AN ADVANCED TESTING PROCEDURE FOR THE PEDESTRIAN-CAR-COLLISION

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ABSTRACT

Pedestrian safety is one of the most discussed topics in vehicle safety right now. There are concerns regarding the realistic implementation of real world accident issues into the EEVC WG17 component testing procedure. The European car industry presented a modified component test in relation to the self commitment.

The key advantages of the current test procedure are easy handling and high reproducibility. They are contrasted by a number of specific problems which the current component test can not address. For example it can not reproduce the effect of the shape of the car's front on the kinematics of a colliding pedestrian. The contact points of a pedestrian on a car's front are car-specific. Therefore no predetermined test zones should be used. For the determination of these car-specific test-zones numerical simulations can be used.

The presented approach for a test procedure combines numerical simulations and component tests into a hybrid-test; it is able to solve most of the mentioned disadvantages of a conventional component test without complicating it unduly. The numerical simulation allows to define the car-specific parameters of the pedestrian-car-collision in terms of localization of the contact, impact angle and velocity of the relevant pedestrian body parts. These parameters are in a second step used as input for the experimental component test. This hybrid-test reproduces real world pedestrian-car-collisions much better. It can be applied to all current and future car concepts (SUV, minivans, cross over concepts etc.) very easily. This method can also be used in the early stages of car development, to improve the preconditions for pedestrian safety. This results in better cost effectiveness.

The key ideas of the hybrid-test will be presented in the paper: Starting with a description of the pedestrian-car-collision a suitable numerical model has been created. Multi body dummies are used to collide with passenger cars under a multitude of conditions (size of the pedestrian, relative location of car and pedestrian, relative speed). The TNO-pedestrian model has been chosen. The procedure has been applied to two very distinct car models. As a result a statistical pattern describing the impact of pedestrians in a collision is generated for the two selected cars. It is shown that the results are considerably at variance to the testing conditions according to EEVC WG17.

TEST PROCEDURES FOR PEDESTRIAN SAFETY

There are two different testing philosophies in vehicle safety. Both of them have specific advantages and disadvantages.

Full-scale tests

In full-scale tests the whole accident event is realistically reproduced. In the end just the human being is replaced by an anthropomorphic test device. The needed dummies are mechanically complex. Additionally an extensive measurement technique is necessary. The layout of the experiment is very time consuming.

In the field of pedestrian safety there are no especially developed dummies to use in full-scale tests. That is the reason why conventional dummies are used. According to this lack of proper test devices the results of the experiments are not able to reproduce the pedestrian kinematics in real accidents fairly [1], [2]. Furthermore the reproducibility of full-scale tests of pedestrian-car-crashes is not guaranteed.

Possibly the use of the newly developed POLAR II-Dummy can solve those problems and lead to a different perspective of the full-scale test in the field of pedestrian safety.

Component tests

In contrast to full-scale tests component tests reproduce just a small part of the whole accident event. Therefore a lot of knowledge about the accident event is required in order to interpret the results in the right way. In simple contexts a component test is an established approach. But in kinematically complex contexts, for example, in the pedestrian accident event, the component test may be inappropriate in certain constellations.

One possible solution for these problems is the hybrid-test described in this paper. Its special characteristic is that the numerical simulation delivers the knowledge of the kinematic of a pedestrian-car-accident. Thereby the geometry of the tested car can be considered in detail. Based on these kinetic data the component tests can be performed and the structural characteristics of the tested vehicle can be analyzed.

THE HYBRID-TEST

The key idea for the presented hybrid-test-procedure is to link accident analysis, numerical simulation and component test (See Figure 1).

Due to the fact that the kinematics of pedestrians primarily depend on the vehicle front shape geometry future car models can be tested with this method as well. The kinematic data depends just secondarily on design details [3], [4]. With this method it will be possible to influence the pedestrian friendliness of a car in a very early stage of the vehicle development process.

