NEW MODULAR ASSESSMENT METHODS FOR PEDESTRIAN PROTECTION IN THE EVENT OF HEAD IMPACTS IN THE WINDSCREEN AREA

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ABSTRACT

The head impact of pedestrians in the windscreen area shows a high relevance in real-world accidents. Nevertheless, there are neither biomechanical limits nor elaborated testing procedures available. Furthermore, the development of deployable protection systems like pop-up bonnets or external airbags has made faster progress than the corresponding testing methods. New requirements which are currently not considered are taken into account within a research project of BASt and the EC funded APROSYS (Advanced PROtection SYStems) integrated project relating to passive pedestrian protection.

Testing procedures for head impact in the windscreen area should address these new boundary conditions. The presented modular procedure combines the advantages of virtual testing, including full-scale multi-body and finite element simulations, as well as hardware testing containing impactor tests based on the existing procedures of EEVC WG 17. To meet the efforts of harmonization in legislation, it refers to the Global Technical Regulation of UNECE (GTR No. 9).

The basis for this combined hardware and virtual testing procedure is a robust categorization covering all passenger cars and light commercial vehicles and defining the testing zone including the related kinematics. The virtual testing part supports also the choice of the impact points for the hardware test and determines head impact timing for testing deployable systems. The assessment of the neck rotation angle and sharp edge contact in the rear gap of pop-up bonnets is included.

For the demonstration of this procedure, a hardware sedan shaped vehicle was modified by integrating an airbag system. In addition, tests with the Honda Polar-II Dummy were performed for an evaluation of the new testing procedure. Comparing these results, it can be concluded that a combination of simulation and updated subsystem tests forms an important step towards enhanced future pedestrian safety systems considering the windscreen area and the deployable systems.

INTRODUCTION

Accident statistics show the need for measures relating to the protection of vulnerable road users, especially pedestrians with approximately 15 % of all road fatalities in Europe and 35 % in Japan (OECD Database, 2005). Since the European Directive and the Japanese Regulation on Pedestrian Protection became effective in 2005, new vehicle models have to fulfil the mandatory pedestrian protection requirements. Consumer testing in Euro NCAP and JNCAP already considered pedestrian protection tests before the introduction of legislation. The Global Technical Regulation (GTR) published in January 2009 is the basis for type approval regarding the pedestrian protection requirements for future cars. All these testing protocols prescribe the use of subsystem tests with free-motion impactors representing the human head, as well as the upper and lower leg.

Although the head impact in the windscreen area, i.e. windscreen and windscreen support, shows significant relevance in real-world pedestrian accidents (Bovenkerk et al., 2007), there are neither mandatory limit values to fulfil nor vehicle system technologies in series application available which focus on this impact area. Innovative active safety systems help to prevent accidents and to reduce velocity, e.g. brake assist systems. Nevertheless, passive safety systems are required for the protection of pedestrians to mitigate injuries in the case of an unavoidable accident. Providing a protection zone for the head impact in the windscreen frame region is a demanding target due to significant goal conflicts with the field of view and the occupant protection.

A possible solution for reducing impact severity in this critical area could be a u-shaped airbag system combined with a pop-up bonnet function to increase the deceleration distance. Such an airbag system is
able to offer comprehensive head protection. For the analysis of these protection techniques, both simulation and hardware testing are used in this study. The structure of the new modular testing procedure is presented and applied on the demonstrator. Pre-testing includes the assessment of the timing of deployable systems and a virtual testing part to simulate the vehicle-pedestrian collision to consider the impact kinematics of the entire pedestrian. Besides, virtual impactor tests should extend the number of impact points. For the development of the vehicle prototype, finite element (FE) and multi-body simulations are used.

Hardware testing is performed by the use of linear impactor tests according to the existing procedures. Also dummy tests are performed, in which the pedestrian is represented by the Polar-II Pedestrian Dummy. Furthermore, new advanced subsystem tests are investigated to analyse the head-neck interaction. The evaluation of head impact in pedestrian protection must take more aspects into account than only the current mandatory required HIC criteria. Such aspects are head-neck loading and possible contacts with sharp edges, as well as potential negative influences of deployable systems concerning a rebound effect.

