ASSESSMENT OF ACTIVE AND PASSIVE TECHNICAL MEASURES FOR PEDESTRIAN PROTECTION AT THE VEHICLE FRONT

Michael Hamacher
fka - Forschungsgesellschaft Kraftfahrwesen mbH Aachen
Germany
Lutz Eckstein
ika - Institut für Kraftfahrzeuge RWTH Aachen University
Germany
Matthias Kühn
Thomas Hummel
German Insurers Accident Research
Germany
Paper Number 11-0057

ABSTRACT

Structural improvements at the vehicle front are state of the art in the field of pedestrian safety today. But due to raising requirements further measures will be needed. The active bonnet for example is the first deployable system that has entered the market. Other passive safety systems, like the windscreen airbag, are part of current research. This applies also to systems of active safety such as autonomous braking. Hereby the collision speed can be reduced or an accident can be even avoided. To assess and compare the safety potential of active and passive pedestrian safety measures on one scale, an assessment procedure has been developed and applied to various measures and vehicle fronts.

An important characteristic of the assessment procedure is its modular design, combining structural characteristics of a vehicle front with accident kinematics and accident research data. Each module can be enhanced or substituted independently. The assessment procedure uses the vehicle model specific Euro NCAP results and adapts the HIC values to the real accident kinematics derived from numerical simulations. Since the kinematics strongly depend on the front design of a car, a categorization has been developed. For each vehicle class respective simulation data is available. Kinematics parameters are the head impact velocity, impact angle and impact probability determined for the particular wrap-around-distance zones of the vehicle front.

The assessment procedure primarily provides an index value which indicates the risk for an AIS3+ head injury due to the primary impact at a collision speed of 40 km/h. It is calculated for children and adults by an injury risk curve. In addition the dependency of this index value from the collision speed is determined based on corresponding simulation data. Beside the head loading also the leg loading is assessed. This is carried out by a simplified index calculation. The secondary impact is evaluated qualitatively.

The assessment procedure brings the evaluation of active and passive safety together. Index values have been calculated for good as well as poor rated vehicles within Euro NCAP and under consideration of varying additional safety systems. It could be shown that the benefit of today's measures applied to the vehicle front is limited. Legal test requirements and consumer ratings insufficiently reflect the vehicle-class-specific relevance of particular front areas. Simulation data points out the A-pillars and the lower windscreen area, which need to be addressed by technical measures. Furthermore there is no "one fits all" measure which performs on the same positive level at all vehicle fronts and for all pedestrian sizes. Therefore measures have to be selected and adjusted for each car front. A windscreen airbag is able to improve adult pedestrian safety significantly. Children however profit more by emergency brake systems with pedestrian detection due to the limited safety potential of an active bonnet. Consequently, future cars should offer both adequate passive pedestrian protection and additional active safety systems. The benefit of relevant passive safety systems as well as reductions in collision speed has been demonstrated by Polar-II dummy tests with an experimental vehicle.

INTRODUCTION

Due to increasing requirements on the part of European legislation as well as consumer ratings pedestrian protection measures have become more important over the past years. Structural improvements at the vehicle front are state of the art in the field of pedestrian safety today. But further measures will be needed. The active bonnet for example is the first deployable system that has entered the market. Other passive safety systems, like the windscreen airbag, are part of current

research. This applies also to systems of active safety such as autonomous braking. Hereby the collision speed can be reduced or an accident can be even avoided. To assess and compare the safety potential of active and passive pedestrian safety measures on one scale, an assessment procedure has been developed within a joint research project of fka and the German Insurers Accident Research.

ASSESSMENT PROCEDURE

An important characteristic of the assessment procedure is its modular design. The particular modules will be presented by means of the experimental vehicle used for the final Polar-II dummy tests.

Modules

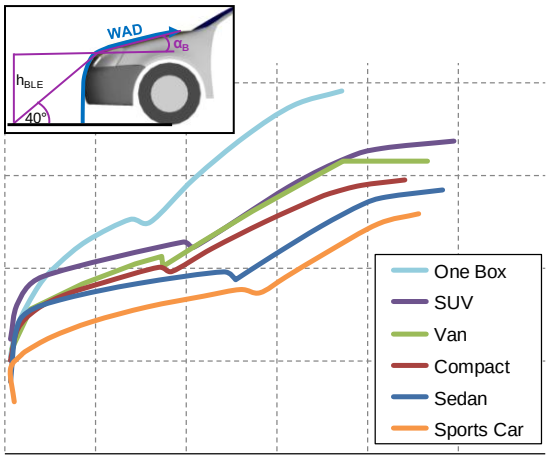
The assessment procedure is divided into six modules. Within the first three modules all vehicle characteristics required for the assessment are determined (Table 1).

Table 1.
Modules of the assessment procedure

1	Measurement and classifi-cation into vehicle class	Vehicle characteristics
2	Simulation and accident kinematics	
3	Structural properties and safety systems	
4	Weighting and adaptation of structural properties	Assessment
5	Index calculation	
6	Qualitative assessment of secondary impact	

The first module is based upon a categorization, which has been developed to consider the different front designs of modern cars and their impact on pedestrian accident kinematics.

Measurement and classification into vehicle class The categorisation comprises six vehicle classes. For each class a representative front has been defined. Figure 1 shows the front contours of those class representatives. Three geometrical parameters are used for the classification of a new car model. The first one is the height of the bonnet leading edge, which has significant influence on the accident kinematics of a pedestrian. The wrap around distance (WAD) up to the bonnet rear edge is relevant for the location of the head impact relative to the vehicle front. The lower the values for this parameter, the higher is the probability for a head impact in the windscreen area. The third characteristic parameter is the bonnet angle, which has an effect on the throw-up distances.



h_{BLE} = Height of Bonnet Leading Edge
WAD = Wrap Around Distance
α_B = Bonnet Angle

Figure 1. Classification into vehicle class.

Since the utilisation of Euro NCAP results is an essential part of the assessment procedure, the vehicle zoning is orientated towards the Euro NCAP grid. For the representation of the relevant impact areas an expansion as well as a finer raster of the grid in longitudinal direction is necessary. Hence, the four Euro NCAP test zones are subdivided and expanded by two more zones. Each zone offers twelve fields. Figure 2 illustrates the defined segmentation using the example of the experimental vehicle, which belongs to the class Sedan.

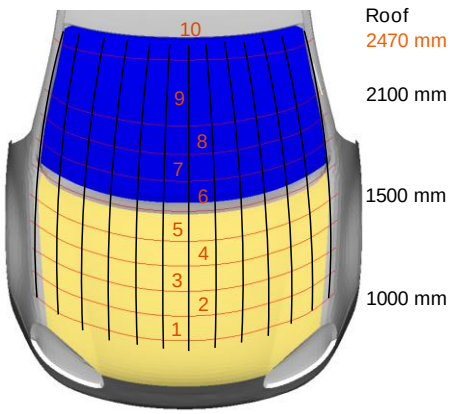


Figure 2. Vehicle segmentation.

The following module assigns values for different kinematics parameters to each of the ten WAD-zones.