Accident data

The analysis of real accident events allows the determination of impact constellations, impact velocities and pedestrian risk groups. This information allows

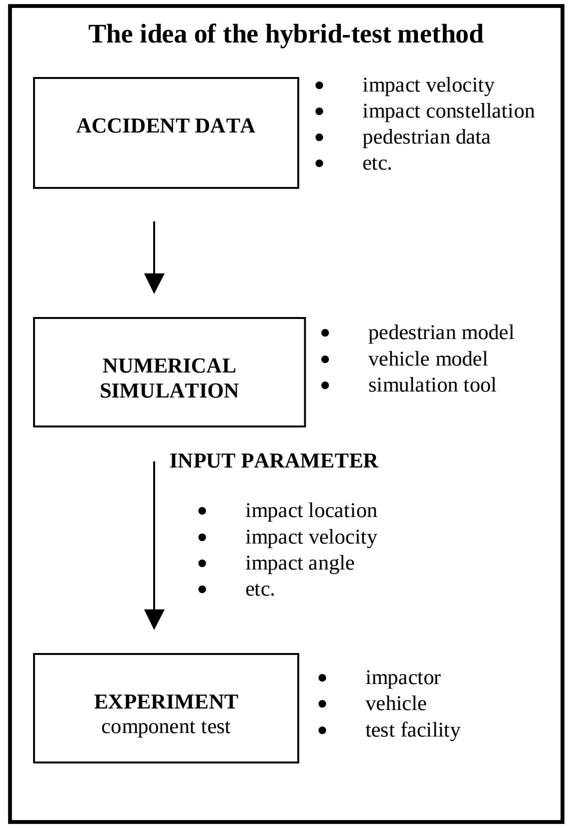

Figure 1. Methodology of the hybrid-test.

to focus on accident events, which are statistically relevant in real life. The necessary information can be extracted from accident databases, like GIDAS[1] or GDV[2] database, which cover German accident events.

In order to present the methodology and feasibility of our method, for this paper previously published statistical material in combination with our own statistical analysis of recent data is used. Our statistical analysis is based on accident data from the GDV. A more complete analysis of accident data will be published later.

[1] GIDAS – German In-Depth Accident Study, in co-operation with BASt and FAT.
[2] GDV – German Insurance Association, Institute for Vehicle Safety, Munich.

Simulation matrix

By means of numerical simulation a great number of accident constellations was simulated for each of the analyzed cars. The simulation was intended to cover as many pedestrian accident constellations as possible. The used parameters were chosen to be as independent as possible from each other.

Fixed parameters:

In order to reduce the number of parameters which have to be included simulations were conducted which show the influence on kinematics of certain settings. The parameters which only minor influence were chosen to be fixed for the purpose of our investigation. This does not imply, that they are negligible for more detailed studies, e.g. considering the biomechanics of accidents. The following parameters were selected as fixed parameters:

- *Deceleration of the car*:

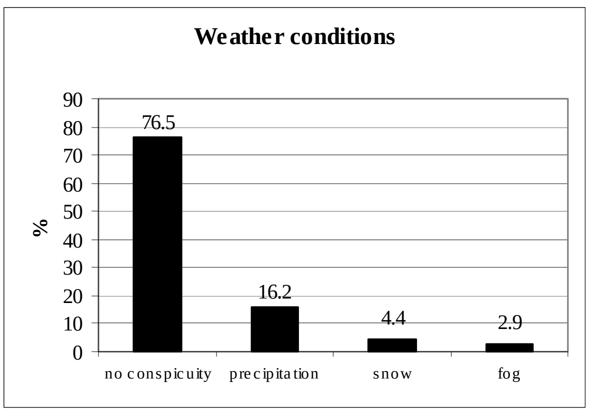

Figure 2. Weather conditions in pedestrian accidents determined from GDV data.

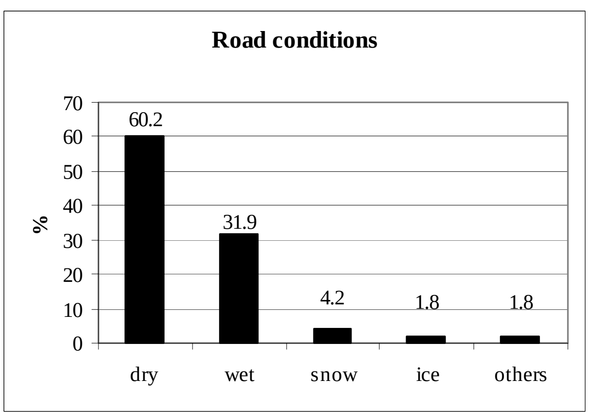

Figure 3. Road conditions in pedestrian accidents determined from GDV data.

The assumption is based on statistical analysis conducted in cooperation with the GDV. In 55 % of all analyzed cases the vehicle brakes before the crash. In combination with dry road conditions (60.2 %) and dry weather conditions (76.5 %) 8 m/s^2 are a realistic assumption for the deceleration of the vehicle in the simulation.