Results of these investigations should contribute to the future development of assessment methods and protection systems for the head impact of pedestrians in the windshield area. Numerical simulations as well as hardware testing should be considered in an evaluation procedure. The main target is to improve the real-world pedestrian protection in the field of passive safety.

**METHODS AND DEMONSTRATORS**

**Modular Assessment Procedure**

Relevant accident cases most likely occur in urban areas with a high variety of impact conditions. For comparable results trying to cover most of this variety, a generic standard configuration has to be defined. Vehicle areas which are not affected by the developed testing procedure (i.e. bumper- or lower bonnet area) are covered in the tests according to the GTR test protocol. All defined boundary conditions in this procedure are derived from a pedestrian impact scenario with a vehicle velocity of 40 km/h.

Boundary conditions for the dummy test considered in this study are used from the “Draft Recommended Practice for Pedestrian Dummy” defined in the SAE Pedestrian Dummy Task Group, which aims for the development of worldwide standards for pedestrian dummies. In addition, the “Certification Standard for Type Approval Testing of Active Deployable Systems of the Bonnet Area” which has been proposed in the context of the UN ECE Global Technical Regulation forms the basis for both simulations and hardware testing. According to these conditions, the configuration contains a lateral walking position of the pedestrian in the vehicle centreline with the leg facing the vehicle in backwards position.

The developed modular testing procedure aims for a combination of the benefits of numerical simulations and hardware testing methods. Furthermore, the testing procedure focuses on the windscreen frame region including the cowl area. Being one of the most obvious possible solutions in this area, the deployable systems, e.g. airbags, play a major role in this testing procedure. Such issues are the main “white spots” in current procedures. The existing procedures form the basis for all the developments. By using numerical simulations of vehicle-pedestrian collisions and of impactor tests for pre-testing, costs for hardware testing can be optimised.

The procedure is divided into two main steps. Step 1 represents the preparation and the pre-testing in virtual tests using simulation methods, while step 2 includes the hardware testing which covers subsystem tests and optionally full-scale dummy testing. In the end, all results are evaluated according to quantitative threshold values or qualitative remarks concerning potential additional injury risks are given. The flow chart of the procedure is shown in Figure 1.

### Step 1: Preparation and pre-testing

<table>
<thead>
<tr>
<th>Vehicle and test preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematics-simulation to calculate Head Impact Time and Area and confirmation of TRT &lt; HIT requirement</td>
</tr>
<tr>
<td>Choice of virtual impact points (usage of deployed position) and virtual head impact testing with vehicle front model</td>
</tr>
</tbody>
</table>

### Step 2: Vehicle testing

| Hardware impact tests on vehicle |
| Chosen impact points from simulation results (If needed: dynamic test with deployable system) |
| Testing of head-neck interaction |

**Test result and evaluation of pedestrian protection**

(Head and neck load)

Figure 1. Flow-chart of the procedure.
The preparation and pre-testing begin with the acquisition of the test vehicle and the corresponding simulation model. This forms the basis for the whole testing campaign. If the simulation model is not provided by the manufacturer, methods of reengineering, such as digitisation methods or simplified models can be alternatively used.

Typical vehicles are classified based on previously conducted simulation studies using generic front shapes (Bovenkerk and Zander, 2008). The classification contains four categories (A: Sedan, B: SUV, C: OneBox, and D: Sports-car) according to different parameters of its front and the resulting impact kinematics, see Figure 2. The method is comparable to the existing IHRA-categorisation with an extension using a Category D with low bumpers and bonnet leading edges (BLEs). These are mainly sports-cars and roadsters. The bonnet leading edge height and the inclination angle of the front ($\alpha_B$) according to the definitions in the “Blue Book”, 2005 (measured in the vehicle middle, $y = 0$, bonnet front to the rear edge) have been identified as the main parameters which determine the impact kinematics.

For the subsystem testing part it is proposed to use the ISO-head-impactors in compliance with the GTR protocol and to adjust their impact parameters in each vehicle category by varying the impact angles and the relevant wrap around distances (WADs, Figure 3 and Table 1). The impact area is marked by using references and WADs that are commonly used in the existing procedures.

For the potentially largest number of Category A "sedan" vehicles, the head impact parameters in the transition of child and adult head impact zone correlate with the GTR. Due to the consideration of the 95th percentile male, the upper boundary is defined as WAD 2300 mm. The WAD-distances are lower with respect to the impact kinematics for SUVs and OneBox-vehicles where the pedestrian is thrown less high onto the front. The contrary effect can be seen for sports-cars and roadsters, where the pedestrian will be thrown higher upwards and the impact angles are steeper at the same time.

