# REVISION OF PASSIVE PEDESTRIAN TEST AND ASSESSMENT PROCEDURES TO IMPLEMENT HEAD PROTECTION OF CYCLISTS

**Oliver Zander**
Federal Highway Research Institute (BASt)
Germany

**Michael Hamacher**
Forschungsgesellschaft Kraftfahrwesen mbH Aachen (fka)
Germany

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## ABSTRACT

Supported by field accident data and monitoring results of European Regulation (EC) No. 78/2009, recent plans of the European Commission regarding a way forward to improve passive safety of vulnerable road users include, amongst other things, an extension of the head test area. The inclusion of passive cyclist safety is also being considered by Euro NCAP. Although passenger car to cyclist collisions are often severe and have a significant share within the accident statistics, cyclists are neither considered sufficiently in the legislative nor in the consumer ratings tests. Therefore, a test procedure to assess the protection potential of vehicle fronts in a collision with cyclists has been developed within a current research project. For this purpose, the existing pedestrian head impact test procedures were modified in order to include boundary conditions relevant for cyclists as the second big group of vulnerable road users.

Based on an in-depth analysis of passenger car to cyclist accidents in Germany the three most representative accident constellations have been initially defined. The development of the test procedure itself was based on corresponding simulations with representative vehicle and bicycle models. In addition to different cyclist heights, reaching from a 6-year-old child to a 95%-male, also four pedal positions were considered. By reconstruction of a real accident the defined simulation parameters could be validated in advance.

The conducted accident kinematics analysis shows for a large portion of the constellations an increased head impact area, which can reach beyond the roof leading edge. The average values for the head impact velocity are below the vehicle speed and with regard to the head impact angles, the average values are almost exclusively below the respective pedestrian protection test angles. Based on the simulation data obtained for the different vehicle models, cyclist-specific test parameters for impactor tests have been derived, which have been further examined in the course of head and leg impact tests. In order to study the cyclist accident kinematics under real test conditions, different full scale tests with a Polar-II dummy positioned on a bicycle have been conducted. Overall, the tests showed a good correlation with the simulations and support the defined boundary test conditions.

Typical accident scenarios and simulations reveal higher head impact locations. An extended head impact area with modified test parameters will contribute to an improved protection of vulnerable road users including cyclists. However, due to significantly differing impact kinematics and postures between the lower extremities of pedestrians and cyclists, these injuries cannot be addressed by the means of current test tools such as the flexible pedestrian legform impactor FlexPLI.

Based on the findings obtained within the project as well as the existing pedestrian protection requirements a cyclist protection test procedure for use in legislation and consumer test programmes has been developed, whose requirements have been transferred into a corresponding test specification. This specification provides common head test boundary conditions for pedestrians and cyclists, whereby the existing requirements are modified and two parallel test procedures are avoided.

## INTRODUCTION

Since more than a decade, test and assessment procedures for the protection of vulnerable road users in the event of collisions with motor vehicles are well established according to Regulation (EC) No. 78/2009 within the framework of European Vehicle Type Approval (European Union, 2009) as well as in Consumer Information Programmes such as Euro NCAP (2016). However, the component test procedures carried out with impactors representing the head and lower extremities are more related to pedestrians rather than to cyclists as the second big group of vulnerable road users.

In 2015, altogether 78.176 bicyclists have been injured in road traffic injuries in Germany, thereof 383 fatally and 14.230 seriously. While for pedestrians a decrease of 40% of fatal injuries (from 900 to 537) and of 30% of severe injuries (from 11.215 to 7.792) could be observed in the years from 2001 to 2015, the number of seriously injured cyclists remained constant at a level of 14.741 in 2001 and 14.230 in 2015. However, the number of fatally injured cyclists decreased from 635 to 383 during the same time period (Statistisches Bundesamt, 2016). A contribution to the decrease of cyclist fatalities may be assumed in the increase of helmet usage frequency in particular for children of ages between 6 and 10 years (76 percent in 2015 compared to 56 percent in 2011). On the other hand, the overall bicycle helmet usage frequency was still at an unsatisfactory level of only 18 percent in 2015 (Federal Highway Research Institute BASt, 2016).

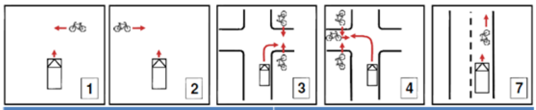
Latest plans of the European Commission in order to improve the passive safety of vulnerable road users and in particular bicyclists refer to an extension of the area for the head impactor tests. The inclusion of passive cyclist safety is also being considered by Euro NCAP and currently under review. Due to certain specific particularities, some vehicle to pedestrian and cyclist collisions are seen as remaining unavoidable regardless the introduction of automated braking initiated by a detection of pedestrians and cyclists. Therefore, an extension of the adult headform zone, including stiff structures around the windscreen frame, windscreen base and the A-Pillars, will be taken into consideration (European Commission, 2016).

## ACCIDENT ANALYSIS

Starting point for the modification of existing pedestrian test procedures towards an extension to cover a broad range of cyclist injuries is an in depth knowledge of real world cyclist accident constellations as well as the latest developments regarding cyclist safety. Based on available accident studies an in depth analysis of cyclist accidents was carried out, including the identification of relevant accident scenarios and parameters such as collision angles, vehicle and cyclist speeds, body impact locations, distribution of cyclist statures and injury causing vehicle parts. Important results are information on the injury severities and frequencies. The analysis of accidents was mainly focused on results from the German In-Depth Accident Study (GIDAS), the German Insurers Accident Research (UDV) as well as the EC funded FP 6 project APROSYS (Advanced Protective Systems).