- *Vehicle pitch during deceleration (pitch angle):*

The vehicle pitch during braking is vehicle specific predefined. For the vehicle A 0.04 m were used, for vehicle B 0.05 m (See Figure 9). This definition corresponds to results of experiments [5].

- *Position of the pedestrian relative to the car:*

The most common impact location of pedestrians at vehicles is the vehicle front. In 67.1 % (See Figure 4) of the cases the front of the vehicle is the initial impact zone for the pedestrian. This constellation leads also to the most serious injuries [6]. In 81.8 % (See Figure 5) of the cases pedestrians are crossing the road, so the car will hit the side of the pedestrian at an angle of approximately 90° (see also [7], [8]). The simulation is focussed on the impact of the right half of the vehicle front against the left side of the pedestrian. That means the constellation represents a pedestrian, who is crossing a road from the right side to the left (See Figure 9). The obtained impact locations can afterwards easily be mirrored to the left half of the vehicle front by using the vehicle symmetry.

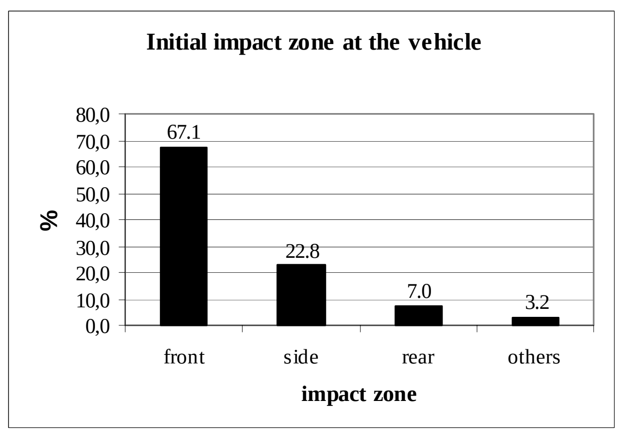

Figure 4. Initial impact zones at the vehicle in pedestrian accidents determined from GDV data.

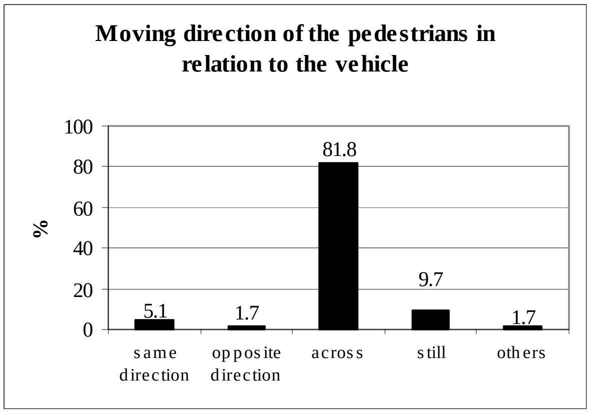

Figure 5. Moving direction of the pedestrians determined from GDV data.

- *Position of arms and legs of the pedestrian model:*

The simulations were conducted with a pedestrian in a walking position. Especially, the position of the arms influence the kinematic of the upper body of the pedestrian. In combination with a different leg position it leads to more or less rotation of the pedestrian around the vertical axis. However in this simulation the position of arms and legs is shown to have only a minor influence on the position of the head impact location (See Figure 6).

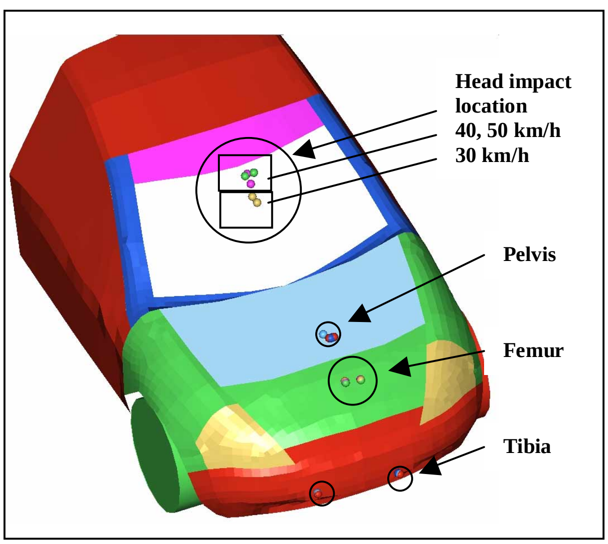

Figure 6. Only minor influence of the position of arms and legs to the head impact location.

