 minutes from the collision.

Three years have passed from this demonstration test. An AACN committee in affiliation with Emergency Medical Network of Helicopter and Hospital (HEM-Net) continued activities to realize AACN and HEMS systems in Japan. Dr. Mashiko was the chairman of the committee and all authors of this paper were involved in activities targeting a real service of AACN and HEMS systems in Chiba prefecture.

OBJECTIVES

The objectives of this study was to develop AACN and HEMS systems, using infrastructure already prepared for the existing ACN (HELPNET) service. At the beginning, after the development of the system, some real accident cases were considered to be used to examin real effectiveness of AACN and HEMS system. However, there were many restrictions of a real accident case usage without proper ammendments of the terms of HELPNET service. Then, the study using real accidents was abondoned and the study of data transmitting simulation in Chiba prefecture for HELPNET, Chiba Fire Department. H.Q. and Hokusoh hospital was planed.

METHODS

To develop AACN and HEMS systems in Japan, the principal elements are described individually in the following.

Algorithm to estimate occupant injury

In this study, the TOYOTA-Nihon University algorithm was developed and utilized [5]. For the demonstration at JARI in Dec. 2011, OTDA developed by Wake Forest University was used. It was developed based on NASS-CDS data. Recently, at JSAE GIA Forum and JSAE comitte on the AACN, many attendees eager to develop Japanese algorithm made by Japanese accident data[2,3]. About 2.8 million of accidents from ITARDA Macro Data in Japan were used to define logistic regression risk curves of fatal and severe injured car occupants. Risk factors of the algorithm are summarized on Table 1. In order to validate this algorithm, combined data from the hospital based in-depth accident study by Nihon University and Nihon Medical University at the Chiba Hokusoh Hospital was used.

Table 1.
TOYOTA-Nihon University Algorithm used for the pilot study in Chiba prefecture.

TOYOTA Nihon University model				
Risk factors		Model 2_Type 1	Model 2_Type 1_P	Model 2_Type 1_K
Intercept		-4.888	-4.931	-5.195
Delta V_{pseudo}	[km/h]	0.094	0.097	0.091
Crash Direction	Front	-0.047	-0.335	0.328
	Near side	1.167	1.069	1.342
	Far side	1.024	0.755	1.361
	Rear	-	-	-
Age	Under 54 years	-	-	-
	55-64 years	0.585	0.437	0.759
	Over 65 years	1.027	0.879	1.171
Belt use	Yes = 1, No = 0	-1.818	-1.901	-1.738
Multiple crash	Yes = 1, No = 0	0.120	0.082	0.169
Vehicle type	Passenger car	-0.288		
	Kei car	-		

Examples of major risk curves are provided in Figure 3. These curves depict injury probabilities for Frontal impact without seatbelt, Frontal impact with seatbelt and Near Side impact with seatbelt. For a delta V of 40 kph, the risk of fatal and severe injury was 53%, 16% and 25%,respectively.

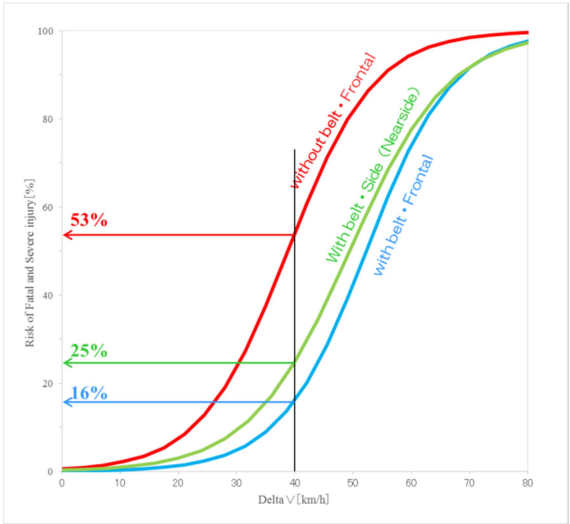

Figure 3. Risk curves of the algorithm used for the pilot study

Threshold for dispatch decision

The threshold for dispatch decision was analyzed and decided using the in-depth accident study by Nihon University and Nihon Medical University at the Chiba Hokusoh Hospital again. Doctors at Hokusoh hospital decided a decision threshold value after analyzing over triage rate and under triage rate for in-depth accident study cases. The decision threshold value seemed to be depended on a HEMS base hospital at which AACN and HEMS systems are used.