**Accident scenarios**

A study of all vehicle to cyclist collisions within the German In-Depth Accident Database GIDAS resulted in five principal accident scenarios related to frontal collisions, as depicted in figure 1, thereof the most important ones with the vehicle driving straight ahead and the bicycle crossing:




| Scenario | Portion within GIDAS (n=2840) [all collisions with passenger cars and bicyclists] |
|---|---|
| Vehicle driving straight ahead, bicycle crossing from the right (1) | 35% |
| Vehicle driving straight ahead, bicycle crossing from the left (2) | 16.4% |
| Vehicle turning right (3) | 10.7% |
| Vehicle turning left (4) | 10.3 |
| Rear impact collision (7) | 1.1% |
| Others | 26.4% |

***Figure 1. Frontal impact scenarios with passenger cars and bicyclists (Helmer et al., 2012).***

According to the accident data the most frequent impact constellation is the vehicle impacting the bicycle with the vehicle front (80 percent with the bicycle crossing from the right and 72 percent when crossing from the left; 59 percent with the vehicle turning to the right and 70 percent with the vehicle turning to the left).This general trend can be confirmed by further studies of different accident databases. Liers (2011) found more than 80 percent of bicyclists having an accident in crossing or turning scenarios; an accident investigation carried out by Kühn et al. (2013) resulted in 76 percent of all cyclists having accidents in the mentioned scenarios. Though bicyclists are more frequently involved in longitudinal accidents than pedestrians, the bicyclists crossing from the left or right side are of the highest relevance. The above mentioned observations were, in principle, confirmed by results of the EC funded FP 6 project APROSYS. On the other hand, Carter (2005) found country specific deviations within the constellations where e.g. in Great Britain a not straight forward movement of the passenger car is of much higher importance within the accident figures than the straight forward one, while in Sweden a turning bicyclist in front of a straight forward driving passenger car has the highest relevance.

## Vehicle speeds

For the identified accident scenarios as depicted in figure 1, the distribution of the collision speeds is given in figure 2:

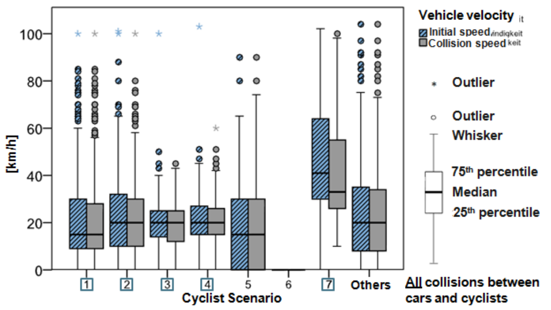



***Figure 2. Frontal impact scenarios with passenger cars and bicyclists – vehicle velocities (Helmer et al., 2012)***

While the accident scenarios 1 to 4 result in a median of approximately 20 km/h for initial as well as collision speed, scenario 7 shows significantly higher values (40 km/h initial speed and 35 km/h collision speed), also due to the higher portion of accidents in rural areas.

Alongside a limitation of the investigations to frontal impacts with MAIS2+ injury severity, the average collision speed increases to 26,8 km/h (median 23 km/h). When focusing on frontal collisions with MAIS3+ injuries the average vehicle speed increases to 36 km/h, which is below the collision speed in accidents with pedestrians, 44 km/h. (Fredriksson et al., 2012).

Altogether, the vehicle collision speeds are lower in accidents with bicyclists when being compared to those with pedestrians. This observation, that was also confirmed by Carter (2005), can be explained, amongst other things, with the higher portion of turning scenarios.

Kühn et al. (2013) found an average vehicle speed in accidents with bicyclists of 20 km/h which is the lowest one of all studies. However, it needs to be considered that the included accidents from the underlying database resulted in an injury severity of MAIS1 or MAIS2 only.

## Bicycle speeds

When moving forward, bicyclists have a significantly higher speed than pedestrians with a median of approx. 15 km/h (Helmer, 2012) regardless their injury severity, whereupon many bicyclists decelerate prior to the collision. This bicycle velocity can be confirmed by all of the considered studies and was also used during the project “SaveCAP” (Rodarius et al., 2012).

## Definition of full scale test scenarios

Full scale test scenarios that will be further taken into account need to have a high relevance in real world accident scenarios on the one hand and to be practicable in terms of simulation and hardware testing on the other hand. Altogether, three full scale test scenarios were defined, see figure 3:

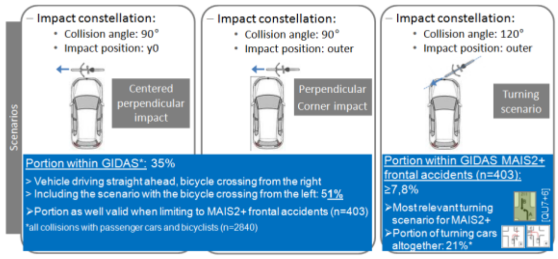



***Figure 3. Accident scenarios for simulation and full scale testing.***

While the first two scenarios follow a perpendicular impact angle, the third configuration is simulating a bicyclist moving oblique towards the passenger car, representing two relevant turning scenarios. The scenario “centered perpendicular impact” foresees an impact of the bicyclist with first point of contact located on the longitudinal vertical vehicle centerplane. During the scenario “perpendicular corner impact” the bicyclist is impacted by the right corner of the vehicle front. The third accident scenario results out of the perpendicular corner impact by rotating the bicycle around the yaw axis of the bottom bracket by 30 degrees towards the vehicle.

As vehicle speed 35 km/h are chosen, resulting from the accident analyses covering the upper limitation of the four accident scenarios on the one hand and the impactor velocities from component testing within the European Pedestrian Safety Regulation on the other hand.

## Distribution of head impact locations, angles and speeds

A GIDAS sample investigated by Zander et al. (2012) consisting of 1414 pedestrian accidents and 2262 cyclist accidents with motor vehicles having the first contact between -85 and +85 cm along the lateral vertical vehicle plane resulted in the head of the cyclists generally impacting the vehicle front rearwards of the pedestrians’ head. A focus on accidents at a collision speed of 40 km/h or lower (1032 pedestrian accidents and 1699 cyclist accidents) emphasized this observation, as illustrated in figure 4:

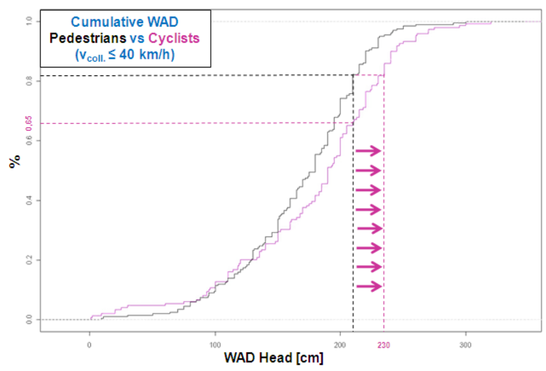



***Figure 4. Cumulative wrap around distances (WAD) of pedestrians and cyclists head impacts at collision speeds up to 40 km/h (Zander et al., 2013).***

Here, WAD 2100, as defined within GIDAS and measured at the accident site, covered approx. 80 % of all pedestrian but only 65% of all cyclist head impacts. Equal effectiveness for cyclists, i.e. coverage of 80% of all cyclist head impacts, could be expected by a rearward extension of the head impact area to WAD 2300. The general trend of cyclist head impacts occurring rearward of the pedestrian head impacts was thus confirmed.