Variable parameters of the simulation matrix:

The remaining parameters for the simulation are shown in table 1. The parameters were also obtained from accident analysis which based on GDV data. In total the combination of all chosen parameters lead to 96 different possible impact constellations.

Table 1.
Initial input parameters for the simulation and its co-domains

Input parameter	Co-domain and step size	Factor	Additional References
Vehicle impact velocity	20-50 km/h Step size: 10 km/h	4	[8], [6], [9]
Pedestrian size	4 Dummy sizes, according to TNO-Human-Models (6yo-child, 5 % female adult, 50 % male adult, 95 % male adult)	4	
Walking velocity	0 km/h and 10 km/h	2	[10], [4]
Initial impact location of the pedestrian	3 positions along the vehicle front, glancing impact included, 0.0 m; 0.4 m; 0.60 m	3	[8], [11], [9]
Simulationen per vehicle: 4*4*2*3=96			

Figure 7 shows the distribution of the vehicle impact velocity for all pedestrian accidents of the data base. Based on these data an initial impact

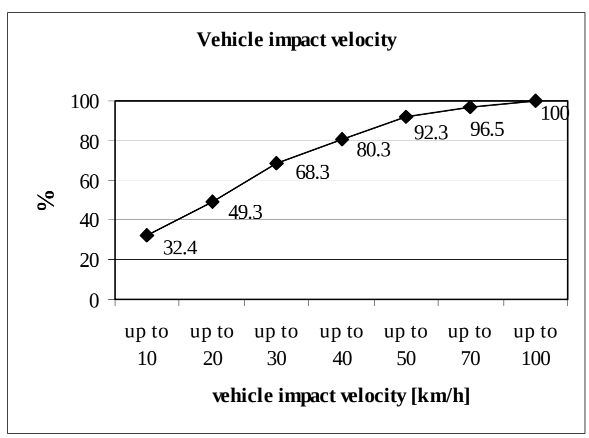

Figure 7. Vehicle impact velocity in pedestrian accidents determined from GDV data.

velocity between 20 km/h and 50 km/h was chosen.

The accident data show also that 89.6 % of all pedestrians are moving when get hit by a vehicle. Out of them 56.1 % of the pedestrians are walking and 15.6 % are running (See Figure 8).

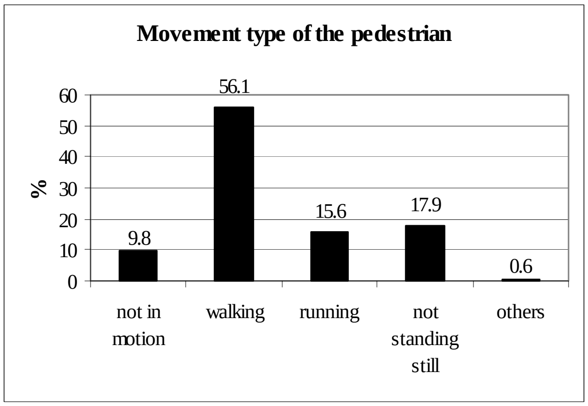

Figure 8. Movement type of the pedestrian determined from GDV data.

Numerical simulation

In our hybrid-test procedure, we intend to stay independent of a special numerical method and of special representations of car and pedestrian. In this way, the method stays open for future refinements of analysis tools. The function of the chosen simulation model has to be guaranteed by an appropriate validation. Validation criteria can be a kinematic comparison with PMHS-tests, a comparison of calculated loads with calculated loads of already validated simulation environments or a comparison with analyzed accidents concerning throwing distance and impact location at the vehicle front.

In this paper the multi body system based simulation software MADYMO was used to perform the analysis. It is a qualified tool for the numerical analysis of systems with few degrees of freedom. The human being with his stiff bones and movable joints can in a first approximation be represented by such a multi body system. The local stiffness of the vehicle structure has only a secondary influence on the impact kinematics of the pedestrian [3], [4]. That is the reason for not using a finite element (FE) analysis for this purpose.

Pedestrian model

The human models developed by TNO were used to represent the pedestrian in the simulation model [12]. They have been developed especially for pedestrian investigations and were validated extensively by TNO using PMHS data. This model is used in many other papers and is known to give good results. The TNO model represents the best choice for these purposes because of the lack of other comparable pedestrian models.