Simulation and accident kinematics The kinematics parameters used within the assessment procedure are the head impact velocity, impact angle and impact probability. The kinematics is determined by simulations with the MADYMO multi-body solver. The simulated scenario is based

on accident research data and describes a pedestrian crossing in front of a vehicle. The collision speed for the assessment of passive safety measures is 40 km/h. For the assessment of active safety systems additional simulations with reduced collision speeds (20, 30, 35 km/h) are necessary. The consideration of four pedestrian models, three impact positions and two walking postures leads to the simulation matrix described by Table 2.

Table 2.
Simulation matrix

4 collision speeds	40, 35, 30 and 20 km/h
4 pedestrian models	6 year old child, 5 %-female, 50 % & 95 %-male
3 impact positions	Centred, staggered, edge
2 walking postures	Leg facing the vehicle is back-wards and forwards respectively
4 x 4 x 3 x 2	96 simulations per vehicle

For the assessment of additional passive safety sys-tems (module 3), like a pop-up bonnet, additional simulations with a collision speed of 40 km/h have to be performed (1 x 4 x 3 x 2 = 24). Figure 3 visualises the head impact for the 50 %-male in central position and at a collision speed of 40 km/h.

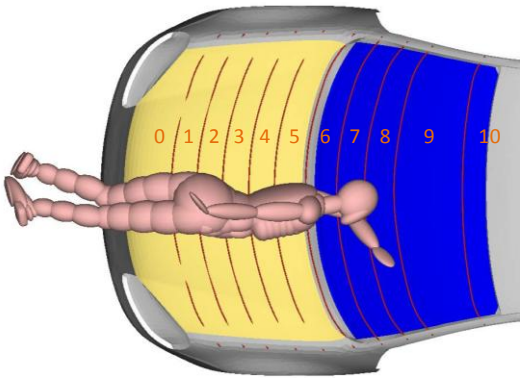


Figure 3. Multi-body simulation.

The interpretation of the simulation data is carried out separately for every velocity and related to the pedestrian models. For each model the area of head impact as well as the highest head impact velocity and angle occurred in the simulations are determined. The head impact area of a model is described by its minimal and maximal WAD for the head impact locations. This interval is used to calculate the throw-up factor f_a, which is a measurement for the throw-up distances achieved by the particular pedestrian height. The values identified for each pedestrian model are used as supporting points for the description of the vehicle-specific accident kinematics.

With the help of a best-fit curve a functional correlation between throw-up factor and body height can be derived, which allows a complete description of the throw-up behaviour. This is the first step towards WAD-zone-related impact probabilities. A second step combines the throw-up behaviour with a pedestrian size distribution. Since the assessment is carried out for children and adults, two separate size distributions have been defined. The outcome of this procedure is shown in Figure 4. Here the WAD-distribution regarding the head impact is given for adults. It is apparent that the WAD-zones 7 and 8, i.e. the lower windscreen area, possess the highest relevance in this regard. The impact locations of the children are more evenly distributed. Relevant are the WAD-zones 2 to 5, all lying on the bonnet.

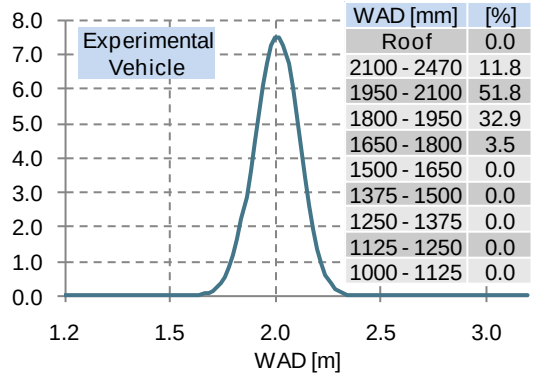


Figure 4. Relevance of the WAD-zones (adults).

After assigning impact probabilities to each WAD-zone, the throw-up behaviour is used for the specification of impact velocities and angles. Therefore the discrete heights of the pedestrian models are transferred into WAD-values. Through linear interpolation between the corresponding velocities and angles respectively, both kinematics parameters can be determined for every WAD. Figure 5 illustrates the correlation between head impact velocity and throw-up distance for a collision speed of 40 km/h.

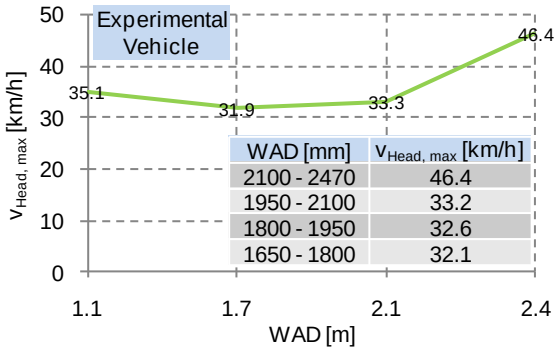


Figure 5. Correlation between maximal head impact velocity and throw-up distance.

In the upper windscreen area the values lie above the collision speed. Therefore the head impact velocities in the relevant WAD-zones of the adults range from 32 to 46 km/h (see table in Figure 5) while the children achieve values from 32 to 35 km/h. To obtain the maximal head impact angels for the particular WAD-zones the procedure has to be carried out analogue.

For every vehicle class representative (Figure 1) generic 3D simulation models have been generated. Those models provide vehicle-class-specific kinematics data. Since this data is available for all of the six class representatives, it is not mandatory to perform and analyse additional simulations. The class-specific kinematics parameters are implemented into the index calculation. They are assigned through the classification of a new car model into the corresponding vehicle class. Alternatively, vehicle-model-specific kinematics data can be used for the application of the assessment procedure, as it has been done in case of the experimental vehicle.

After transferring the accident kinematics parameters to every WAD-zone, the structural properties of the vehicle front have to be devolved.

Structural properties and safety systems The structural properties are described by the Head Injury Criterion (HIC). These data is taken from the respective Euro NCAP spreadsheet of the car to be assessed. Rules have been defined for a reasonable assignment of the HIC-values to the particular fields of the vehicle segmentation. Since the Euro NCAP test zones have been subdivided the respective WAD-zones receive the same HIC-values, however possess different impact probabilities (Figure 6). When an additional passive safety system like a windscreen airbag is implemented, the structural properties have to be adapted within the protected area. In case of the windscreen airbag, the HIC-values of all fields fully covered by the airbag are reduced to a general value of 500, an advanced airbag design assumed. The performed Polar-II dummy test with a prototype airbag confirms the specified HIC-value.

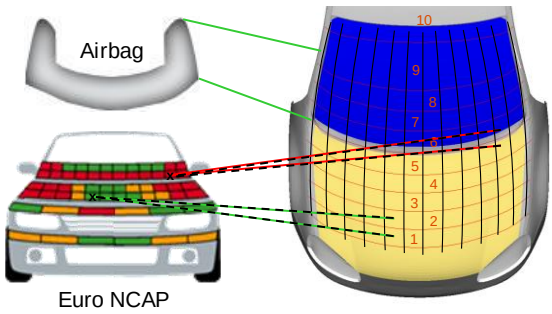


Figure 6. Assignment of structural properties.