By using human body model simulations and virtual test methods, the EC-funded FP6 project APROSYS confirmed that independent from the vehicle shape the cyclist head impact is generally located further back on a vehicle as the pedestrian head, often beyond WAD 2100. On vehicles with large bonnet leading edge heights cyclists are very often prevented from sliding up the bonnet, with head impact locations more frequently within the current pedestrian head impact zones (Watson et al., 2009).

Zander et al. (2013) reported about a series of five full scale tests with a sedan shaped car against an adult and a child dummy placed on an adult bicycle with child seat. The vehicle speed was 40 km/h in all tests with the aimed first point of contact of the adult dummy at vehicle longitudinal centerline. The tests resulted in the 50th percentile male head impact only partly covered by the currently defined adult head impact area, see figure 5. In two cases the impact locations of the adult head were significantly beyond WAD 2100.


***Figure 5. HII dummy head impact locations on the vehicle front (Zander et al., 2013).***

Full scale tests with the Polar-II dummy carried out during the SaveCAP project showed the same tendencies with WAD between 2000 and 2500 (Van Schijndel et al., 2012).

Altogether, in depth accident data, human body model simulations as well as full scale dummy tests indicate that during collisions with passenger cars, in most cases the cyclist head impact occurs rearward of the pedestrian head impact. Furthermore, the longitudinal rear head impact boundary of WAD 2100 does not sufficiently cover the cyclists' head.

A further analysis of GIDAS accident data regarding the distribution of the bicyclists' point of first contact on the vehicle front (Meinecke et al., 2007) resulted in bicyclists impacting the right vehicle front slightly more frequently than the left side. The difference between point of first contact of bicyclist and bicycle is negligible, see figure 6:

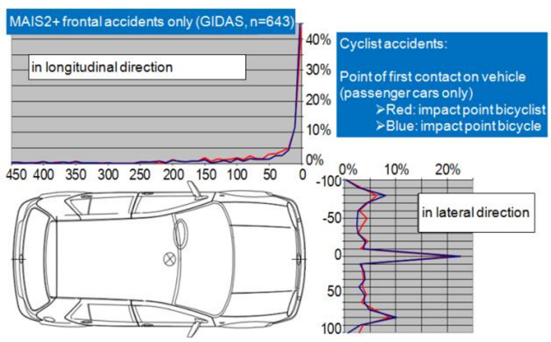



***Figure 6. Distribution of point of first contact in vehicle lateral direction (Meinecke et al., 2007).***

When looking at the head impact angles, partly significant differences between pedestrian and cyclist head impacts were found in human body model simulations from APROSYS. Simulations against MPV, Supermini and Large Family Cars resulted in shallower cyclist head impact angles compared to those of the pedestrian.

For SUV, the cyclist head impact angles were slightly steeper, but for both cyclists as well as pedestrians higher than during the simulations with the remaining vehicle categories. (Watson et al., 2009).

No huge differences between pedestrians and cyclists were found for the head impact velocities except for the large family car with significantly higher cyclist head impact velocities. (Watson et al., 2009).

## SIMULATION PROGRAMME

### Simulation setup

Aim of the present study was the development of a bicyclist test procedure by modifying the pedestrian impact parameters like impact areas, speeds and angles to cover a broad variety of cyclist accidents and impact scenarios as well. Therefore, a simulation matrix including representatives of all relevant vehicle categories, cyclist statures and bicycles was developed, also taking into account different pedal orientations, impact constellations and vehicle speeds.

The representatives of six vehicle categories developed by Hamacher (2010) along with their portions in the German vehicle fleet as of 1 January 2013 are depicted in figure 7. The categorization is, in principle, based on the vehicle front geometry and on parameters such as the height of the bonnet leading edge, bonnet angle, windscreen to bonnet angle and WAD of the bonnet rear edge.

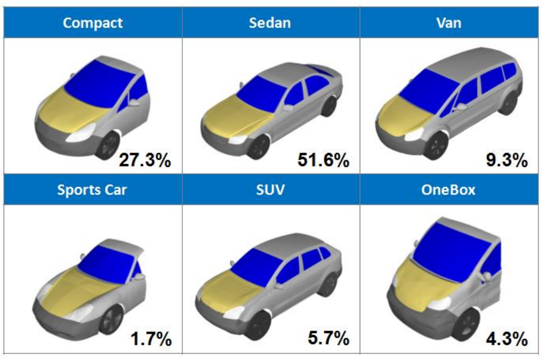



*Figure 7. Representatives of six vehicle categories for simulations (Hamacher et al., 2010).*

Within the simulations, altogether four bicyclist statures seated on representative bicycle models were used: the 6 year old child, the 5$^{th}$ female, the 50$^{th}$ male and the 95$^{th}$ male, with heights and masses as illustrated in figure 8:

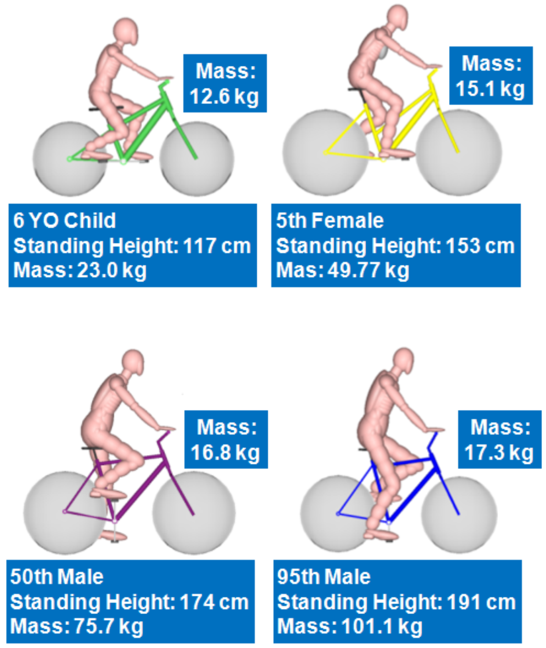



*Figure 8. Bicyclist and bicycle models for full scale human body model simulations.*

Four different pedal orientations were chosen: impacted leg to the rear, impacted leg upwards, impacted leg downwards, impacted leg to the front.