Algorithm result screen design

A sample algorithm result (in Japanese language) is provided in Figure 4. The screen consisted of four areas. At the upper left part, there was text information on Accident ID and time, name and color of the involved vehicle, GPS data and address of the accident spot. At the lower left part, there was a map showing the accident spot. At the upper right, there were crash conditions, such as Delta V and airbag deployment and risk of fatal and severe injury of front occupants. Finally, at the lower right, some comments were added.

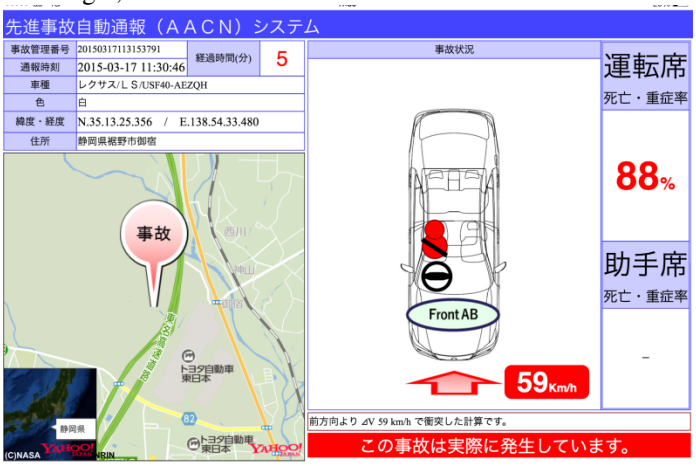

Figure 4. An algorithm result transferred to Tablet PC

AACN scheme in Chiba prefecture

A prototype AACN scheme for the pilot study in Chiba prefecture is provided in Figure 5. The circled numbers in the figure represent the step by step process of the AACN scheme. There were two DCMs in the test vehicle. One was an original DCM initially equiped and the other was an additional DCM for the pilot study. Each step follows below.

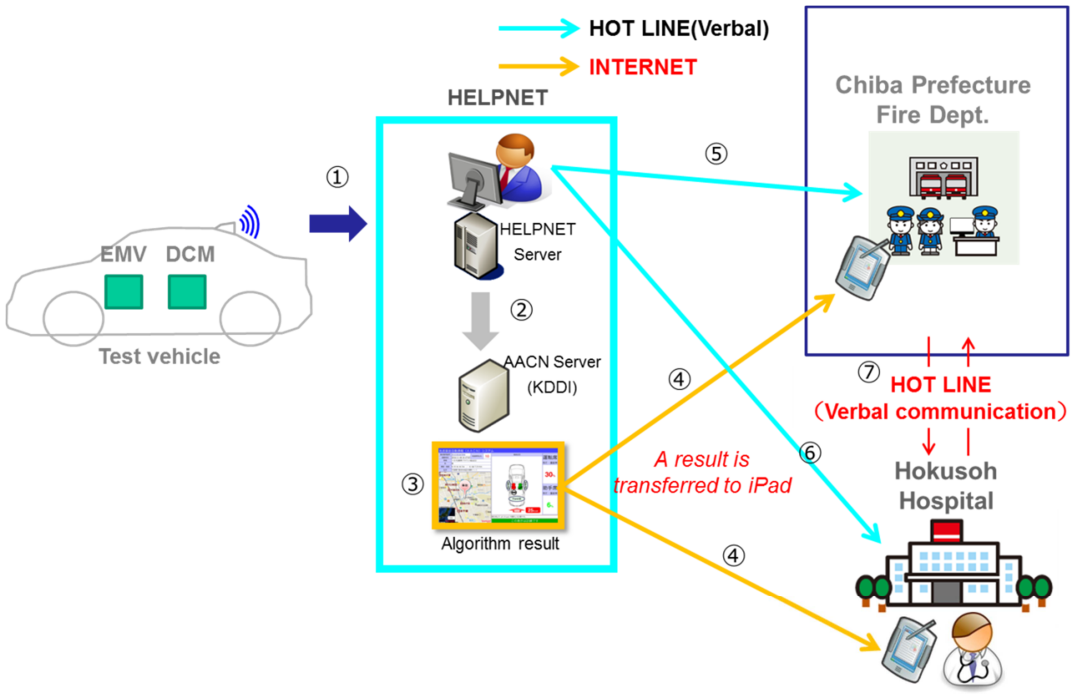

Figure 5. AACN scheme for the pilot study in Chiba prefecture

Step 1 The AACN scheme was triggered by an airbag deployment signal. EDR data of a test vehicle was transmitted to HELPNET server. GPS data and vehicle ID were also transmitted.