In addition to the HIC-values, the results of the legform impactor tests are considered as well for the assessment of a car. Those results can be directly used for the calculation of the leg index (module 5).

Additional passive safety systems usually not only influence the structural properties but also the accident kinematics. This also applies to the adaptive bumper and the active bonnet (pop-up bonnet), which are regarded beside the windscreen airbag. Those systems have been assessed individually and in combination. The consideration of the kinematics influence requires additional simulations with revised models. Figure 7 shows the modified simulation model of the experimental vehicle for a combination of adaptive bumper and active bonnet.

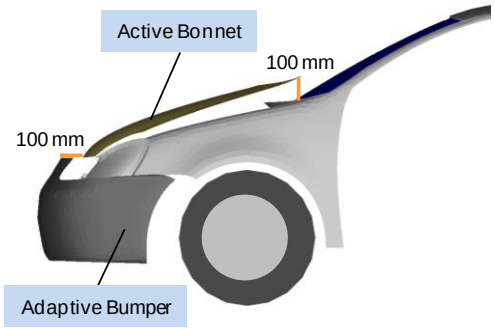


Figure 7. Simulation of adaptive bumper and active bonnet.

The retraction of the bumper happens inertia controlled with an artificially increased bumper weight. The deployment of the bonnet is rigid (locking system). With the help of coupled simulations (multi-body pedestrian models and FE vehicle models) the modelling of additional safety systems could be enhanced. The assessment of the windscreen airbag resorts to the kinematics of the active bonnet.

In contrast to the adaptive bumper, which only affects the values for the leg loading, the active bonnet leads to reduced HIC-values in the corresponding WAD-zones. If the active bonnet is part of the standard equipment of a car (e.g. current BMW 5 series and Mercedes E-class) those values can be taken from the Euro NCAP spreadsheet. Otherwise generic HIC-values have to be used for a simplified assessment. In this case a general value of 700 is defined for the fields lying on the bonnet. Only the lateral and rear boundary areas keep their values. The risk coming from the gap at the bonnet rear edge is addressed by a minimum value of 1500. The implementation of a windscreen airbag minimises the risk due to the rear bonnet gap, so that most of the front is rated “green”.

Weighting and adaptation of structural properties Within the fourth module of the assessment procedure the structural properties are combined with the accident kinematics. For the weighting and adaption of the HIC-values several factors are defined. Those factors are integrated into the calculation formula of the head index (module 5). Each factor represents one of the kinematics parameters evaluated in module 2.

The weighting of the particular vehicle fields with regard to the impact probabilities is carried out by relevance factors. Two relevance factors are defined, one for the lateral and one for the longitudinal direction. Data of the German Insurers Accident Research reveals an approximately equal distribution of the impact locations in lateral direction, so that the associated relevance factor ($R_{j,lateral}$) gets a constant value. The relevance factor in longitudinal direction ($R_{i,WAD}$) represents the impact probabilities of the particular WAD-zones at a specific collision speed.

The Euro NCAP tests are performed with definite boundary conditions, i.e. constant values for impactor velocity and angle [1]. The velocity factor ($V_{i,j}$) adapts the standardised Euro NCAP head impactor results to the maximal head impact velocities coming from the kinematics analysis. The definition of the velocity factor is based on analytical approaches and simulation results. Figure 8 illustrates the relationship between HIC-value and impact velocity. On the basis of the Euro NCAP result at the regarded test location it enables the determination of correspondent HIC-values for both reduced and increased impact velocities without conducting further tests.

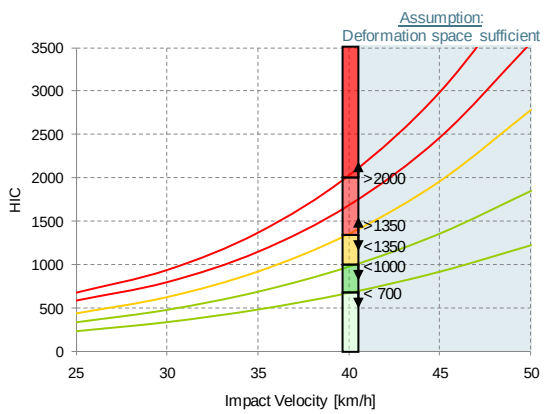


Figure 8. HIC-velocity diagram.

The correlation between head impact velocity and HIC-value is related to the stiffness at the test location. The behaviour for a stiff area with high HIC-values is more dependent on impact velocity than for a flexible area. Although the presented velocity factor definition is primarily validated for the bonnet, the stiffness based approach behind it in principle allows an application to the windscreen area. Hence, and due to the complex and unpredictable behaviour of the windscreen, no separate definition of the velocity factor is used here.

Finally, the velocity related HIC-values are adapted to the maximal head impact angels of the particular WAD-zones. This is done qualitatively by the angle factor ($W_{i,WAD}$). Criterion is the deviation from the particular Euro NCAP impactor angle. A deviation of more than 10° results in a reduction and increase respectively of the HIC-value by 10 % (Table 3).

Table 3.
Definition of angle factor

$W_{i,WAD}$	Maximal head impact angle (α_{max})	
	Child zone (50°)	Adult zone (65°)
0,9	$\alpha_{max} < 40°$	$\alpha_{max} < 55°$
1,0	$40° \leq \alpha_{max} \leq 60°$	$55° \leq \alpha_{max} \leq 75°$
1,1	$\alpha_{max} > 60°$	$\alpha_{max} > 90°$

Simulations with varied impactor angles demonstrate, that the defined adaptation is a conservative estimate. With regard to real accident events this is reasonable, since the free-flying impactors do not represent the biomechanics of the neck and upper body area.

Index calculation The assessment of the primary impact is divided into a head as well as a leg index, with the head index representing the fundamental part of the procedure. While the head index resorts to all of the previously presented modules, the assessment of the leg loading is based on a simplified index calculation that only requires the results of the legform impactor.

The assessment of the head loading is geared to the VERPS-index [2]. In contrast to the VERPS-index the simulation results are not used to define boundary conditions for separate impactor tests but for the described adaptation of existing Euro NCAP results towards the accident kinematics. Furthermore, the vehicle categorisation and segmentation as well as the simulation set-up are different. Commonalities can be found regarding the definition of the relevance factors and the underlying injury risk curve for the head loading.

The injury risk curve shown in Figure 9 assigns a probability for an AIS 3+ (Abbreviated Injury Scale) head injury to each HIC-value, i.e. a severe to fatal injury (AIS 0 = uninjured, AIS 6 = fatally injured). For an exemplary HIC-value of 1000 the risk of a AIS 3+ head injury is stated with 24 %. The appropriate function forms the basis of the

index calculation and enables the assignment of an injury risk to every vehicle field.