The impact constellations were derived from the accident scenarios as the centered perpendicular impact, the perpendicular corner impact and the oblique impact from the turning scenario, see figure 9. Also the speeds were taken from the in depth data where vehicle speeds of 35 km/h almost cover the average speed in accidents with MAIS3+ injuries and where bicycle speeds showed a median of around 15 km/h.

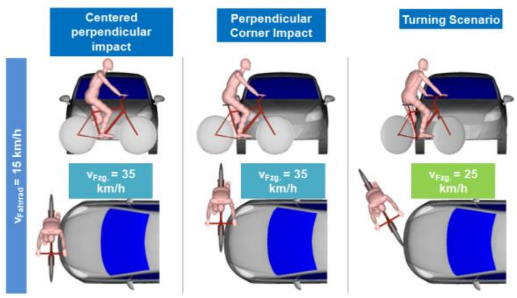



*Figure 9. Impact scenarios for simulations.*

The chosen setup resulted in altogether 288 simulations with six vehicle models, four bicyclist statures, three impact constellations and four pedal orientations.

## Simulation results

**Head impact locations** The locations for the head impacts on the six different vehicle categories are shown in figure 10. It can be seen that except for the One Box category the currently defined rear end of the pedestrian headform test zone (WAD 2100) does not cover the range of bicyclists. In particular the higher statures (50th male and 95th male) for Limousine, Compact Car and Sports Car often impact the vehicle front with the head beyond WAD 2100, up to WAD 2500 and more. This observation is also valid for Van and SUV when focusing on the perpendicular corner impact.

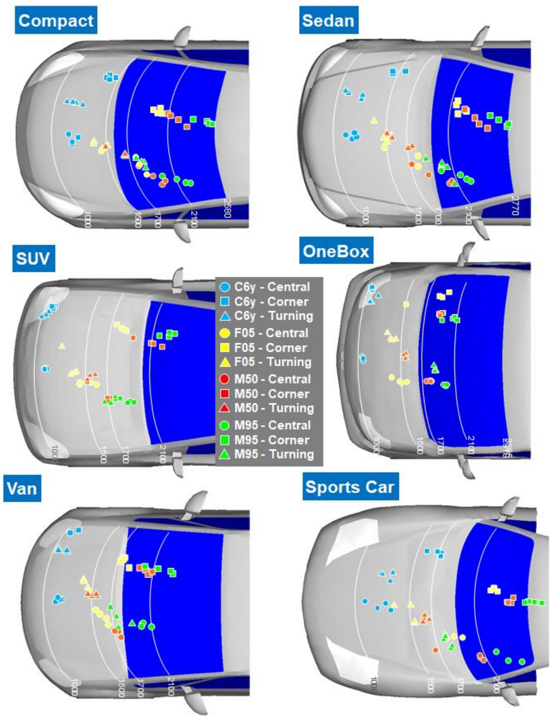



*Figure 10. Head impact locations.*

Furthermore, the wrap around distances for the corner impact are higher than for the centered perpendicular impact and the turning scenario.

A modified test procedure would therefore suggest a rearward extension of the head test area until WAD 2500 except for OneBox vehicles where the current limitation of WAD 2100 could be sufficient.

**Head impact velocities** The relative head impact velocities for the perpendicular simulation setups show a certain variety starting between 10 km/h and 45 km/h with average speeds between 28 km/h for the SUV and 32 km/h for the Sports Car (figure 11). Except for the OneBox category, all vehicles show a slight tendency of higher impact speeds with higher wrap around distance lines, but with a mostly low coefficient of determination. Besides, the impact speed seems higher for the windscreen than for the bonnet area.

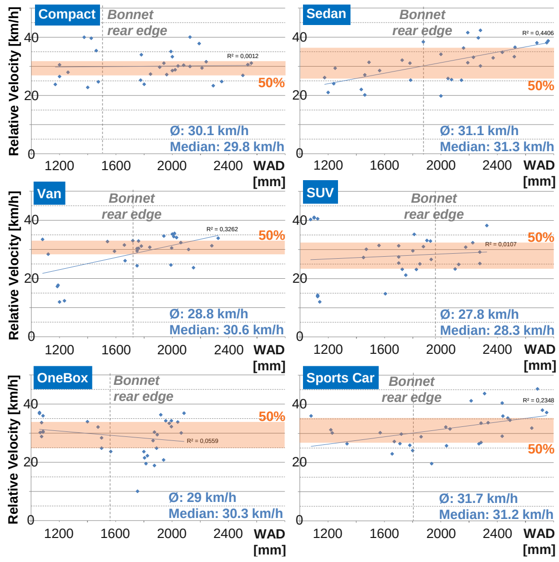



*Figure 11. Relative head impact velocities.*

The simulations carried out suggest a head impact velocity of 35 km/h, corresponding to the definition in pedestrian protection. For the OneBox category, the definition of a separate value is not necessary.

**Head impact angles** A high scatter of head impact angles can be observed over all vehicle categories and impact areas for the perpendicular simulation setups, see figure 12. The centered impacts usually result in higher head impact angles than the corner impacts, where negative angle values can also occur. Differences are partly significant, also depending on the stature of the bicyclist and the pedal orientation.

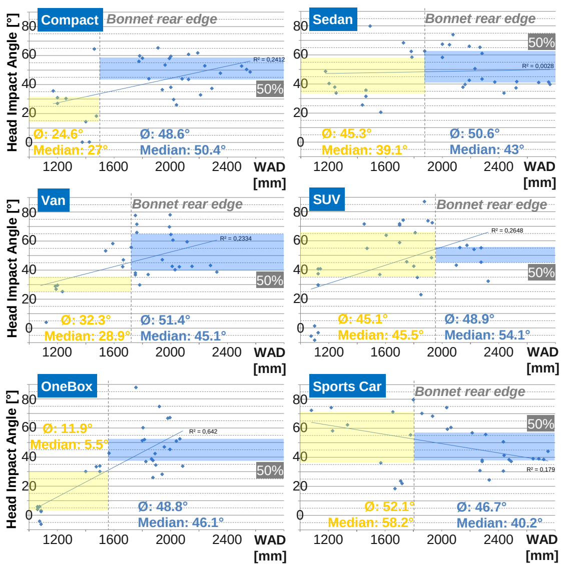



*Figure 12. Head impact angles.*

Excluding the OneBox category, the average impact angle results in 38° on the bonnet up to WAD 1700. On the windscreen and the remaining bonnet area the average angle is 51°. Thus, the results of the simulations suggest a head impact angle of 35° on the bonnet up to WAD 1700 (also taking into account weighting effects between the vehicle categories). For the windscreen area and the remaining part of the bonnet an impact angle of 50° seems appropriate. For the OneBox category, according to Figure 12, a head impact angle of 35° would also be reasonable in the bonnet area up to WAD 1700 mm. The calculated average value of 11.9° is exclusively due to the low angle values of the 6 year old child, whose head impact locations are just in front of the bonnet leading edge. Here, a head impact angle of 5° is suggested. The windscreen angle would not differ from the remaining vehicle categories and would remain at 50°.