But there is still room for improvement concerning the biofidelity of certain body regions of the TNO human model. It seems that the lateral stiffness of the shoulder is too high so that the kinematic behaviour is different in comparison to reality. Furthermore the child model results from scaling the adult model without any adjustments.

With this model it is not possible - and not intended in our study - to predict injuries.

Vehicle model

Both analyzed vehicles were numerically represented as body models using rigid-FE-sets. So the models include just geometry information without any stiffness data. There is no deformation possible. In case

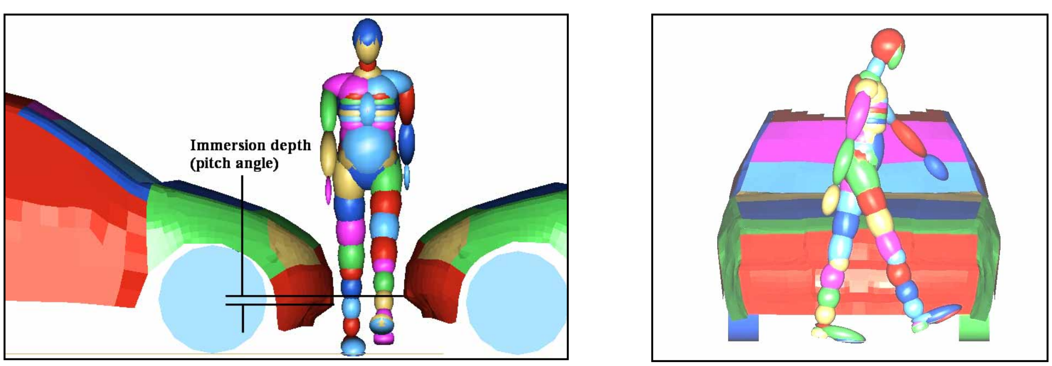

Figure 9. Influence of vehicle pitch (left side) and walking position of the pedestrian model in front of the vehicle (right side).

of contact interactions ellipsoid-node contacts were used to reproduce the stiffness characteristics. The knowledge of the global stiffness characteristics of the vehicle front is sufficient for these purposes. For defining the global stiffness of the vehicle front, EURO-NCAP-component tests were used. From the acceleration curves for the different vehicle front areas the global stiffness data was determined.

The fronts of the vehicles were divided into the following segments with the correspondent stiffness data according to test areas of EEVC WG17 (See Figure 10):

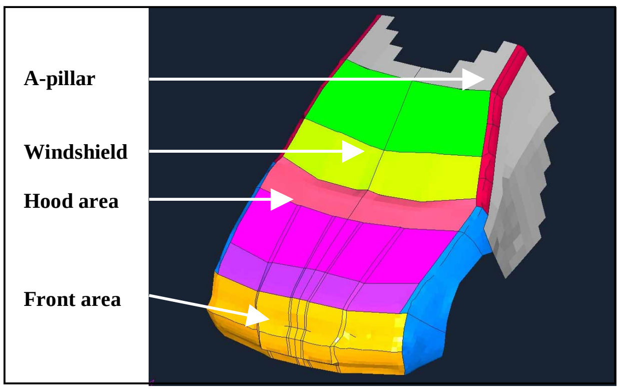

Figure 10. Segments of the vehicle front shown for vehicle B.

Validation of the simulation model

For a first validation of the simulation model (vehicle and pedestrian) the horizontal throwing distance is used. The throwing distance is an accepted measure in the field of accident reconstruction. In addition a real accident was analyzed and simulated to determine the quality of the model.

The calculated results were compared to throwing distances derived from carefully analyzed real accidents [13]. In Figure 11 it is clearly shown that all calculated values of the throwing distance are within both curves. In order to determine the throwing distance all four human model sizes were used at vehicle impact velocities of 30 km/h and 40 km/h. The 50 % male human model was also tested at 20 km/h and 50 km/h. Obviously the dissipation of energy resulting from injuries of the human model (e.g. fracture of bones) and from inelastic contact between dummy and vehicle is sufficiently correct.