Step 2 AACN server received vehicle data to input the algorithm from HELPNET server every 30 seconds. Other information, such as accident time, vehicle ID and GPS information were also received.

Step 3 AACN server calculated a risk of front occupants using the algorithm and arranged an algorithm result screen.

Step 4 AN algorithm result screen was transmitted to Tablet PCs at Chiba prefecture Fire Department H.Q. and Chiba Hokusoh hospital simultaneously (also at the accident spot).

Step 5 HELPNET operator called Chiba prefecture Fire Department H.Q. by HOT LINE. This step was usual HELPNET ACN operation. In addition, in case of AACN, HELPNET operator confirmed the arrival of an algorithm result screen on Tablet PC at the H.Q..

Step 6 After a call to Chiba prefecture Fire Department H.Q., HELPNET operator called Chiba Hokusoh hospital by HOTLINE. In case of high risk of the front occupant, a doctor was send to the accident spot by a helicopter.

Step 7 Verbal communication was made between Chiba Hokusoh hospital and Chiba prefecture Fire Department H.Q. to decide a rendezvous spot for a helicopter and an ambulance.

RESULTS

A total of 6 cases of transmission from 2 accident spots were carried out during the first pilot test period in March, 2015. No error transmission occurred and of the AACN system seemed to function as intended. Within a minute from the airbag deployment signal, the algorithm result screen arrived simultaneously on Tablet PCs at both Chiba Hokusoh hospital and Chiba prefecture Fire Department H.Q.

The effectiveness of AACN and HEMS systems are not established yet because a transmission test with HEMS activated by AACN was not finished at the time of writing this paper.

DISCUSSIONS

This study was orgnized by the AACN committee under Emergency Medical Network of Helicopter and Hospital (HEM-Net). It was natural that Chiba Hokusoh hospital, as a pioneer of HEMS base hospital in Japan, contributed a fundermentl part of this study. In Japan, there are 47 helicopters for HEMS and 49 HEMS base hospitals, as of March, 2015. In order to cover all of Japan, the number of cooperative HEMS base hospitals should be increased step by step. The authors had selected 6 HEMS base hospitals from Hokkaido to Kyusyu in Japan. A similar pilot study should be planed for each hospital.

Regarding the AACN algolithm, the authors adopted a newly developed algorithm by Nihon University in this study. Based on ITARDA macro accident data, logistic regression risk curves were produced. Many other algorithm were based on in-depth accident data such as NASS-CDS [6-14]. Comparing with in-depth accident data, ITARDA macro accident data had limited information. For example, there is no information on CDC-code, Delta V, MAIS, ISS etc.. However, ITARDA macro data seemed to be suitable for algorithm risk factors used in this study according to evaluation result using in-depth accident study carried out between Nihon University and Nihon Medical University Chiba Hokusoh hospital.

Regarding the threshold for dispatch decision, the authors adopted a decision value calculated using in-depth accident study at the same hospital. The over triage rate and the under triage rate were analyzed. It became obvious that a decision threshold value depended on each HEMS base hospital. However, there was no other HEMS base hospital which conducted an individual accident study. This issue needs to be solved in future.

CONCLUSIONS

The AACN and HEMS pilot system in Chiba prefecture was developed in cooperation with Nihon Medical University Chiba Hokusoh hospital, which was a pioneer of HEMS base hospitals, and Chiba prefecture Fire Department Head Quarters.

At some spots in Chiba prefecture, transmitting tests were carried out and prototype system operated as intended. Within a minute from airbag deployment signal, the algorithm result screen arrived on Tablet PCs at both Chiba Hokusoh hospital and Chiba prefecture Fire Department Head Quarters simultaneously.

To expand this pilot study on AACN and HEMS system widely, the next step was scheduled among other HEMS base hospitals in Japan.

ACKNOWLEDGEMENTS

The authors thank Prof. Nishimoto of Nihon University for a contribution to development and evaluation of the algorithm used in this study and continuous in-depth accident study collaboration with Nihon Medical University Chiba Hokusoh hospital.