An overview of bicyclist specific test parameters is given in table 1.

**Table 1.**
**Overview of test parameters for bicyclist test procedure.**

| Test area | Vehicle area | Impactor speed | Impactor angle |
|---|---|---|---|
| Child head area **(WAD 1000 - 1700 mm)** | Fwd BLE | 35 km/h | 5° |
| | Bonnet | 35 km/h | 35° |
| | Windscreen | 35 km/h | 50° |
| Adult head area **(WAD > 1700 - 2500 mm)** | Bonnet | 35 km/h | 50° |
| | Windscreen | 35 km/h | 50° |

**Lower extremities** A possible modification of pedestrian test and assessment procedures to address the protection of bicyclists does not refer to the head protection only but needs to also include the lower extremities. Therefore, an evaluation of the loadings on the leg of the bicyclist was also taken into account during this study. The different pedal orientations resulted in completely differing test setups and impact constellations. Due to the fact that the available pedestrian lower extremity surrogate FlexPLI is representing the knee and tibia of the $50^{th}$ male, this part of the study was also focused on the $50^{th}$ bicyclist only. As point of first contact the longitudinal vertical vehicle centerplane was chosen and thus the centered perpendicular impact. During the simulations, the primary impact revealed the high influence of the pedal orientation, the bonnet leading edge height as well as the first contact height (i.e. first contact below, above or at knee height) on the loadings of the bicyclists' leg. For the subsequent investigations, the lower pedal orientation for the impacted leg was chosen, given the highest possible comparability with the pedestrian test conditions in terms of legform orientation, see figure 13:

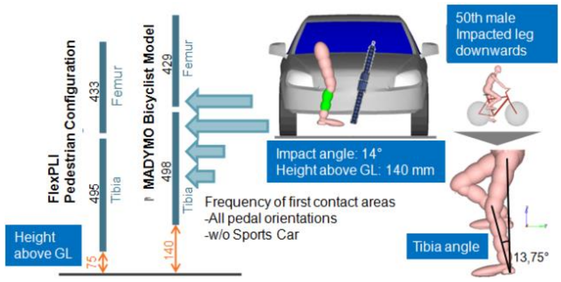



***Figure 13. Test configuration for bicyclist specific leg impact test at an impact speed of 35 km/h.***

Tests with the flexible pedestrian legform impactor FlexPLI are defined with an impact height of the lower impactor edge at 75 mm above the ground level. Pedal orientation and the use of the $50^{th}$ male cyclist (based on the FlexPLI representing the lower extremities of a $50^{th}$ male pedestrian) suggest an impactor height of 140 mm above GL with the FlexPLI inclined by 14 degrees, as depicted in figure 13.

## TEST PROGRAMME

Subsequent to the performed simulations and the derived test parameters, full scale tests using the POLAR-II pedestrian dummy were performed for a validation of the human body model simulations. In a next step, hardware impactor tests with the pedestrian child and adult headform as well as the pedestrian lower legform impactor FlexPLI were carried out. As test vehicle a popular Sedan representative for the POLAR-II and headform tests and a compact car representative for the lower legform tests were chosen.

### Full scale tests

In order to investigate the validity of the performed human body model simulations, three full scale tests with the POLAR-II pedestrian dummy seated on a representative bicycle model were performed against a sedan vehicle and compared to the kinematics and results of simultaneously conducted simulations with a $50^{th}$ MADYMO against the identical vehicle model. Like in the simulations, as impact configurations the centered perpendicular impact, the perpendicular corner impact and the turning scenario were taken, see figure 14:

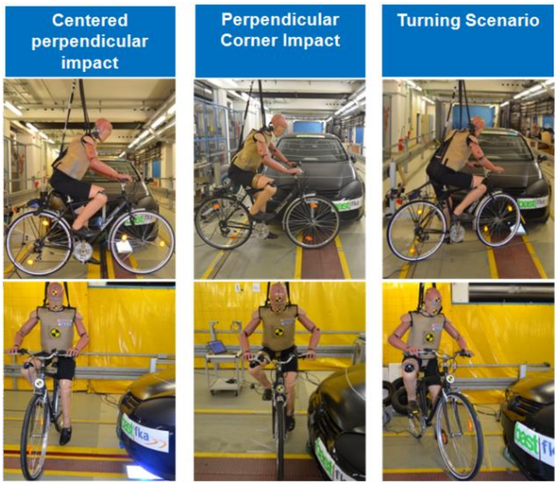



***Figure 14. Test setup for full scale vehicle tests with POLAR-II.***

In all three tests, the significant influence of the elbow on the subsequent kinematics of the bicyclist could be demonstrated. In the turning scenario e.g., when impacting the vehicle front with the forearm, the windscreen was penetrated by the elbow joint and the upper body was supported by the underlying instrument panel, avoiding a contact between head and vehicle front. This was not the case during the simulations where a head contact occurred in all three configurations. Altogether in terms of bicyclist kinematics, impact location and head impact time, a good correlation between simulation and hardware test could be observed, as exemplarily shown for the perpendicular corner impact in figure 15. Where a head impact on the vehicle front occurred, the relative head impact velocities however showed some differences.

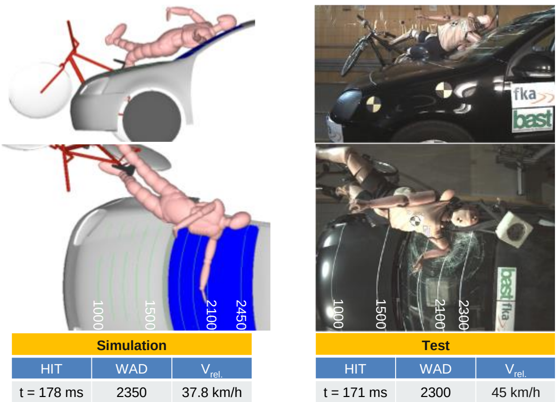


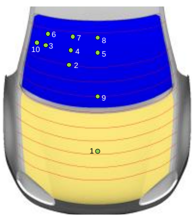

***Figure 15. Comparison between HBM simulation and hardware test for perpendicular corner impact (vehicle speed = 35.0 km/h and 35.9 km/h).***

With the comparative tests, the used simulation models could be validated regarding the bicyclists' kinematics. Therefore, they represent reasonable tools for the investigation of head impact conditions of bicyclists.