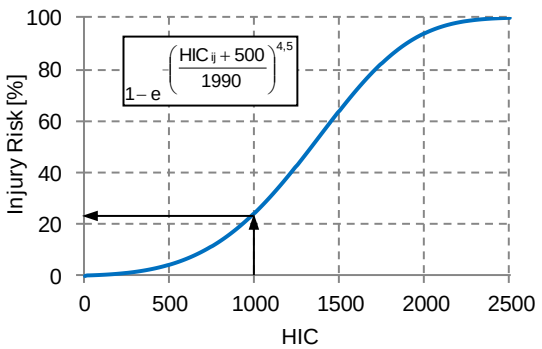


Figure 9. Injury risk curve for a AIS 3+ head injury [3].

The index calculation is based on a totals formula, which sums up the HIC-dependent injury risk of the individual vehicle fields in consideration of their relevance (Equation 1).

$$\sum_{i=1}^{10} R_{i,WAD} \cdot \left(\sum_{j=1}^{12} 1\text{-}e^{-\left(\frac{HIC_{ij} \cdot V_{ij} \cdot W_{i,WAD}+500}{1990}\right)^{4,5}} \cdot R_{j,lateral} \right) \qquad (1).$$

i	Number of WAD-zones in longitudinal direction
$R_{i,WAD}$	Relevance factor in longitudinal direction, dependent on WAD-zone
j	Number of fields in lateral direction
HIC_{ij}	Euro NCAP HIC-value in particular field of vehicle front
V_{ij}	Velocity factor in particular field of vehicle front
$W_{i,WAD}$	Angle factor in particular WAD-zone
$R_{j,lateral}$	Relevance factor in lateral direction, constant = 1/12

The head index reaches values between 0 and 1. It becomes apparent how the data out of the particular modules goes into the index calculation. The definition of the vehicle segmentation is represented by the indices i and j. By means of the relevance factor in longitudinal direction the impact probabilities due to the throw-up behaviour and the pedestrian size distribution are assigned to each of the ten WAD-zones. The velocity and the angle factor are directly integrated into the injury risk function, where they adapt the HIC-value of the individual vehicle fields to the simulated accident kinematics.

The leg index is also based upon an injury risk curve. The leg test zone within Euro NCAP comprises six fields arranged at the bumper in lateral direction [1]. The measured results require no further adaptation due to the initial contact characteristic of the leg impact. For the leg loading three injury parameters are defined by Euro NCAP, tibia acceleration, knee bending angle and knee shear displacement. For each of these parameters corresponding injury risk curves for the EEVC lower legform impactor are applied on the basis of [4] and [5]. The crucial injury criterion regarding the tibia acceleration is the tibia fracture, while for the knee bending angle and the shear displacement the risk of a collateral ligament damage and cruciate ligament damage respectively is relevant. For the index calculation the injury risk of each parameter is added up over the six leg impact areas, which are weighted equally. For the assessment only the injury parameter with the highest injury risk is considered. In case of the experimental vehicle the tibia acceleration causes the highest value. Here the injury risk for a tibia fracture is 13 % and thus results in a leg index of 0.13 for the experimental vehicle.

Since the legform impactor represents the leg of a 50 %-male the leg index can only be specified for adults. Furthermore, vehicles possessing very high bumpers are not tested with the legform impactor, so that for those vehicles no leg index values can be calculated. In general the approach is also transferable to the Flex-PLI legform, corresponding injury risk curves presupposed.

The whole assessment procedure is processed automatically with the help of a MS Excel-tool. When using vehicle-class-specific kinematics data the only input needed for the calculation of head and leg index are the impactor results stated in the Euro NCAP spreadsheet.

Assessment of active safety systems Within the index calculation module the assessment of active safety systems is regarded separately. Assessment criterion is the reduction in collision speed achieved by the particular system. The approach is based on the conducted simulations with reduced collision speed. For those reduced velocities the corresponding head index values are calculated and act as supporting points for the velocity related index calculation. By interpolation between the respective supporting points an index value can be determined for every speed reduction (Figure 10).

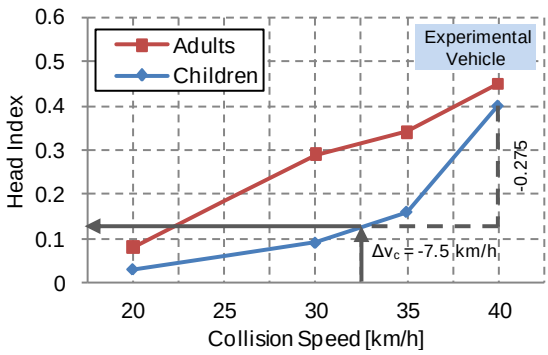


Figure 10. Velocity related index calculation.

The index values given in Figure 10 are calculated for the basic version of the experimental vehicle, i.e. no additional safety systems are implemented. Starting point for the assessment of active safety systems marks the passive safety index at a collision speed of 40 km/h, which amounts to 0.45 for adults and 0.4 for children. The additional supporting points describe the influence of a reduced collision speed on the index value. For children an assumed decrease in velocity of 7.5 km/h leads to an index reduction from 0.4 to 0.125. The children benefit from the homogeneous structural properties of the bonnet area. Here the forward displacement of the head impact locations due to the reduced collision speeds implicates no negative consequences, since the children still impact in the bonnet area. This does not apply to adults. At the initial collision speed of 40 km/h the area of the central windscreen, including the accordant A-pillar sections, is most relevant for the head impact of this pedestrian group (>60 %). Since the central windscreen is rated "green" by Euro NCAP, the resulting passive safety index is moderate. For reduced collision speeds the relevance of the critical cowl area rises due to the forward displacement of the head impact locations coming along. At a collision speed of 30 km/h more than 75 % of the adults impact in the cowl und lower windscreen area. The poor Euro NCAP results within the corresponding WAD-zones counteract the positive effect due to the reduced head impact velocity, so that adults do not benefit in the same manner as children.

The illustrated correlation between collision speed and head index value forms the interface between active and passive safety. For the application of the presented approach to a real system, the average deceleration in relevant accident scenarios has to be known. Such system-specific data can only be determined on the basis of an external test protocol. The underlying boundary conditions should correspond to the general assessment scenario, which describes a pedestrian crossing in front of a vehicle driving with a velocity of 40 km/h. Thereby, the comparability to the assessment of passive safety measures is guaranteed.

However, the general capability of different generic systems can be estimated with the help of an accident analysis and transferred into according head index values. Based on given system specifications speed reductions can be derived for all accident cases conforming to the defined scenario. To demonstrate the potential of autonomous braking, three generic systems are specified. For those systems the percentage of avoidable and unavoidable cases referred to the relevant accident events within the database of the German Insurers Accident Research is identified.

All accidents not avoided by the particular system are classified with respect to the achieved speed reduction. Furthermore, a failure rate is defined by means of the number of cases where the active safety system did not come into action.

For all three generic systems equal braking performances on dry and wet road ($a_{max,dry}$= 9.5 m/s^2, $a_{max,wet}$= 7 m/s^2) as well as an autonomous braking are assumed. Differences arise regarding the time of braking prior to the collision (TTC) and the capability of the sensor technology. A driver model is not considered since here only the general methodology for the assessment of active safety systems is to be demonstrated.