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ASSESSING MECHANISMS OF INJURY AS PREDICTORS OF SEVERE INJURY FOR ADULT CAR AND TRUCK OCCUPANTS

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Paper Number 15-0427

ABSTRACT

This study evaluates Mechanisms of Injury (MOI) that can be rapidly assessed at the scene of accident and may be used as predictors of severe injury for traffic accidents involving occupants in cars or trucks. The objective is to increase the knowledge of how MOI can be used to differentiate whether a patient is severely injured or not. This knowledge can be used to improve trauma triage systems. Furthermore, an objective is to analyze safety differences between cars and light/heavy trucks. The scope is adult occupants of cars, light and heavy trucks injured in accidents registered in the Swedish Traffic Accident Data Acquisition (STRADA) database from 2003 to 2013. Partition between severe and non-severe injury was done according to the Injury Severity Score (ISS) with ISS > 15 as definition of severe injury. The MOIs considered were: belt use, airbag deployment, posted speed limit, elderly occupant (age ≥ 55 years), sex, type of accident (single, intersection, turning, head-on, overtaking, rear end, tram/train, wild animal or other) and location of the accident (urban or rural). The different MOI were evaluated individually using univariate chi-square tests and together using multivariate logistic regression models. Results show that belt use is the most crucial factor determining risk of severe injury for all vehicle types. Age is the second most important factor, with elderly occupants exhibiting a higher risk. Head-on accidents are the most dangerous for cars and light trucks while single accidents are the most dangerous for heavy trucks. Belt use compliance is much lower for truck occupants. This appears to be the main reason for the frequency of severe injury being higher for truck occupants than for car occupants.

INTRODUCTION

Rapid transport of severely injured trauma patients to a trauma center substantially decreases mortality [1, 2]. Medical examination of the patient with support from a triage protocol and observations of characteristics of the accident are the main tools emergency personnel have for recognizing patients with severe injury. Schoell et al. [3] stated that improvement of triage systems is nowadays the most important area to address to continue reducing fatal and severe injuries for motor vehicle accidents. Therefore, maintaining, updating and improving trauma triage systems is of utmost importance.

Triage systems are in general primarily based on physiological and anatomical criteria and secondly on Mechanisms of Injury (MOI). The value of MOI is to detect occult injuries and reduce undertriage. A study with around one million trauma patients concluded that using physiologic and anatomic criteria alone lead to undertriage [4]. This strongly supports the use of MOI in triage systems.

In Sweden RETTS [5] is the most widespread triage system. The MOI that apply for motor vehicle crashes are: occupant ejected from vehicle, vehicle rollover, person entrapped, and deployment of airbag. For car accidents there is an additional criteria: estimated speed > 60 km/h. We believe that risk for severe injury can be predicted with higher precision, i.e. with reduced overtriage and/or undertriage, by adding complementary MOI to the triaging process.

In order to improve triage systems for traffic accidents this study evaluates the predictive power of severe injury for MOI that can rapidly be assessed at the scene of accident. In addition a comparison between cars, light and heavy trucks of how these MOI relate to injury severity was performed.

The scope of the study is adult occupants in cars, light and heavy trucks for accidents registered in the Swedish Traffic Accident Data Acquisition (STRADA) database for eleven years, from 2003 to 2013. The evaluation of the predictors is performed by comparing the proportion of patients with severe injury for each level of the

variable, univariate analyses of association with probability of severe injury using chi-squared tests and multivariate analyses using logistic regression models. The logistic regression models were developed in the studies by Buendia, Candefjord et al. [6, 7].

METHODS

STRADA is the Swedish Transport Administrations national information system for traffic accidents occurring on the public roads of Sweden. It included two sources of data, independent reports from the police and the hospital treating the patient. The database is contained in a Microsoft Access® database file. An introduction to STRADA is available in [8].

Between calendar years 2003 to 2013 near 650 000 injured persons can be found in STRADA. Each accident has a unique ID which is shared between the police report and the hospital report and is the link between accident and patients. We included only accidents involving injured occupants traveling in a car or a truck where both a police and a hospital report were available. In the case of cars, subjects with missing information in any predictor considered were not included.

The observations were divided into cars, light trucks, i.e. trucks with total weight up to 3500 kg, and heavy trucks, i.e. trucks with a total weight over 16 500 kg, according to the Swedish official classification of trucks. Trucks of medium weight were not considered because they were not sufficient in numbers to feed a model with enough statistical power.