**Headform tests**

Due to an error in the script used for the post processing of the simulations, which was only detected and corrected after the head impactor test series had been carried out, the definition of the test parameters does not correspond to the derived cyclist-specific test parameters. With a test angle of 50° for the bonnet point and 70° for the windscreen points and a test speed of 40 km/h, the parameters largely reflect the Euro NCAP pedestrian protection specifications. Thus, they represent the currently highest requirements and are therefore found appropriate for examining the defined extension of the test area.

A number of 11 headform tests were carried out, thereof one test with the child headform impactor on the bonnet (impact angle 50°) and nine tests with the adult headform impactor on the windscreen (impact angle 70°). The remaining adult headform test was repeated on impact position 2 but fired at an angle of 65° (according to the current pedestrian test procedure). An overview of impact locations and test results is given in figure 16:



| Test | Pos. | Locat. | WAD [mm] | Angle | HIC |
|---|---|---|---|---|---|
| 1 | 1 | Bonnet | 1280 | 50° | 596 |
| 2 | 2 | WS | 2100 | 70° | 816 |
| 3 | 2 | WS | 2100 | 65° | 254 |
| 4 | 3 | WS | 2250 | 70° | 388 |
| 5 | 4 | WS | 2250 | 70° | 881 |
| 6 | 5 | WS | 2250 | 70° | 980 |
| 7 | 6 | WS | 2375 | 70° | 377 |
| 8 | 7 | WS | 2380 | 70° | 457 |
| 9 | 8 | WS | 2414 | 70° | 263 |
| 10 | 9 | WS | 1800 | 70° | 1666 |
| 11 | 10 | WS | 2250 | 70° | 2694 |

***Figure 16. Headform test locations and HIC results.***

The impact points in the centre of the windscreen (2,4,5) resulted in higher HIC results than the locations close to the upper and lateral windscreen frame if latter ones having at least a distance of one impactor diameter to the periphery (3,6,7,8). When located close to the A-Pillar (10) or windscreen base (9), resulting in a contact with the underlying structure, significantly higher values are obtained.

For impact position 2 the steeper impact angle produced a higher HIC result. Furthermore, the result at the center of the bonnet (1) was lower than that of a comparative test carried out on the same location with a steeper angle of 65°. The general tendency of increasing test results with increasing impact angles was also confirmed in tests within the EC funded FP7 research Project AsPeCSS (Ferrer et al., 2014).

Regarding the definition of ambient conditions for a modified impactor test procedure, the impactor test results disclosed some limitations of the suggested parameters. The minimum distance between impact points and A-Pillar should remain at one impactor diameter in order to prevent irreversible damages to the test tool without any additional benefit regarding the knowledge about the actual vehicle safety performance. Furthermore, the unrepeatable fracture behavior of windscreen glazing remained being an open issue. Figure 17 depicts the time history curves of headform impact point 2 at an impact angle of 65° (resulting in a HIC calculation of 254) and a repetition of this test resulting in HIC 1085:

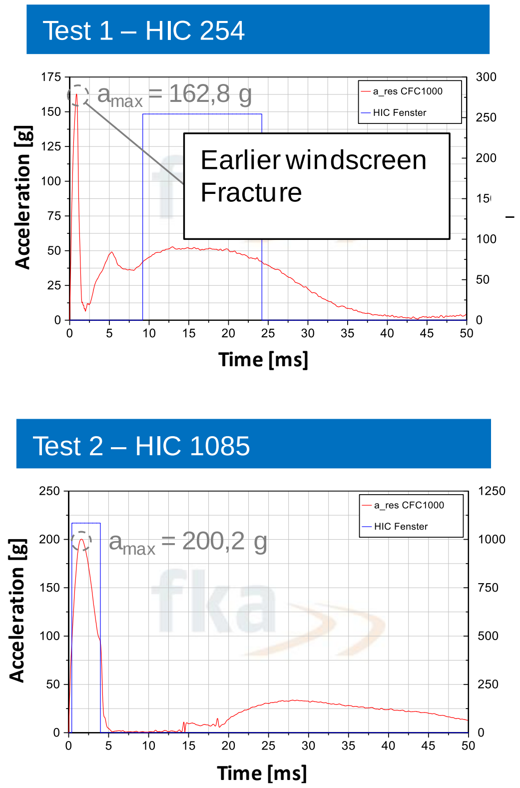



***Figure 17. Comparison of windscreen fracture behavior.***

While during the first test the windscreen fracture occurs at an earlier point in time with a lower peak acceleration, the HIC calculation is based on the subsequent deceleration phase. The second test shows the windscreen fracture later in time and the HIC calculation including this first high peak acceleration.

**Lower legform tests**

Four tests with the FlexPLI were carried out at 35 km/h against a compact car with first point of contact at longitudinal vertical vehicle centerplane and at the end of the bumper test area as defined within UN-R 127.02, taking into account angled impacts against oblique surfaces. The tests were performed using the FlexPLI baseline impactor as well as the FlexPLI equipped with an upper body mass (UBM), representing the torso of a pedestrian. All tests were performed at an impactor inclination angle of 14° and an impact height of 140 mm above GL, taking into account the simulated pedal orientation. The impact angle was realized by inclination of the vehicle by 14° around its longitudinal vehicle centerplane. The resulting height displacement at point of first contact was considered along with the determination of the actual out of the nominal impactor height. The tests were also compared to pedestrian component tests with the FlexPLI carried out during the EU-funded FP7 project AsPeCSS against the identical vehicle and impact locations (Ferrer et al., 2014).

The peak results for tibia bending moments and knee elongations (cruciate ligaments ACL/PCL and medial collateral ligament MCL) are depicted in figure 18. For both impactor variants (baseline and with UBM) and impact locations (y0 and end of bumper test area) most of the peak tibia bending moment results with the FlexPLI in perpendicular position relative to the vehicle were higher than those acquired with the inclined impactor. Only the ligament elongations were sometimes marginally higher with the impactor inclined. Since due to the pedal orientation a pre-bending of the legform would be needed for a correct setup of the knee area, the elongations could not be taken into account and the assessment had to focus on the tibia area only. Here, all results were far below the current impactor limits for legislation and consumer testing. Furthermore, from the higher impact speed within the current pedestrian test procedures (40 km/h) an additional benefit may be expected for the cyclists as well. The chosen setup and results don't show justification for an additional or modified FlexPLI impactor test to specifically cover lower extremity injuries of the cyclists.