The first system defined does not work in rain and snow and brakes 500 ms prior to the collision with the pedestrian. The index calculation for this system is illustrated in Figure 11 using the example of the experimental vehicle. The assessment is exemplary conducted for adults, starting with the index value at 40 km/h (0.45). Each branch of the scheme possesses a probability based on the performed accident analysis. For the accidents mitigated by the system the analysis groups the achieved speed reductions in 5 km/h intervals and assigns corresponding percentages. For the index calculation (see Figure 10) the average speed reduction of each interval is used, which is a simplification. It would also be possible to calculate a separate index value for each individual accident case instead of grouping them. When an accident is avoided by the active safety system, the resulting injury risk of the pedestrian is zero, which leads to an analogous index value. The opposite case occurs when the system fails in a particular accident case. Here the index value is not reduced.

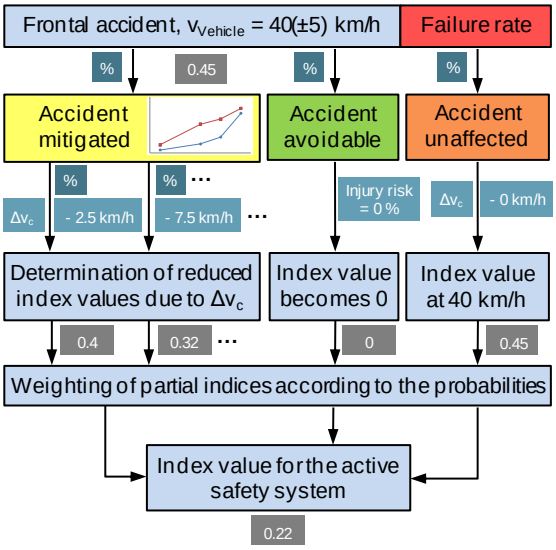


Figure 11. Assessment of an autonomous brake system (system 1, adults, experimental vehicle).

The partial indices are weighted by the assigned probabilities and add up to the total index value for system 1, which is 0.22. Compared to the passive safety index the value is halved.

The second generic system detects pedestrians in rain and snow but does not operate in darkness. The time of braking is equal to system 1. Finally an optimal braking system is defined with no restrictions on sensing and an increased braking initiation time (TTC = 700 ms). The corresponding index results for children and adults will be discussed together with the passive safety values after the presentation of the last assessment module.

Qualitative assessment of secondary impact

For the assessment of the secondary impact additional multi-body simulations have been conducted with each of the generic vehicle class representatives. A validation of the simulation models on the basis of real accident cases has shown, that characteristic parameters like the vehicle-sided contact points as well as the longitudinal and the lateral throwing range of the pedestrian can be reproduced realistically. The throwing range describes the distance between the place of collision and the final position of the pedestrian on the road in longitudinal and lateral direction.

The assessment of the secondary impact is based on three pillars, the general kinematics, the probability of an initial head contact and the contact forces during head impact. Those criteria are transferred into qualitative statements on secondary impact (moderate, critical, very critical).

The assessment of kinematics is conducted with the help of four general scenarios (Table 4), conditional on the different vehicle geometries.

Table 4.
General scenarios

Scenario	Description
1	Pedestrian is thrown forwards after the impact (distinct flight phase)
2	Pedestrian is thrown backwards over the vehicle (high velocities), dropping to the side or backwards
3	Pedestrian is thrown up on the vehicle and slips off the bonnet. (dependent on vehicle deceleration)
4	Pedestrian is immediately thrown on the ground and possibly overrun by the vehicle

Decisive for the kinematics is the ratio of the vehicle sided initial impact point to the centre of gravity height of the pedestrian as well as the overlap of pedestrian and vehicle due to the height of the bonnet leading edge. The kinematics parameters regarded for assessment of the secondary impact are the vertical and rotatory velocity components as well as the dropping angle of the pedestrian while disengaging from the vehicle. The dropping angle enables a general estimation with respect to the danger of overrun.

For the determination of the head impact probability the simulation results are analysed at the time of the initial contact of the pedestrian with the road. The corresponding snap-shot reveals the position of the pedestrian. Does the head contact the road first, i.e. in advance of the other body parts, the head loading is particularly high. Those cases are referenced to the total number of simulations with the particular vehicle class representative. Thus, the head impact probability can be specified qualitatively with the help of an assessment schema for every generic model.

The head loading due to the impact on the road is considered by the last part of the approach. For this purpose the head contact force recorded by MADYMO is analysed. Criterion forms the maximum value in z-direction, which is averaged over the respective vehicle class.

Table 5 summarises the outcome of the assessment and shows a qualitative comparison of the particular vehicle classes.

Table 5.
Qualitative comparison of the vehicle classes regarding secondary impact

Vehicle Class	Children	Adults
Compact	critical	critical
Sedan	critical	moderate
Van	critical	critical
SUV	very critical	very critical
One Box	very critical	very critical
Sports Car	moderate	moderate
moderate	critical	very critical

The vehicle classes SUV and One Box turn out to be particularly critical due to disadvantageous kinematics combined with a high head loading. The classes Compact, Sedan and Sports Car show more favourable kinematics, coming from the distinct throw-up behaviour, which trends to cause a less critical secondary impact. This does not apply in an analogous manner to the class Van. Here the steeper bonnet angle affects the results adversely.

A reduction in collision speed benefits the kinematics within the simulations and leads to a

decrease in altitude and throwing range. At an appropriate speed reduction the pedestrian does not disengage from the vehicle but slips off the bonnet. Overall, the probability of an initial head contact as well as the contact forces during head impact are reduced. Hence, an autonomous brake system also addresses the secondary impact, which increases its safety potential and forms an advantage compared to measures of passive safety.

INDEX RESULTS

The head index values calculated for the experimental vehicle are illustrated in Figure 12. For the sake of clarity, the results of the second generic brake system are omitted. The given correlation between head index and collision speed enables a conversion of the safety potential of passive measures into an equivalent reduction in collision speed.

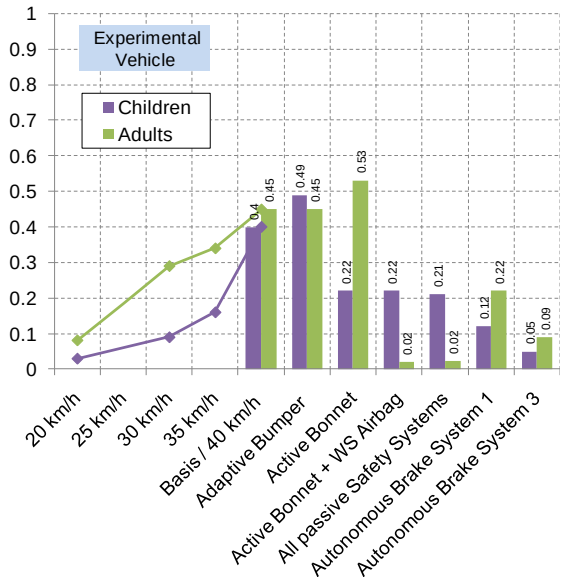


Figure 12. Head index results.