The total number of accident victims was 29 128 for cars, 2 775 for light trucks and 922 for heavy trucks. They were injured in 22 607, 2 608 and 903 accidents for cars, light trucks and heavy trucks, respectively.

Casualties were classified as severely injured or not according to the Injury Severity Score (ISS) with ISS > 15 used as definition of severe injury, i.e. a victim with ISS > 15 is classified as severely injured and a victim with ISS < 15 is classified as non-severely injured. This was the dependent variable for all analyses. The proportion of severely injured was 2.0 % for cars, 2.9 % for light trucks and 4.0 % for heavy trucks. The MOI used as predictors are detailed in Table I.

The software used for the statistical analysis was IBM SPSS Version 22. Chi-squared tests were used to assess the univariate association with probability of severe injury for each predictor, where the null hypothesis was no association. $p < 0.05$ was considered statistically significant, casting doubts over the null hypothesis. The multivariate analyses were performed using logistic regression modelling. *p*-values and odds ratio (OR) for each predictor were derived. Logistic regression is a maximum-likelihood method commonly used in studies of traffic accidents, see e.g. [9, 10].

Table 1: MOI description. For each MOI level the percentage of casualties having that characteristic is given.

Predictor	Levels	Frequency			Description
		Cars (%)	Light Trucks (%)	Heavy Trucks (%)	
Belt Use	Unknown		12	17	Whether the casualty was using the seat belt at the moment of the accident
	Unbelted	94	8.7	28	
	Belted	5.9	79	55	
Airbag Deployment	Unknown		33	50	Whether the airbag was deployed at the moment of the accident in case there was an airbag in the seat of the casualty
	Undeployed	60	38	45	
	Deployed	38	26	1.6	
	No Airbag	2.1	2	2.9	
Accident Type	Turning	23*	4.4	1.7	Classification according to the following types of accident: Intersection, collision of vehicle in an intersection; Turning, collision with a vehicle on a turning maneuver; Head-on, frontal collision of vehicles; Overtaking, collision with a vehicle on a overtaking maneuver; Single, vehicle collides with stationary object or departs from the road; Rear End, one vehicle collide with another from behind, Tram/Train, a vehicle collide with a tram or a train, WLA, a vehicle collide with a WLA, Other, other kind of accident.
	Intersection	23*	13	2.8	
	Head-on	13*	11	13	
	Overtaking	13*	2.2	1.3	
	Single	31	34	61	
	Tram/Train	0.2	0.5	1.2	
	Rear End	27	28	14	
	WLA	3.2	2.8	0.8	
	Other	3.1	4.2	3.8	
PSL	Unknown		11	12	Posted Speed Limit in the segment of road where the accident took place
	30	1.2	1.1	0.5	
	40	0.8	0.7	0.3	
	50	29	18	12	
	60	1	1.2	0.3	
	70	31	30	26	
	80	4.3	4.4	5.5	
	90	20	18	29	
	100	2.9	3.9	2.7	
	110	8.8	9.7	12	
	120	0.7	0.9	1.2	
Accident Place	Unknown		8.8	8	Whether the accident took place in an urban or rural environment, i.e. in or out a population center. Circumvallation roads are considered urban.
	Urban	38	27	15	
	Rural	62	64	76	
Elderly	Under 55	78.4	84	83	The age 55 years old was used because the National Expert Panel's decision to retain age 55 as a criterion for consideration in the Field Triage Decision Scheme (Sasser et al., 2012).
	Over 55	21.6	16	17	
Sex	Male	54	82	92	Whether the victim was male or female
	Female	46	18	7.6	

***For car accidents Overtaking was merged with Head-on and Turning was merged with Intersection.**

RESULTS

Belt use and its relation to frequency of severe injury are shown in Figures 1 and 2 respectively. Results of the univariate analyses are shown in Table 2 which includes degrees of freedom, *p*-value for each predictor and the percentage of severely injured patients associated with each predictor level. Table 3 shows the results for the multivariate logistic regression models. For each predictor the statistical significance (*p*-values), β-coefficients for the regression equation and OR are shown.