Additionally, a real accident was analyzed and simulated which has been documented in great detail. The pedestrian model was scaled and the correspondent vehicle model was numerically represented. The

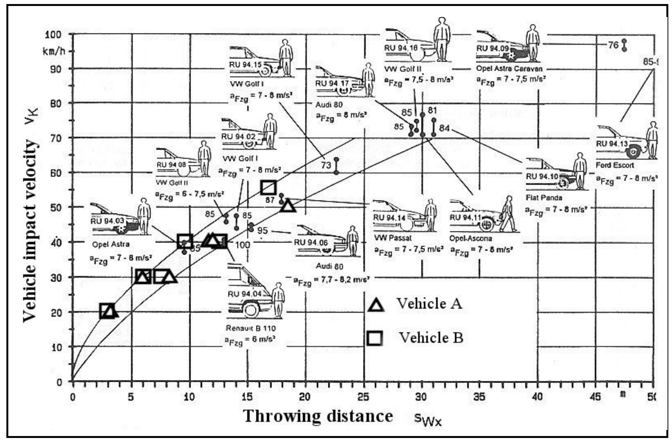

Figure 11. Calculated throwing distances and comparison with values of accident reconstruction based on [13].

results of the simulation correspond very well to the observed accident data. This confirms the quality of the simulation model. The results of the simulated accident will be published in detail later.

Component test

The legislation is asking for feasible, reproducible and significant test methods. The test tools should be robust and the results of measurements should have minimal tolerances. Within the work of EEVC working groups 10 and 17 a component test with simple but robust test forms for lower leg, upper leg and head was developed [14]. The headform and lower legform seem to be able to test the mechanical behaviour of the hit vehicle parts properly. So these testforms according to EEVC WG17 are proposed to be used also for the component test within the hybrid test. The biomechanical limits are still under discussion even for the EEVC WG17 procedure. Nevertheless, we are using these limits for our approach keeping in mind that they probably have to be revised.

COMPARISON OF THE RESULTS WITH EEVC WG17 REQUIREMENTS

In order to directly compare the results of the kinematic simulations with the EEVC WG17 conditions only the results with an impact velocity of 40 km/h were used. The other conducted simulations serve to classify EEVC WG17 conditions or other test methods and to get a broader picture of the primary impact.

Lower leg

The impact velocity against the lower leg is not significantly modified by car geometry. The impact locations of the lower leg depend directly on the posture of the pedestrian. So changes in terms of lower leg impact conditions have to be derived from results of accident analysis. Inclusion of subtle design features of the vehicle front which modify the first contact between pedestrian leg and bumper would have to be analyzed by FEA. (See Figure 12)

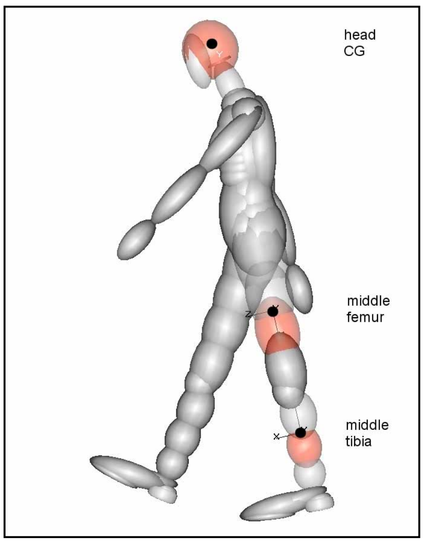

Figure 12. Human model in walking position. The analyzed body regions are marked with a dot.

Upper leg

The impact of the upper leg and the pelvis can kinematically not be described as exactly as the head or the lower leg impact. The impact velocities can not directly be converted into test conditions, because of effects due to adjacent body parts. At the time of highest loads in the femur the relative speed between car and femur is almost zero. At this time the pedestrian is sliding up onto the hood and rolls around the bonnet leading edge. Test conditions for a modified test procedure can only insufficiently be derived for the upper leg/pelvis using this simulation model. So at this point no vehicle shape dependent test condition could be created. The question occurs whether the upper legform test really represents real life. (See Figure 12)

Head impact

Head impact location

The simulations show that EEVC WG17 in many cases does not properly represent the wrap around distance of pedestrians hitting the front of a vehicle. This results in large differences between the calculated head impact location and the head impact areas according to EEVC WG17 (fig. 13). Already a 50 % human model can encounter head impact at WAD > 2.1 m at 40 km/h. The WAD is vehicle specific. For vehicle B the WAD for adults (5 %, 50 %, 95 %) is in the range of 1.57 m < WAD < 2.37 m. For vehicle A the WAD for adults is in the range of 1.63 m < WAD < 2.41 m.