For children the sole implementation of an adaptive bumper has negative consequences for the head loading since it causes increased head impact velocities. This also applies to the active bonnet but due to the reduced HIC-values within the relevant impact area, the index can be almost halved compared to the basic value. As expected, a windscreen airbag offers no additional protection for children. The covered area is not relevant with respect to small pedestrian heights. The index value for the combination of all regarded passive safety systems lies only slightly below, coming from lower head impact angles caused by the adaptive bumper. The highest safety potential for children offer autonomous brake systems. The velocity dependent index progression illustrates, that small velocity reductions already lead to a significant decrease of injury risk. For the optimal generic braking system the index is eight times lower than the basic value. System 2 adds up to 0.24 and lies slightly above the passive safety level.

For adults the index results show a different behaviour. Due to the good Euro NCAP results of the windscreen area, the resulting safety index of the basic vehicle is comparable to the value of the children. However, the corresponding Polar-II dummy test (see next chapter) reveals, that the HIC-values for the windscreen can be considerably higher in a real-life accident. Against this background, the determined safety potential of a windscreen airbag has to be rated even higher. A windscreen airbag forms the most effective safety measure for adults, while the adaptive bumper as well as the active bonnet offer no benefit for the head loading as long as they are applied separately. The active bonnet even has a negative effect in case that no windscreen airbag is implemented, coming from the forward displacement of the head impact locations. Thereby the relevance of the critical cowl area as well as the gap at the bonnet rear edge increases significantly. At the same time, this behaviour is the reason for the high protective function of the windscreen airbag, which forms an enhancement of the active bonnet. Due to the forward displacement caused by the deployed bonnet the inflated airbag is able to cover most of the relevant impact area. Hence, the adult risk of a severe head injury amounts only to 2 %, which is confirmed by the low HIC-value measured in the corresponding Polar-II dummy test. Autonomous brake systems offer a high safety potential for adults as well. But even the value for the optimal generic braking system does not reach the level of a combination of active bonnet and windscreen airbag. As for the children the index values of the particular braking systems are strongly dependent on the sensor technology. System 2 for example reaches only a value of 0.32.

As already mentioned above, the leg index value for the experimental vehicle adds up to 0.13, representing the injury risk for a tibia fracture. To calculate a leg index value for the adaptive bumper, additional legform impactor tests have to be conducted. Since such tests have not been part of the research project, only an estimated value based on the available Polar-II dummy test results can be given. Here, the measured reduction in tibia acceleration between the basic and adaptive bumper design is 23 %. Applying this percentage decrease to the Euro NCAP legform results of the basic vehicle leads to a leg index of 0.09 for the adaptive bumper. The achieved injury risk mitigation is quite small, since the results of the basis vehicle are already on a low level due to its pedestrian friendly bumper design.

Besides the experimental vehicle further cars out of all classes have been assessed. Index values have been calculated for good as well as poor rated vehicles within Euro NCAP and under consideration of the presented additional safety systems. The assessment is carried out based on the kinematics data of the particular vehicle class representatives. The corresponding index values reflect the differences in passive safety and amplify poor test results in cases where they occur in relevant WAD-zones.

Additionally, the calculated index results enable a direct comparison of the regarded passive and active safety measures. While autonomous braking systems are beneficial for all vehicle classes, passive safety systems have to be selected and adjusted for each individual car front. The application of an active bonnet for example reduces the injury risk for children but can be disadvantageous for adults. With regard to sedan shaped vehicles adults benefit strongly from the additional implementation of a windscreen airbag, whereas it offers only little protection for SUVs. Here the impact locations of both pedestrian groups lie on the bonnet, so that the cowl area is not relevant.

In general the basic index values for children are below those for adults, since children profit from the good passive safety level in the bonnet area nowadays. For adults however the simulation data points out the A-pillars and the lower windscreen area, which need to be addressed by technical measures. Currently legal test requirements and consumer ratings insufficiently reflect the high relevance of those areas.

Autonomous braking systems offer the advantage, that they address both pedestrian groups in a similar manner. For children they show the highest safety potential of all assessed measures due to the limited impact of an active bonnet on the structural properties. This does not apply to a windscreen airbag, which is able to reduce the critical HIC-values in the cowl and lower windscreen area significantly. Apart from the class SUV an autonomous brake system has to possess a high performance as well as reliability to protect adults in the same way than a windscreen airbag does. Active systems generally require an adequate passive safety to be most effective. The more capable an active system is, the less relevant the differences in passive safety of a good and a poor rated car become.

POLAR-II DUMMY TESTS

With the help of the experimental vehicle the effectiveness of the assessed safety systems is demonstrated in tests with the Polar-II pedestrian dummy from Honda. The selected vehicle represents an average front design with a high relevance in road traffic and it is designed to current pedestrian safety standards.

Experimental Vehicle

The experimental vehicle is equipped with an adaptive bumper, an active bonnet and a windscreen airbag. These systems are implemented in a way, that the basic as well as the modified version of the vehicle can be tested. Figure 13 illustrates the modifications made to the vehicle.

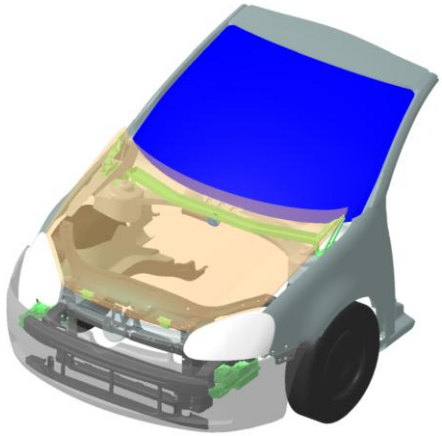


Figure 13. Implementation of safety systems.

The adaptive bumper is realised by linear guides combined with gas springs, which damp the impact of the pedestrian legs. Since both front cross members are moved together with the foam element and the covering, the existing passive pedestrian protection of the basic vehicle is preserved. The bumper is tested in deployed position, i.e. no actuating elements as well as sensor technology are used. As in the simulations its travel distance is 100 mm. Tail hooks fix the bumper after retraction.

Due to the implementation of a windscreen airbag beneath the bonnet rear edge, additional actuating elements for the lifting of the bonnet are not required. The bonnet deployment is carried out by the inflating airbag. Therefore additional hinges are applied in the area of the bonnet leading edge while the series bonnet hinges are modified in a way, that they allow an upward movement of 120 mm.

The windscreen airbag has been designed and implemented in cooperation with Takata. For the integration of the folded airbag an appropriate receptacle is necessary. It is designed as a three-piece tray that follows the curved run of the bonnet leading edge. The airbag receptacle is mounted to the strut towers and additionally fixed in the

middle. This implicates a disassembly of the wiping system. The inflator is installed central at the underside of the airbag receptacle, where an opening is provided. An identical hole pattern of airbag and inflator allows a gastight connection. The U-shaped windscreen airbag reaches at its outer side, i.e. the area of the A-pillars, till a WAD of about 2250 mm. The covering of the middle section goes till a WAD of about 2000 mm. Hence, together with the active bonnet a major part of the Euro NCAP test range is protected.