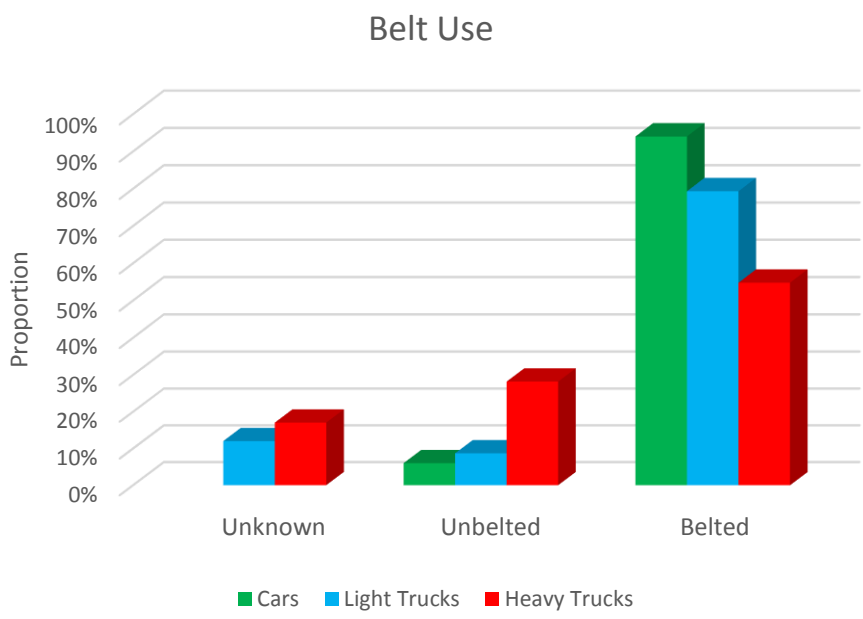

Figure 1: Belt use compliance for the different occupant groups. Note that subjects classified as unknown were removed in cars.

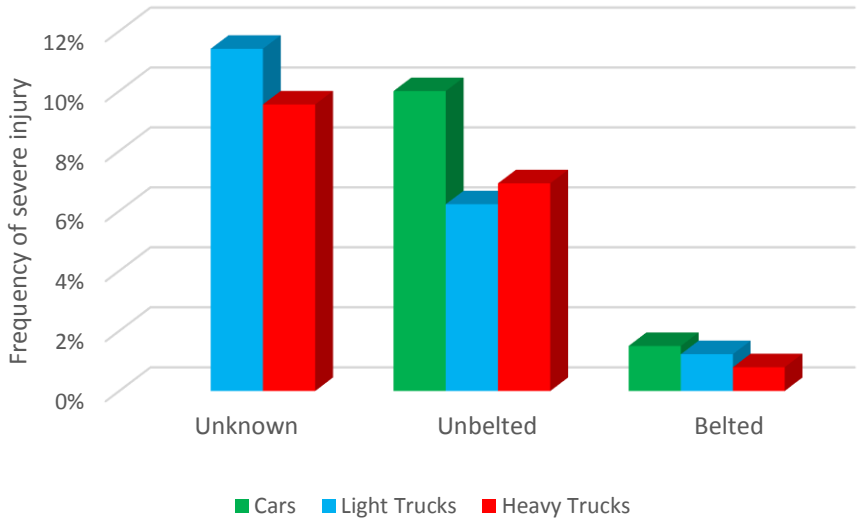

Figure 2: Frequency of severe injury versus belt use. Note that subjects classified as unknown were removed in cars.

Table 2: Univariate analysis of MOI using chi-square tests of association. *p*-values and percentage of severely injured patients associated with each of its levels are shown.