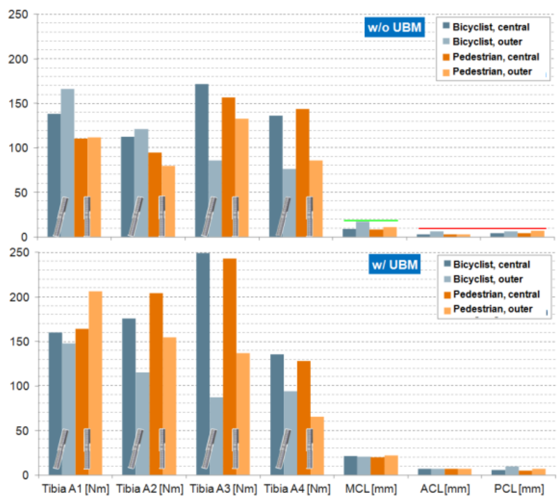



***Figure 18. Peak bending moment and elongation results in tests with FlexPLI and FlexPLI-UBM (perpendicular and inclined).***

Altogether, it is recommended to focus the revision of the pedestrian test procedures to the headform area, only. In case of any modifications of the lower legform test procedure for a more specified inclusion of cyclists, a simulation of the correct knee bending angle and influence of the bicycle would need to be taken into consideration.

## TEST PROCEDURE

Based on findings from accident research, human body model simulations and impactor tests, at first instance an impactor test procedure solely towards the protection of bicyclists in the event of a collision with passenger cars was defined. In a second step, this procedure was combined with the pedestrian test procedure following a holistic approach for an improved protection of vulnerable road users including cyclists.

### Bicyclist test procedure

Test parameters derived from simulation results conclude an extension of the headform test area starting at WAD 1000 until WAD 2500 or the windscreen rear reference line, whatever line is more forward, with headform tests at an impact speed of 35 km/h. The impact angle in the bonnet area up to WAD 1700 is set at 35° and beyond WAD 1700 at 50° related to the ground level. On the entire windscreen, regardless the longitudinal boundaries, the windscreen angle is set at 50° related to the ground level. In case of head impact points located forwards to the bonnet leading edge reference line, the impact angle is 5°, different to the Euro NCAP Pedestrian Testing Protocol (20°, 2016). Lateral limitations are the side reference lines as defined within Commission Regulation (EC) No. 631/2009 and the Euro NCAP Pedestrian Testing protocol.

Impactor tests suggest a minimum distance of one impactor diameter (165 mm) between the impact point and the solid strip along the periphery of the A-pillars in order to avoid hard contact resulting in damage of the impactor. A further limitation is set by the boundary between rear windscreen and roof with a minimum distance of half an impactor diameter to the windscreen rear reference line (WRRL), regardless its WAD, excluding the roof area from the test procedure in case of shorter vehicle front geometries. No minimum distance requirement is set between impact points and the bonnet rear reference line (BRRL).

A division between the adult and child headform test area is done at WAD 1700.

In line with Commission regulation (EC) No. 631/2009, a minimum of nine tests with the child and adult headform impactor are to be performed within the child and adult headform zone on the bonnet, thereof three in each of the two outer and in the middle third. In case of the adult headform zone located on the bonnet not providing the prescribed minimum distance of one impactor diameter between the impact points, the number of tests is to be reduced accordingly. In the windscreen area, a minimum of twelve tests is to be performed.

An overview of test areas and impact angles are illustrated in figure 19:

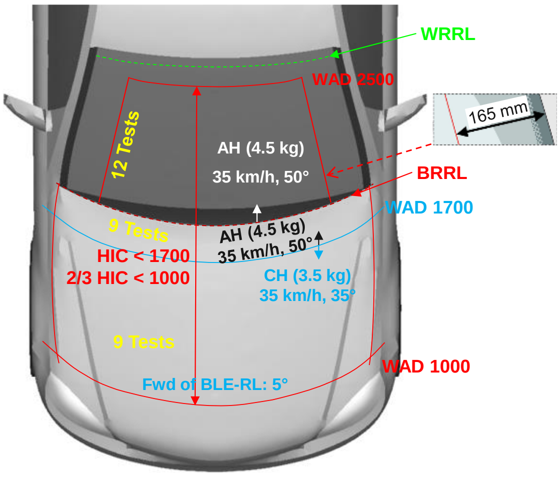



*Figure 19. Standalone bicyclist test procedure.*

The requirements related to the head performance criteria are applied to the entire headform area. In two thirds of the test area, the head injury criterion HIC must not exceed 1000. In the remaining third, the HIC must not exceed a value of 1700. The head performance zones ("HIC 1000 zone" and "HIC 1700" zone) are to be determined by the vehicle manufacturer prior to testing. Both zones do not have to, but may consist out of several parts that do not need to be directly connected with each other.

### Combined vulnerable road user test procedure

The previously described test procedure for bicyclists takes into account the findings from bicyclist accident investigations, bicyclist human body model simulations and impactor testing as boundary conditions, only. Though offering the best possible protection of bicyclists during an accident when using the currently available impactors, it is not expected these test procedures being introduced as a second vulnerable road user procedure in parallel to the existing pedestrian test procedures as prescribed in legislation as well as consumer information programmes. Therefore, there will be the need for merging both the pedestrian test procedures as well as the new procedures focusing on the protection of bicyclists to a combined vulnerable road user test procedure, aiming at the best possible protection for both road user groups.

Taking into account the expired monitoring phase for headform tests against the windscreen in Pedestrian Safety Regulation (EC) No. 78/2009, an extension of the headform zone including the windscreen in order to adequately address the protection of cyclists is indispensable. This modification is also of benefit for the pedestrians. The head impact velocity does not need to be modified and remains at 35 km/h.

Within the bonnet test area, most of the pedestrian test parameters such as impact areas, impact angles and HIC limits are taken over from the European Regulation. This results in an impact angle of 50° in the child headform area and of 65° in the adult headform area until WAD 2100, since these angles are steeper than the bicyclist angles. Beyond WAD 2100, an impact angle of 50° is defined according to the bicyclist test procedure.