The WAD for children differs even more between both vehicles than those for adults. For vehicle A the WAD is in the range of 1.27 m < WAD < 1.39 m. For vehicle B the WAD is just in a range of 1.16 m < WAD < 1.29 m. These results can be explained by different vehicle front geometries. The more curved front shape of vehicle A permits an easier slide up onto the hood. That leads to larger WAD values for vehicle A.

The impact location area for the child headform according to EEVC WG17 meets the calculated results for both analyzed vehicles.

In contrast to the child impact zone the impact zone for the adults can clearly exceed a WAD of 2.1 m. There is a high probability for head impact in the windshield area for smaller vehicles. Even if a 5 % female pedestrian is hit by a car at 40 km/h, the impact location of the head can already be in the windshield area. The upper windshield frame can also be touched by a pedestrian's head if it is located within the WAD of 2.4 m. (See Figure 12)

Head impact angle

The head impact angle is described by a weighted average $\overline{\varphi}_{Head}$[3] of all calculated head impact angles at a vehicle impact speed of 40 km/h.

[3] The exact weighting procedure will be discussed in a separate paper.

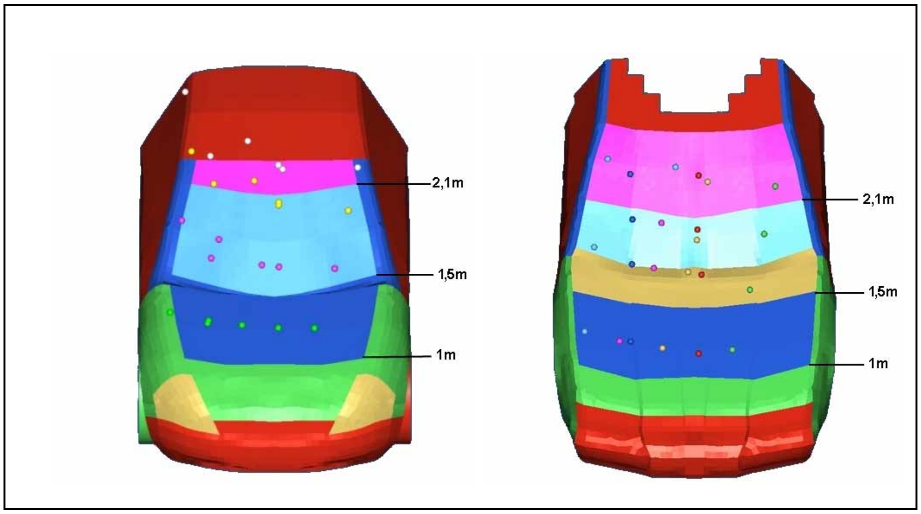

Figure 13. Impact test zones according to EEVC WG17 (excluding the windshield area) for vehicle A and vehicle B in comparison to calculated head impact locations at a vehicle impact speed of 40 km/h.

Table 2.
Calculated kinematic factors (f_k) and wrap around distances (WAD)

	H [m]	**Vehicle A**		**Vehicle B**	
		WAD [m]	f_k = WAD/H	WAD [m]	f_k = WAD/H
6 yo-model	1.16	1.27 .. 1.39	1.09 .. 1.20	1.16 .. 1.29	1.0 .. 1.11
5 %-model	1.52	1.63 .. 1.90	1.07 .. 1.25	1.57 .. 1.80	1.03 .. 1.18
50 %-model	1.74	1.94 .. 2.13	1.15 .. 1.22	1.95 .. 2.07	1.12 .. 1.19
95 %-model	1.91	2.19 .. 2.41	1.15 .. 1.26	2.20 .. 2.37	1.15 .. 1.24

The head impact angle for the 6 year old child model is little vehicle specific. In relation to the children size different vehicle front shapes appear very similar.

The head impact angle for the adults differ more in the range of analyzed vehicles. This can be explained by the different body heights of the adults. The height varies from 1.52 m for the 5 % female to 1.91 m for the 95 % male. The length of the front hood is the key factor for the head impact angle. If the pedestrian's head hits a small vehicle the head impact angle will be relatively small in comparison to vehicles with longer front hoods or less inclined windshields.

Head impact velocity

The parameter $(v_k/v_0)_{90\%}$ indicates the value which is not exceeded in 90 % of the analyzed cases. If the number of analyzed cases is sufficient, there will be only 10 % of accident constellations which exceed the parameter v_k/v_0.

The head impact velocities of vehicle A and B differ only for the adults. The value for the children is virtually the same for both vehicles. Differences in impact kinematic appear only on taller pedestrians. The head impact velocity is smaller for vehicle A.