Tests

Four tests are conducted. At first the basic vehicle is tested with a collision speed of 40 km/h (basic test), corresponding to the general accident scenario used for the assessment of passive safety. This test is repeated with the modified vehicle (system test), demonstrating an optimised passive safety equipment. Finally, the benefit of a reduction in collision speed is exemplified by two additional tests carried out with the basic vehicle at collision speeds of 30 as well as 20 km/h.

Pedestrian dummy The Honda Polar-II dummy has been specially developed for the performance of full-scale tests and is supposed to reproduce the kinematics and loadings of a 50 %-male during a vehicle-pedestrian collision. It is subdivided into eight body regions with own sensing elements. The Polar-II dummy possesses a detailed reproduction of the thorax as well as a complex knee joint. The deformable tibia is designed to have human-like force-deflection characteristics in lateromedial bending up to the point of fracture. [6]

The dummy is positioned centred in walking posture with the head orientated normal to the driving direction of the experimental vehicle. The leg facing the vehicle is backwards and the wrists are tightly bound. The adjustment of the dummy is carried out according to the posture and the joint alignments respectively given in [7]. Hence, a consistent and repeatable test setup is guaranteed. The dummy is connected via a belt with a release mechanism, which is activated by running over a trigger. This happens ca. 50 ms prior to the impact, so that the dummy is free-standing at contact with the vehicle. After the primary head impact a full braking of the vehicle is initiated, corresponding to the recommendation in [7]. Conclusions regarding secondary impact cannot be drawn since the dummy is caught by a net, which is mounted 12 m behind its initial position.

Test evaluation At first the results of the basic and the system test are compared to illustrate the improvement of passive safety. The extended bumper of the modified vehicle causes a time offset regarding the hip impact, which is compensated in the following by the deployed bonnet and the inflated airbag. Therefore the primary head impact occurs almost isochronous in both tests. For the system test the head impact time is 118 ms while the basic test achieves a head impact time of 120 ms. Here, the head subsequently strikes through the windscreen and hits the instrument panel at t = 130 ms (Figure 14). The vehicle velocity reached at the basic test lies about 1 km/h above the intended collision speed.

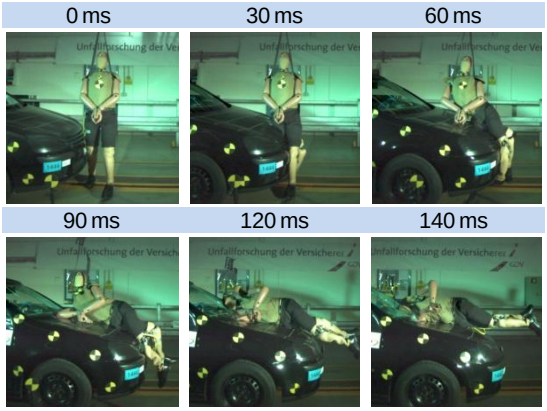


Figure 14. Basic test with a collision speed of 41 km/h.

Figure 15 illustrates the system test. The yellow black tapes sideways at the bumper visualise its retracting movement. At the same time the bonnet is lifted by 120 mm due to the inflating airbag, which subsequently absorbs the head impact.

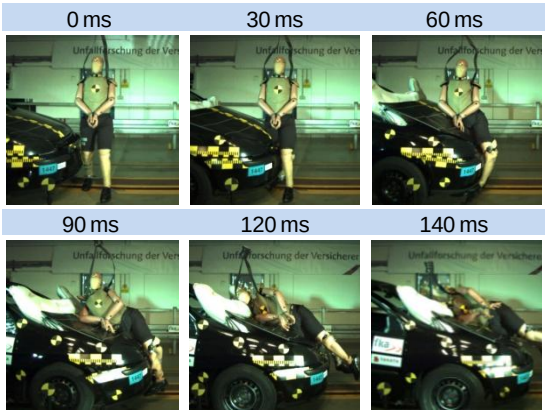


Figure 15. System test with a collision speed of 40 km/h.

The WAD for the head impact location amounts to 1940 mm in case of the basic test and 1860 mm (measured with undeployed bonnet) for the system test. The forward displacement of the head impact location is caused by the bonnet deployment. Both tests show a good conformance to the simulation results.

The measurement results confirm the high safety potential of the windscreen airbag. A comparison of basic and system test shows a reduction of the maximum head acceleration from 203 g to 72 g (Figure 16). The second peak in the acceleration curve of the basic test results from the head impact on the instrument panel. The curve occurring in the system test is smoother. Here the deceleration phase is longer and on a lower level. This is also reflected by the corresponding HIC_{15}-values. While the basic test reaches a value of 1736, the system test exhibits only a value of 566, which equals a reduction by 67 %.

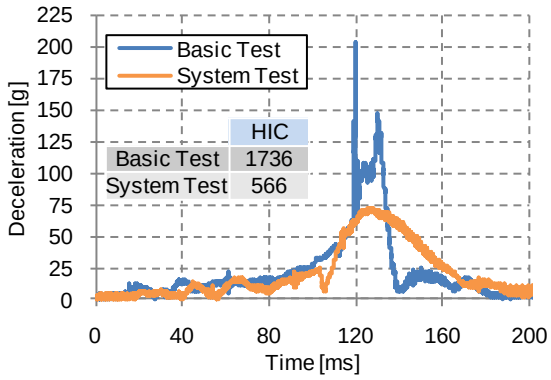


Figure 16. Head acceleration progression.

For the adaptive bumper the measurement results prove an increased safety potential as well. In Figure 17 this is exemplary demonstrated for the tibia acceleration in y-direction. The coordinate system of the dummy is oriented such that the positive x-axis is normal to the front of the dummy while the positive y-axis points laterally towards the right, i.e. towards the vehicle. Besides the tibia acceleration, also the maximum values for the resultant force as well as the bending moment in x-direction are reduced significantly. The maximum force value decreases from 4167 to 2330 N. For the bending moment a reduction from 216 to 163 N is achieved. The values for the opposite leg behave in a similar manner.

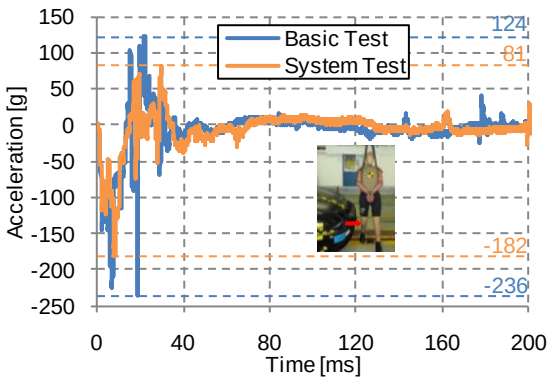


Figure 17. Tibia acceleration a_y of vehicle-oriented leg.

The benefit of a reduction in collision speed is demonstrated by two additional tests with a collision speed of 30 as well as 20 km/h. Those tests are conducted with the basic vehicle. Figure 18 shows the 30 km/h test. The reduced velocity leads to an increased head impact time of 143 ms, going along with a forward displacement of the head impact location (WAD = 1820 mm). The maximum head acceleration amounts to 162 g.