For the multi-body or coupled vehicle-pedestrian simulations which analyse the kinematics, the head impact time (HIT) and the corresponding locations for each specific vehicle have to be evaluated. In these simulations, the previously determined boundary conditions should be proven. Adjustments of the parameters listed in Table 1 concerning a possible new vehicle category have to be taken into account. The comparison of the total response time (TRT) of the system to the head impact time confirms its functionality (TRT < HIT). Furthermore, the vehicle system has to be in deployed position until the head contacts. That leads, at the same time,
to a sufficient activation time of the system in the case of lower vehicle velocities. If this condition is not fulfilled, a major additional danger occurs due to the opposite directions of the head impact velocity and the bonnet movement.

Step 1 includes the choice of impact points in the marked windscreen area (cowl and windscreen, see Figure 3). The virtual impactor simulations help to identify hard points on the vehicle front (Puppini, 2008). Potentially critical impact points from the previously conducted vehicle-pedestrian simulations can be added. The virtual head impact test forms the transition from step 1 to step 2. Using the specified impact angles, velocities, areas and impactor masses, the numerical head impact simulations supplement the hardware tests on the test points. For the hardware tests, the existing head impactor tests with the modified boundary conditions according to the impact area and the angle are applied.

The second focus in hardware testing apart from the linear head impact is the head and neck load due to the head-neck interaction. Increasing neck loads through large rotations, e.g. caused by the gap at the rear bonnet edge, are an additional risk especially if deployable systems are used. The final step of the modular testing procedure is the evaluation of the pedestrian protection potential by analysing the test results. In general, the scope of the vehicles should consider mainly passenger cars, for which the existing procedures have originally been developed for:

- All M1 vehicles
- All M2 and N1 vehicles up to 3.5 t gross-vehicle mass
- Excluding “Flat Front Vehicles” (with D(R-Point driver seat - front axis) < 1000 mm)

Due to their front geometry with often short bonnets and higher inclination angles of the windscreen, so-called “Flat Front Vehicles” require system solutions which are often incomparable with the sedan shaped vehicle solutions (Fassbender and Hamacher, 2008).

In the following paragraphs, an overview and breakdown of the proposed steps of the presented procedure will be given.

**VEHICLE AND TEST PREPARATION**

**Experimental Vehicle**

For the investigation and demonstration of the developed testing procedure, a reference vehicle is chosen. An average shaped sedan vehicle of the defined Category A (Opel Signum) is upgraded with a pop-up bonnet in combination with an external airbag, developed and provided by TAKATA (both numerical and hardware model).

Modifications of the series version related to the hinges in the bonnet rear area, the latch in the front and the integration of the airbag module are the main changes. For the bonnet rear hinge, linear and rotational joints are considered. Due to advantages in kinematics, the rotational hinge solution is chosen. This solution means no risk of self-locking effect, which could be caused by kinematics and friction in the linear guidance. The whole system of hinges and bonnet forms a 4-point hinge kinematics. In a series application, the rear hinges have to be locked in the daily operation position by integrating e.g. shear bolts or pyrotechnical bolts. The necessary clearance for the hinges can be reduced to a space which is comparable to the series hinges. The sheet thickness of the prototype hinges is 5 mm.

The series latch is replaced by two front hinges, which have to be changed into a two latch system in a possible series application. The pivot requires a location which is positioned as far as possible towards the front to avoid collision with the surrounding parts when lifting up the bonnet up to 120 mm. In addition, the front hinges have to be fully covered by the bonnet. Lifting of the bonnet is realised by the lower chamber of the airbag and covering the windscreen area by the upper airbag chamber.

The airbag module is integrated. Fixation points for the module are both suspension towers and the water box. An additional function of the module as a strut bar can also be introduced.

The gas pressure during the deployment of the airbag is measured in a relatively calm area (less gas flow). When fully deployed, the airbag volume is approximately 90 l. A water box cover, which is also fixed laterally and replaces the series plastic cover of this area, is necessary to guide the airbag directly without obstructions towards the windscreen. Sharp edged parts in the airbag deployment area are removed or covered.