Variable	*p*			Variable Levels	Percent of subjects suffering severe injury for each variable level		
	Cars	Light Trucks	Heavy Trucks		Cars (%)	Light Trucks (%)	Heavy Trucks (%)
Belt Use	< 10e-4	< 10e-4	< 10e-4	Unknown		11	9.6
				Unbelted	10	6.2	6.9
				Belted	1.5	1.2	0.8
Airbag Deployment	0.0030	< 10e-4	0.18	Unknown		5.4	5.4
				Non-deployed	1.8	1.1	2.6
				Deployed	2.3	2.2	0.0
				No Airbag	2.6	3.6	3.7
Accident Type	< 10e-4	< 10e-4	0.17	Turning	1.2*	0.8	0
				Intersection	1.2*	1.7	0
				Head-on	6.1*	9.2	0.8
				Overtaking	6.1*	0	0
				Single	2.4	3	5.5
				Tram/Train	2	27	9.1
				Rear End	0.3	0.9	3
				WLA	2	1.3	0
				Other	1.9	4.3	0
PSL	< 10e-4	0.24	0.62	Unknown		3.5	3.7
				30 Km/h	0.6	0	0
				40 Km/h	0.8	0	0
				50 Km/h	0.9	1.6	7.4
				60 Km/h	1.0	0	0
				70 Km/h	2.1	3.1	5.1
				80 Km/h	2.5	1.7	2.0
				90 Km/h	4.1	4.4	2.6
				100 Km/h	1.1	0.9	0.0
				110 Km/h	0.9	3.3	3.7
				120 Km/h	1.1	4	9.1
Accident Place	< 10e-4	0.23	0.17	Unknown		3.3	0
				Urban	1	2	4.9
				Rural	2.6	3.2	4.3
Elderly	< 10e-4	0.0001	0.45	Under 55	1.6	2.4	3.8
				Over 55	3.6	5.7	5.1
Sex	< 10e-4	0.18	0.60	Male	1.4	3.1	4.1
				Female	2.5	2	2.9

***For car accidents Overtaking was merged with Head-on and Turning was merged with Intersection.**

Table 3: Multivariate analysis of MOI using logistic regression models. *p*-values, β coefficients and odds ratio are shown.

Predictors	β			*p*			e^{β}		
	Cars	**Light Trucks**	**Heavy Trucks**	**Cars**	**Light Trucks**	**Heavy Trucks**	**Cars**	**Light Trucks**	**Heavy Trucks**
Belt (Unbelted)				< 10e-4	< 10e-4	< 10e-4			
Belted	-2.1	-2	-2.4				0.18	0.14	0.090
Unknown		0.22	0.33					1.2	1.4
Airbag (Non-deployed)				0.33	0.20	0.28			
Deployed	0.10	0.31	-16				1.4	1.4	< 10e-4
No Airbag	0.34	1.4	2.1				1.6	4.0	8.2
Unknown		0.64	0.60					1.9	1.8
Over55/Under55	0.92	0.78	0.48	< 10e-4	0.0050	0.29	2.7	2.2	1.6
Female/Male	0.33	-0.32	-0.18	< 10e-4	0.39	0.82	1.4	0.73	0.84
Place (Urban)				< 10e-4	0.28	0.60			
Rural	0.48	0.48	0.51				1.6	1.6	1.7
Unknown		0.53	-18					1.7	< 10e-4
ATC (Head-on)				< 10e-4	< 10e-4	.85			
Intersection	-1.5*	-1.5	-16				0.23*	0.22	< 10e-4
Other	-1.2	-1.1	-17				0.29	0.33	< 10e-4
Overtaking	**Ref***	-19	-16				**Ref** *	< 10e-4	< 10e-4
Rear end	-2.7	-2.4	1.5				0.07	0.09	4.7
Single	-1.1	-1.4	2.0				0.34	0.24	7.3
TramTrain	-0.43	0.90	2.0				0.65	2.5	6.5
Turning	-1.5*	-2.5	-16				0.23*	0.080	< 10e-4
Wild	-1.4	-2.6	-17				0.25	0.072	< 10e-4
PSL (Unknown)				< 10e-4	0.25	0.85			
30 Km/h	**Ref**†	-17	-19				**Ref**†	< 10e-4	< 10e-4
40 Km/h	1.1	-16	-18				2.9	< 10e-4	< 10e-4
50 Km/h	0.6	-0.85	1.1				1.8	0.43	2.9
60 Km/h	0.87	-18	-17				2.4	< 10e-4	< 10e-4
70 Km/h	1.0	-0.14	.50				2.7	0.87	1.7
80 Km/h	1.2	-0.72	.040				3.5	0.49	1.0
90 Km/h	1.5	0.51	-0.27				4.4	1.7	0.76
100 Km/h	0.85	-0.18	-18				2.3	0.83	< 10e-4
110 Km/h	0.40	0.55	-0.14				1.5	1.7	0.87
120 Km/h	0.86	0.84	0.26				2.4	2.3	1.3

***For car accidents Overtaking was merged with Head-on and Turning was merged with Intersection.**

†30 Km/h was the reference for cars unlike for trucks where the reference was "Unknown".