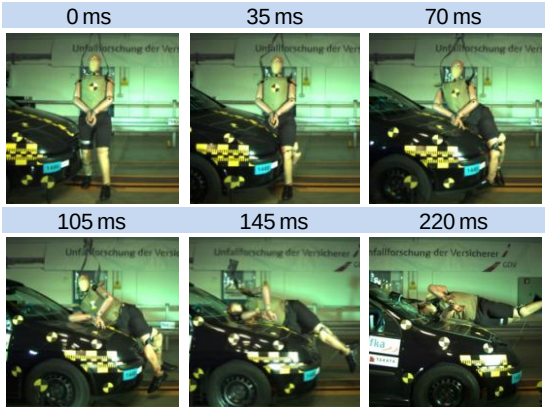


Figure 18. Test with a reduced collision speed of 30 km/h (basic vehicle).

The described effect becomes even more apparent for a collision speed of 20 km/h (Figure 19). Here the head impact time is 211 ms, which is almost 100 ms longer than for the basic test with 40 km/h. A significant difference also exists regarding the location of the head impact. Compared to the basic test the forward displacement adds up to 240 mm, resulting in a WAD of 1700 mm. This leads to a primary head impact on the bonnet rear edge, followed by an impact on the lower windscreen frame. The maximum head acceleration of 116 g lies above the value achieved by the airbag.

Figure 19. Test with a reduced collision speed of 20 km/h (basic vehicle).

Figure 20 illustrates the rise in head impact time as well as the reduced head loading due to a lower

collision speed. For all three tests conducted with the basic vehicle the corresponding head acceleration curves are given together with the HIC_{15}-values. In case of the basic vehicle a speed reduction about 10 km/h brings the HIC-value measured by the polar dummy below the common threshold of 1000. A collision with 20 km/h results in a further significant reduction of the HIC-value, which also becomes apparent within the assessment procedure. Here, the velocity related HIC-value calculated for the corresponding field of the vehicle segmentation amounts to 396, which is close to the test result of 340 and corroborates the presented approach (Figure 8).

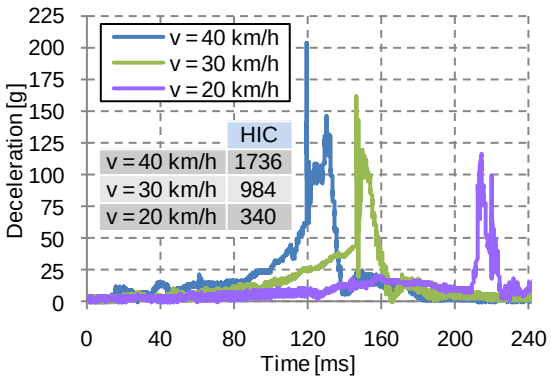


Figure 20. Velocity-dependent head acceleration progression (basic vehicle).

The low HIC-value reached in the 20 km/h test does not imply, that the safety potential regarding the primary head impact is generally higher compared to a windscreen airbag. The head impact occurred in that part of the cowl area, which achieved the best Euro NCAP test result (HIC = 1444). Therefore higher values have to be expected for other impact locations within the cowl area. Furthermore, a head impact on the rear bonnet edge, as it happens in the 20 km/h test, is always critical. For such a contact both the area of force application and the force magnitude are decisive for the arising injuries. The measurement of the acceleration at the centre of gravity of the head allows no direct conclusions regarding the area of force application. [8] Therefore the HIC does not reflect this critical loading case. The problem becomes apparent by an exemplary comparison of the resulting upper neck force measured by the dummy. For the 20 km/h test the maximum magnitude amounts to 6.5 kN while the airbag achieves a value of 2.9 kN at a collision speed of 40 km/h.

The windscreen airbag forms a very effective measure for the protection of adult pedestrians since it is able to reduce the head injury risk significantly in the most relevant impact area of sedan shaped vehicles. On the other hand, a speed reduction due to an active brake system is beneficial for both pedestrian groups as well as all affected body regions. Additionally there is a positive influence on secondary impact. Nevertheless, a hundred percent reliability cannot be guaranteed for an active system and a speed reduction by 20 km/h is a challenge which demands high system requirements. Hence, the best pedestrian protection is provided by an integrated approach, combining measures of active and passive safety in a reasonable way.

CONCLUSIONS

The presented assessment procedure brings the evaluation of active and passive safety together and allows a general estimation of the risk for a severe head injury due to the primary impact. To validate the assessment procedure index values have been calculated for good as well as poor rated vehicles within Euro NCAP and under consideration of varying additional safety systems. It could be shown that the benefit of today's measures applied to the vehicle front is limited. Legal test requirements and consumer ratings insufficiently reflect the vehicle-class-specific relevance of particular front areas. For adults the simulation data points out the cowl, the A-pillars and the lower windscreen area, which need to be addressed by technical measures. Furthermore there is no "one fits all" passive measure which performs on the same positive level at all vehicle fronts and for all pedestrian sizes. Therefore measures have to be selected and adjusted for each car front. A windscreen airbag is able to improve adult pedestrian safety significantly. Children however profit more by emergency brake systems with pedestrian detection due to the limited safety potential of a pop-up bonnet.

The effective use of active safety systems generally demands an adequate passive pedestrian safety, as shown by the velocity related index calculation within the assessment procedure. Consequently, future cars should follow an integrated safety approach. Besides the head loading, this is moreover beneficial with respect to the leg loading as well as the secondary impact, which are also considered by the assessment procedure. The performed Polar-II dummy tests demonstrate the benefit of both the regarded passive safety systems and the reductions in collision speed.

REFERENCES

[1] N.N.
European New Car Assessment Programme (Euro NCAP)
Pedestrian Testing Protocol, Version 5.1
January 2010

[2] KÜHN, M.; FRÖMING, R.; SCHINDLER, V.
Fußgängerschutz - Unfallgeschehen, Fahrzeuggestaltung, Testverfahren
Springer-Verlag, Berlin, 2007

[3] INTERNATIONAL STANDARD
Motorcycles - Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles
Part 5: Injury indices and risk/benefit analysis
Reference number: ISO 13232-5:2005(E)
Geneva, 2005

[4] MATSUI, Y.
New injury reference values determined for TRL legform impactor from accident reconstruction test
International Journal of Crashworthiness.
Vol. 8 No. 2 pp. 89-98, 2003

[5] MATSUI, Y.
Biofidelity of TRL Legform Impactor and Injury Tolerance of Human Leg in Lateral Impact
STAPP Car Crash Journal Vol45, 2001

[6] N.N.
POLAR II User's Manual, Version 2.2
HONDA R&D CO., LTD. TOCHIGI R&D CENTER
Japan, 2008

[7] N.N.
Surface Vehicle Recommended Practice
SAE International Document j2782
Dummy Task Group, Draft Recommended Practice for Pedestrian Dummy
Performance Specifications for a 50th Percentile Male Pedestrian Dummy
SAE International, 2007

[8] BOVENKERK, J.
Fußgängerschutz Testverfahren für den Frontscheibenbereich am Kraftfahrzeug
Schriftreihe Automobiltechnik
Institut für Kraftfahrzeuge, RWTH Aachen University, 2009