The modifications of the vehicle according to the external airbag system require some additional clearance in the water box area. In the series vehicle such a system has not been considered in the early design and the development process. Therefore, the whole wiper system is removed during the following investigations. Changes of the vehicle front are implemented in such a way that the series status of the vehicle can be restored quickly. Necessary cut-outs, especially for placing the airbag module, are an exception. The changes are summarised, and the wrap around distances are marked in Figure 4. The potential impact point for the 50th percentile
male is shown. It is expected that the impact location of the human model in simulations and dummy tests will be nearly identical.

Multi-body / Coupled Vehicle-Pedestrian Kinematics Simulations

The following comparative analysis always refers to the active deployable airbag system’s performance with a series vehicle without the implementation of pedestrian safety measures. This comparison should help to evaluate the potential of both the new testing procedure and the future pedestrian safety systems.

Multi-body simulations using Madymo or coupled simulations using Madymo and LS-Dyna are performed to investigate the impact kinematics with the main focus on the location and timing of the head impact. The results form an important input for triggering the subsystem impactor in relation to the airbag system in the following hardware testing part. The coupled simulations in Figure 6 show that the head impact of the 50th percentile male takes place at HIT = 128 ms in the transition zone of the bonnet and windscreen of case 1 representing the series version without the deployable system.

Figure 4. Modifications on the series vehicle and FE-Model (Category A).

Virtual Model

For the pre-tuning and development of the experimental vehicle and the virtual part of the testing procedure, a simulation model of the vehicle front is built up. All relevant components are transferred into a CAD model using the “ATOS I system” for scanning components and CAD for re-engineering the whole front geometry (Figure 5). The vehicle model contains the front-end with bumper, cross member and crash boxes, fender, bonnet and the body with longitudinal beams, suspension towers and A-pillars. The engine package is included as a simplified rigid surface.

Figure 5. Re-engineering of the vehicle front

The numerical airbag model of TAKATA is integrated into the FE simulation. These simulations contain the definition of the lifting mechanism through the airbag deployment and in a second step head impactor simulations using the timing derived from the multi-body simulations as an input. The design changes for the experimental vehicle prototype are implemented in the simulation model (Figure 4).
Comparison of the two cases shows an offset of about 10 ms towards an earlier head impact in case 2 with respect to case 1 due to the deployable system. In that case, the head would impact most likely in the open bonnet rear gap, which is covered by the airbag in the reference vehicle. Simulations with same boundary conditions using the 6 y/o child model indicate that the earliest head impact on the bonnet front is at t = 60 ms in activated position. The airbag is fully deployed after 40 ms (TRT).

For the considered impact speed and a sufficient activation time of more than 200 ms of the airbag, which will guarantee the deployed position until the head contacts in the case of lower velocities (i.e. higher head impact time), it can be concluded that the requirement TRT < HIT is fulfilled.

The simulations underline that the upper bonnet and lower windscreen area play an important role for the head impact. This area offers lower protection potential in contrast to the bonnet and windscreen middle, due to the high stiffness and reduced deformation space. Average sedan shaped vehicle fronts in general show this impact scenario.

Choice of Virtual Impact Points / Virtual Head Impact Testing with Vehicle Front Model

FE simulations using LS-Dyna software are carried out to evaluate the function of deployable systems and to identify a particular choice of hard points in the car front. Figure 7 shows such a simulation grid on the vehicle front with regular (marked as a grid structure, white points) and additional points which can be identified from the vehicle-pedestrian simulations (stars) or which are simply identified as additional potentially critical points (red ones).

![Figure 7. Virtual tests on a grid.](image)

The simulations in Figure 8 show an adequate function of the whole lifting mechanism. The acceleration outputs of the impactor model indicated a good performance. In this sequence, an impact at t = 0 ms is shown. This is in the time period, where the airbag model is fully deployed when t = -100 ms is the triggering time. In the virtual test series, different impact points are evaluated. For the comprehensive presentation, the impact point of the 50th percentile male in the middle of the bonnet rear area will be presented with the main emphasis in the following considerations.