In general the calculated values of head impact velocity are significantly smaller than the values according to EEVC WG17. The range of impact velocities varies from $(v_k/v_0)_{90\%}$ = 0.77 for vehicle A up to $(v_k/v_0)_{90\%}$ = 0.88 for vehicle B. Both values are significantly lower than the EEVC WG17 test condition of $(v_k/v_0)_{90\%}$ = 1.0 applied to all tested cars.

Table 3.
Calculated values for head impact angle and head impact velocity at 40 km/h

		$\overline{\varphi}_{Head}$	$(v_k/v_0)_{90\%}$
Vehicle A	Child head	43.3°	0.57
	Adult head	40.3°	0.77
Vehicle B	Child head	48.6°	0.57
	Adult head	51.6°	0.88

Suggestions for an advanced testing procedure

The aim of the proposed modification of the testing procedure according to EEVC WG17 is to create realistic test conditions for all relevant forms of vehicles. The testforms and the testing procedure should be maintained. The measured answers of the head and lower leg testforms are compared to the EEVC-limits. The relevance of an upper leg test still has to be evaluated in more detail. Our preliminary results indicate, that it has to be changed considerably [15]. In this paper no verification of the limits was conducted. In general there is still the need for clarification since the limits for biomechanical loads are different from each other in various proposals for component tests [16], [17].

The calculated values of $(v_k/v_0)_{90\%}$ for the head impact velocity are vehicle specific. So a head impact test should be performed with this vehicle specific value in order to properly represent reality. The choice of a higher head impact test velocity does not lead to a larger number of protected pedestrians.

At this point we are not proposing modifications of the EEVC testforms although the need might arise. The modifications of the testing procedure refer to an adjustment of testing locations. The number of modifications increases from alternative 1 to alternative 2 and finally to alternative 3.

The question occurs whether the upper legform test is statistically relevant. This has to be resolved before the test is to be implemented into a legal procedure. At the moment, we do propose, not to include the upper legform testing procedure.

Alternative 1

The first proposed alternative is very close to the EEVC WG17 test method. Alternative 1 only considers that pedestrians are hit by the vehicle front.

This alternative deals only with adjustments of the head impact requirements. The fixed test impact zones (1.0 m, 1.5 m, 2.10 m) are maintained. The windshield area and the A-pillars are not to be tested. The values for the head impact angle and the head impact velocity are to be defined by simulations separately for child head and adult head. The initial vehicle impact velocity for the simulation is 40 km/h according to EEVC WG17.

Alternative 2

A vehicle speed of 40 km/h is defined. The head impact conditions regarding impact angle, impact velocity and impact location are calculated for adult and child. Test points should also be placed on the windshield, their exact position still has to be defined. It is not useful to test the A-pillar or the upper and lower windshield cross-members. They have to be stiff for structural reasons and are obviously dangerous for impacting pedestrians. But the probability to hit these areas is different for various car geometries, so relative judgements are possible without a test. This situation has to be reconsidered, if methods become practical to “soften” the windshield pillars and cross-members.

Alternative 3

Head impact conditions are defined separately for the child, the 5 %, the 50 %, and the 95 % adult. The vehicle impact speed and the impact orientation are chosen according to accident analysis. About ten representative impact points (excluding windshield frame) will be selected. In order to weight these test points the conditions are defined according to the representation of percentiles in European population and according to impact velocity distribution derived from accident analysis.

At present a reasonable choice between the alternatives is difficult. Practical tests will have to show how a discriminative test alternative should look like.

NEXT STEPS

In the presented paper the basic methodology of the hybrid test has been shown. Its advantages and disadvantages have been discussed and assessed. For two vehicles the procedure was exemplary described. The obtained results show the suitability of numerical simulations to produce the necessary kinematic data for a component test. The differences between the calculated results and the test requirements according to EEVC WG17 show the necessity to define vehicle specific testing conditions. This seems to be the only practical way to get closer to reality with a component test.

The results of the simulation also show the need for improved pedestrian models. Especially the shoulder, which is to stiff in lateral impact, and the scaled child model show room for improvement.

For the upper leg impact no satisfactory test conditions could be defined. Additional analysis has to be conducted in order to define a suitable test procedure. The need for a test can not clearly be based by resent accident analysis.

In a next step the calculated test conditions and the developed test alternatives will be used to conduct a component test applied to real vehicles. This work will show the effect of the test alternatives to pedestrian friendliness.

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