DISCUSSION

Proportion of severely injured subjects versus belt use

The proportion of severely injured subjects was higher for trucks than for cars, and higher for heavy trucks than for light trucks. The frequencies were 4.0 % for heavy trucks, 2.9 % for light trucks and 2.0 % for cars. These results were surprising because larger vehicles, especially heavy trucks, were expected to be safer due to heavier weight and the occupant compartment being placed higher above the wheelbase. Large differences in compliance of belt use were found to be the cause of these surprising results. These differences can be observed in Figures 1 and 2. Figure 1 shows that the percentage of belted subjects is much higher in cars than in trucks, and the compliance is particularly low at 55 % for heavy truck occupants. Figure 2 indicates that for belted and unbelted occupants, cars are less safe than both types of trucks.

In both types of trucks a significant percentage of cases had belt use registered as unknown, which is probably a consequence of that it was reported by the patient himself/herself. Figure 3 shows that cases where belt use was unknown have even higher frequency of severe injury than unbelted cases, a surprising finding for which we currently have no explanation. However, it is likely that most of these cases were unbelted. For cars, cases where belt use was reported as unknown were not included in the analyzed data since a high discrimination power was achieved when eliminating cases with missing information.

Belt use was by far the most significant predictor for all vehicle types. Moreover it was the only variable that was statistically significant for heavy trucks ($p < 0.05$). It should be noted that the statistical significance of the predictors is highly influenced by the size of the datasets, e.g. more predictors were statistically significant for cars. Nevertheless a comparison of the predictors between different vehicle types can be made according to their ranking within a vehicle type.

Association of the different predictors with probability of severe injury

It is difficult to draw conclusions regarding airbag as being a valuable predictor of severe injury. One reason is that the level was unknown for many truck accidents, another is that airbag deployment is likely to be biased towards more severe crashes. Moreover for heavy trucks only 15 cases had deployed airbag, with no severely injured occupants. However, it can be concluded that the association of airbag deployment with probability of severe injury is much smaller than for belt use. We recommend that use of airbag deployment and not belt use as criteria in RETTS should be reconsidered and further evaluated in field studies.

Regarding type of accident note that for cars overtaking accidents were merged with head-on and turning accidents were merged with intersection [6]. The effect of merging these types of accidents is weak because the number of accidents classified as overtaking and turning were relatively small. For cars and light trucks head-on accidents are the most dangerous ones, whereas rear-end accidents are the most common but the least dangerous. The results are very different for heavy trucks where single accidents are by far the most common as well as the most dangerous. It is surprising that for heavy trucks rear-end accidents showed a higher probability of severe injury than head-on accidents. These results show that different types of accidents have similar consequences for cars and light trucks but are very different for heavy trucks.

In all types of vehicles the majority of accidents included in this study occurred in roads with PSL 50, 70, 90 and 110 km/h, with over half of the accidents taking place on roads with PSL 70 and 90 km/h. Roads with PSL 90 km/h are most dangerous for cars and light trucks, whereas roads with PSL 50 km/h have the highest risk of severe injury for heavy trucks, which was unexpected. This result should be interpreted with caution since it is based only on 100 subjects.

Rural environments produced a substantially higher proportion of severely injured than urban environments for all types of vehicles. Despite that heavy trucks showed a higher proportion of severely injured in urban environments, after adjusting for all other predictors, i.e. in the multivariate logistic regression model (Table 3), the OR showed that rural environments are a risk factor with positive association. This may partially be due to that PSL 50 km/h, which was the PSL with highest associated risk of severe injury for heavy trucks, was correlated with urban environment.

Occupants over 55 years old has a substantially higher probability of being severely injured than younger occupants in all three types of vehicle. However this factor is more prominent for cars than for light and heavy trucks. Regarding sex, women have a higher risk of sustaining severe injury for cars but a lower risk for trucks. In principle women are more vulnerable to trauma than men [10], however for trucks this result points in the opposite direction.

CONCLUSIONS

Belt use is the most important factor influencing the risk of sustaining severe injury for occupants in cars and trucks involved in traffic accidents. We recommend including belt use as criteria for triage protocols. There is a need for information campaigns and other means for increasing belt use compliance for cars and trucks, in particular for heavy trucks.

The finding that single accidents account for over 60 % of all heavy truck accidents that produce injuries, and that this is the most dangerous type, point to a need for innovations to reduce them.

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