![Figure 8. LS-Dyna head impactor simulation, t in [ms].](image)

HARDWARE VEHICLE IMPACT TESTS

Impactor Tests

In the hardware tests, the experimental vehicle is tested according to EEVC WG 17 and GTR testing protocol by extending the impact area to the windscreen region as described in the new testing procedure (Category A, cowl area: WAD 1770 mm, 65° impact angle with adult head). Currently, testing of the bonnet rear area is only included in the Euro-NCAP-procedure. Due to the current availability at ika, the 4.8 kg EEVC WG 17 adult head impactor is used instead of the proposed ISO headform. The velocity of the head impactor is 40 km/h. In the hardware testing, three impact points are chosen in the context of this study. The potentially critical impact points which might be identified in the virtual tests and the chosen impact points for the hardware tests are shown in Figure 9.

![Figure 9. Potential critical impact points and tested points for Category A - Sedan.](image)
Furthermore, the previously defined testing area is compared to the current Euro NCAP zone. The most significant change is the increased wrap around distance of 2300 mm for Category A (Sedan) when considering the 95th percentile male.

Figure 10 shows the subsystem test on the expected impact point of the 50th percentile male (point 1). In general, these conditions correlate with the results of the multi-body model simulations in previous studies (Bovenkerk et al., 2009). Regarding the impact location on the bonnet rear edge, the position of the impact point is one third on the bonnet itself and two thirds on the lower windscreen zone, which is covered by the airbag system.

For triggering and timing the impact of the headform, the previously determined head impact time (HIT) from the numerical simulations is used (about 120 ms). With the first impact of the leg, a pedestrian impact sensing time (ST) of \( t = -20 \) ms is estimated, so that the impact time of the head impactor is at \( t = 0 \) ms after triggering the airbag at \( t = -100 \) ms. After \( t = 40 \) ms, the airbag is in a fully deployed mode, so that there is a sufficient safety margin with respect to time until the head impacts. During the whole contact phase, the airbag fully covers the rear bonnet area and the A-pillars. The acceleration outputs from the simulations are correlating with these tests. For the determination of the optimum airbag pressure, it has to be considered that too high inner pressure and thus low energy absorption of the airbag itself lead to elastic behaviour with a strong rebound effect that can be reduced by the use of vent holes.

Tests with Polar-II Pedestrian Dummy

In a second (additional) test series, the overall kinematics of the real-world accident are investigated by using the Honda Polar-II Dummy. In addition, these tests form an input for the analysis of the neck loads which cannot be investigated by the common linear impactor testing methods.

The biofidelity of this dummy enables the reconstruction of a realistic pedestrian accident with an average sedan car front. A detailed description of the Polar-II Dummy can be found in (Takahashi et al., 2007). In addition, the potential of using the external airbag system in the future can be investigated close to reality. Taking into consideration that there are currently only very few vehicles equipped with deployable systems and none with external airbags, the availability of real-world accident data from such vehicles will be far in the future. Confirmation of benefit in real-world accidents is therefore not possible.

Results of the dummy tests are compared to the performed vehicle-pedestrian simulations. Furthermore, a comparison of the series vehicle and the modified version using the airbag system is included. Merging all these results, it becomes more clear that using a combination of subsystem tests and simplified simulations and with the dummy test as an option for complex systems is an adequate method to evaluate the protection potential of a car.

The dummy is positioned according to the defined boundary conditions, i.e. vehicle faced leg backwards and the position of the dummy in the vehicle centreline. The release mechanism of the dummy is triggered approximately 50 ms prior to impact and braking takes place 100 ms after impact. Figure 11 gives an overview of the test set up and the distances at the ika crash test facility.

Figure 12 shows the comparison of high speed sequences of the dummy tests with the series vehicle and the modified vehicle using the airbag system. In both cases, the vehicle velocity is 40 km/h. Triggering of the airbag system is realised by contact sensors on the bumper. The first impact of the leg corresponds to \( t = 0 \) ms. After the leg impact, the hip impact for both cases takes place at \( t = 40 \) ms; following this, the full body wraps around the vehicle front and has flat contact on the bonnet. After the shoulder impact between 100 ms and 120 ms, the first contact of the head takes place at 131 ms in the first case and at 121 ms in the second case with
the deployed bonnet and the activated airbag. In this case, an offset of approximately 10 ms to an earlier time occurs for all body regions after the upper leg impact due to the lifted bonnet.

The timing of airbag deployment complies with the results of the head impactor tests. Wrap around distances to the head impact point are 1830 mm in the first case and 1860 mm in the second case proving the expected impact point on the bonnet rear (point 1). After 200 ms the dummy flight phase starts, and the dummy separates from the vehicle (not shown).

The contact location of the upper leg is on the first third of the bonnet. Further bonnet deformation results from the whole body contact. Figure 13 shows the post-crash scenario of both tests regarding the head impact. The deformations of the rear edge of the bonnet and the locally cracked lower windscreen for case 1 without airbag indicate the locations of the head contacts. The damage of the windscreen centre results from the release device after the head impact and has no influence on the test results. In comparison to the series version, there is nearly no deformation of the lower windscreen area in the modified version.

HEAD-NECK TESTING

There are different possibilities to include the evaluation of the head-neck interaction. On the one hand, the dummy test results regarding the interaction forces, moments and angles can be used. On the other hand, in the case of lacking availability of a dummy test, trends of these values can be derived from the previously conducted numerical vehicle-pedestrian simulations. Additional subsystems can be applied which are proposed by Kalliske and Bovenkerk (2009), see Figure 14.

The first head-neck subsystem testing method (1) uses a pendulum impactor which is fixed to the head impact test bench. The main purpose of this
The method is to record contact forces in the case of an edge impact. The contact area has to be evaluated additionally by pressure foils and included in the calculations for the determination of the contact pressure acting on the head. Furthermore, the neck rotation angle can be statically measured. This angle can be very high in the case that the head rotates into a deployed bonnet rear gap.

The free motion impactor in method (2) uses an eccentric neck mass leading to a more biofidelic representation of the influence of the body, which introduces a head rotation through the neck. Subsequently, the linear and the rotational acceleration responses are recorded. This enables to evaluate the head rotation, in addition to the HIC-values. The dimensions of the impactor spheres are based on the existing adult headforms.

In this paper, these methods will be used to include a qualitative assessment of additional risks regarding the head-neck interaction.

**TEST RESULTS AND EVALUATION OF PEDESTRIAN PROTECTION**

**Subsystem Testing**

The outputs of the linear impactor tests concerning the head accelerations and the resulting HIC-values are presented in Figure 15. The virtual and hardware impactor tests do not lead to different evaluation results. Tests and simulations are in good correlation. In all three cases it can be shown that the requirement of the HIC-value below 1000 of the modified vehicle can be met with a significant safety margin. Compared to these results, the testing of the series vehicle leads to a higher acceleration level and therefore all the HIC-values are above 1000. The A-pillars are completely covered by the airbag in the modified version. Testing the region without an airbag was left out due to the clearly lowest available deformation space and highest structural stiffness, which would result in an extremely high HIC-level.

Table 2 shows an evaluation matrix for the modified vehicle including the possible additional injury risks of the analysed impact points. Some of them are conflictive.

<table>
<thead>
<tr>
<th>Point No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Bonnet rear</td>
<td>Hinge area</td>
<td>Airbag</td>
</tr>
<tr>
<td>HIC</td>
<td>Low (591)</td>
<td>Medium (840)</td>
<td>Low (500)</td>
</tr>
<tr>
<td>Rebound</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Risk of edge Contact</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Head rotation</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>

On the one hand, the HIC on the airbag is at the lowest level and there is no significant risk of head contact with sharp edges. On the other hand, the rebound of the head is at a high level due to the low energy absorption of the airbag itself. The combination of the energy absorption through the bonnet with an underlying airbag on point (1) seems to be a good compromise. Furthermore, sharp edges of the deployed bonnet rear gap have to be avoided by solutions which cover this area. Such an exposed bonnet rear may also result in a higher neck rotation angle as well as in higher angular acceleration due to the possible pendulum movement of the head. Kalliske and Bovenkerk (2009) listed these effects as potential new injury risks.

**Dummy Testing**

For the evaluation of the test results, the head and neck outputs of the dummy are exemplarily shown. The diagrams in Figure 16 to Figure 18 show the head and neck loading for the two cases. These curves illustrate the result of the series vehicle in red colour and the modified vehicle with the airbag system in grey colour. Further on, the first head contact is marked.

![Figure 15. HIC-values of the chosen impact locations.](image)

![Figure 16. Head CG acceleration.](image)
Head CG acceleration curves show a decrease of the maximum acceleration from the series vehicle $a_{\text{max, series}} = 186$ g to $a_{\text{max, mod}} = 83$ g, which results in a decrease from $\text{HIC}_{15, \text{ series}} = 1212$ to a value of $\text{HIC}_{15, \text{ mod}} = 705$. Reducing the HIC-value by 42 % with regard to the series vehicle and going at the same time significantly below the limit of $\text{HIC} = 1000$, defined by EEVC WG 17, indicate the protection potential of an airbag system in the windscreen area. Due to the influence of the airbag and increasing of available deceleration space, the shape of the acceleration peak is transformed from a straight high peak into a broader peak on a lower level. The influence of the changed vehicle shape, caused by the lifting of the bonnet by the airbag, on the acceleration of the head CG is starting from 120 ms with an earlier increase until 160 ms with a later decrease of acceleration.

Neck forces and moments in the lower and upper neck load cells are shown in the following diagrams. Shear forces in $x$- and $y$-direction do not play the most significant role; they neither show any tendencies of differences nor exceed any defined threshold value. The force component in vertical $z$-direction is of dominating influence. Tension forces at a maximum level of 2000 N change into a higher level of compression forces for the series vehicle with a magnitude of over 5000 N which exceeds the FMVSS 208 limit of 4000 N (red area). The two cases differ significantly after 135 ms. The modified vehicle shows a maximum compression force of 2000 N, which is below this limit value (grey area).

A comparison of the head trajectories in testing and simulation is shown in Figure 19. A correlation between the head kinematics in the flight phase can be seen. The upper leg movement does not correlate due to the contact stiffness definition of the simplified multi-body model. In general, the results regarding the impact timing and location of the head, which are the main focus of this paper, are comparable. It has to be considered that in this version of the model, the airbag is not included in the simulation model, and therefore the impact angle is significantly higher due to the exposed rear gap.

CONCLUSIONS

In this paper, a modular structured procedure for pedestrian impact testing was proposed according to a combination of hardware and virtual tests. Two main steps concerning preparation and pre-testing with vehicle-pedestrian and impactor simulations as well as a hardware testing phase are included. First, the boundary conditions for the linear impactor tests were pre-defined within four vehicle categories including Sedan, SUV, OneBox and Sports-car front shape. These categories were based on the bonnet leading edge height and the inclination angle of the front. The second step includes impactor tests and optionally dummy tests. As an extension of the existing linear head impactor tests, new impactors developed in the APROSYS project were presented. These tests enable a better evaluation of the head-neck interaction.
A sedan shaped car was used as the virtual and physical test environment. By using a human model in multi-body and coupled simulations, test conditions regarding the impact point and the timing were defined. The simulations would also be able to create further test input data such as tendencies for head-neck loading output.

To confirm the simulation results obtained with the whole pedestrian model, Polar-II Pedestrian Dummy tests were performed. A good correlation between the human model simulation and the Polar dummy test could be reached with respect to impact point and timing. Furthermore, it could be shown that such an approach of combining simulation and testing is able to cover also particularities of deployable passive safety systems such as an airbag, e.g. with respect to triggering.

In the evaluation part of this modular procedure, the pedestrian protection potential of passive safety systems referring to an airbag in comparison to current non-activated vehicle front structures were presented. Even hardware testing could show that advanced safety systems involving airbags will have a big potential to protect pedestrians well in real-world accidents. As an example, the head and neck loading was considered. In this study, the outcome of using an airbag was a HIC reduction of 42% and a reduction of the neck compression forces of about 60%, as well as a neck moment reduction of about 30%. However, the focus was not on the sensing system, which is necessary for the series application of such a deployable airbag system.

It could be shown within this paper that new testing methods consisting of a combination of simulation and subsystem testing lead to an improved evaluation of pedestrian protection and complement each other. Vehicle-pedestrian collision simulations are concluded to be an efficient way to estimate the influence of the vehicle front shape on the impact parameters. Impactor simulations offer the multiplication of analysed impact points and the identification of most critical points. The hardware tests allow the verification of simulation results. The final evaluation includes additional aspects for complementing the HIC-value with the consideration of impact forces and the head-neck interaction. Further research is needed in the development and application of these new testing methods including subsystems for the head-neck interaction. For a more biofidelic representation of the real-world accident, it is recommended to continue research on improved impact evaluation.

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