A minimum of nine headform tests are to be performed with the child headform impactor in the child headform area and with the adult headform impactor in the adult headform area, thereof three tests with both impactors are to be conducted in each of the two outer and in the middle third. As for the bicyclist test procedure, if the adult headform zone on the bonnet does not provide the prescribed minimum distance of one impactor diameter between the impact points, the number of tests is to be reduced accordingly.

The HIC assessment is done separately for the bonnet and windscreen area. For the bonnet area, the combined VRU procedure follows the requirements according to Regulation (EC) No. 78/2009, where in one halve of the child headform area the head injury criterion must not exceed a value of 1000 and in the remaining half a value of 1700. Furthermore, in two thirds of the entire bonnet test area a HIC of 1000 and in the remaining third a HIC of 1700 must be met. Altogether, the test conditions and requirements on the bonnet are in line with those of the European Regulation except for an impact angle of 20° (standalone bicyclist test procedure: 5°) forwards to the bonnet leading edge reference line, derived from the Euro NCAP Pedestrian Testing Protocol (2016).

Furthermore, different to the current Pedestrian Safety Regulation, no minimum distance to the bonnet rear reference line is defined so that tests can be performed to the entire bonnet top starting at WAD 1000 and within the lateral boundaries.

Tests to the windscreen area are an extension to the current pedestrian test procedure within legislation. The test area is defined, in principle, according to the bicyclist test procedure, but due to the previously discussed windscreen fracture behaviour subdivided into an assessable and a monitoring area. The fracture behavior becomes critical especially in case of impact points not within reach of the underlying structure, and thus where the windscreen itself is the only tested element. At this point in time, repeatability issues with the fracture behavior of the glass would not allow a fair assessment and thus, these areas are suggested to be tested, as done within Phase 1 of the European Regulation, for monitoring purposes only, being compared with HIC 1000 being the value in many cases not exceeded during impactor tests, as demonstrated in the previous test programme. Along with the subdivision of the windscreen test area into an assessable and a monitoring area the testing efforts can be lowered, significantly reducing the influence of unpredictable glass fracture behavior on the test results.

The borderline between assessable and monitoring windscreen area is defined by the windscreen mid reference line (WMRL). The WMRL is defined as the WAD on where the distance between the impact point and the underlying structure, measured in impact direction (65° (WAD ≤ 2100) or 50° (WAD > 2100) on the windscreen), is 100 mm. The windscreen area located forwards to the WMRL is the assessable area while the area located rearwards of the WMRL is the monitoring area. All type approval relevant test points need to be located within the assessable area. The definition of the WMRL follows the default to green definition within Euro NCAP, where every impact point with a distance of more than 100 mm to the underlying structure, measured in impact direction of the particular headform, is defaulted green with a HIC assessment of a value less than 650 (Euro NCAP, 2016).

Where the WMRL is located rearwards of WAD 2500, tests are only performed until WAD 2500 as being the most rearward location of the headform test area.

A minimum of nine headform tests are to be performed in the assessable area of the windscreen. The number of tests may be reduced in case of smaller areas and minimum distance requirements of one impactor diameter between the impact points cannot be met otherwise.

On one third of the assessable windscreen area the HIC may not exceed a value of 1000. On the remaining two thirds the HIC may not exceed a value of 1700. As for the standalone bicyclist test procedure, these zones are to be determined by the vehicle manufacturer prior to testing. Again, both zones do not have to, but may consist out of several parts that do not need to be directly connected with each other.

In addition to the headform tests within the assessable area, a number of three impactor tests are to be performed in the monitoring area and to be compared with a nominal value of HIC 1000. The selection of impactor tests in the monitoring area should also consider potential injury causing vehicle parts such as camera or radar systems. The test results are to be recorded and to be transmitted to the responsible type approval authority. Based on the results, an adaptation of the procedure may be considered after some years.

An overview of the combined vulnerable road user test procedure, including test areas, reference lines, impact angles and performance criteria is depicted in figure 20:

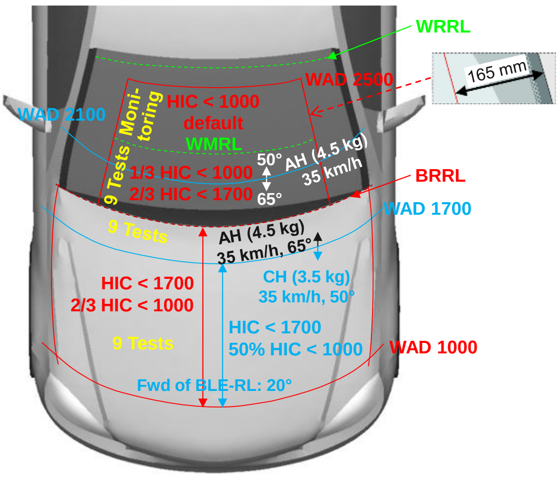



*Figure 20. Combined vulnerable road user test procedure.*

Figure 21 gives a summary of the test conditions for the combined vulnerable road user test procedure including the different impact areas and impact angles with a standardized impact speed of 35 km/h.

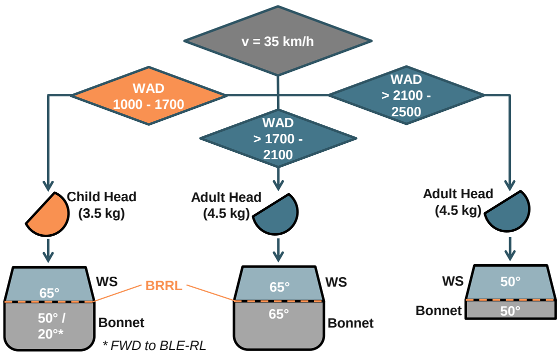



*Figure 21. Test conditions for the combined vulnerable road user test procedure.*

Independently from the surface to be tested, the child headform impactor is used in longitudinal direction between WAD 1000 and WAD 1700. The adult headform impactor is used in the area longitudinally limited by WAD 1700 and WAD 2500 or the WRRL respectively, whatever distance line is more forward. The impact angles depend on the area to be tested and the impactor to be used. For tests on the bonnet an impact angle of 50° is used for the child headform impactor. Regarding the adult headform impactor an impact angle of 65° is defined until WAD 2100, while beyond WAD 2100 an impact angle of 50° has to be considered. In case of an impact point located forwards to the bonnet leading edge reference line (BLE-RL), the impact angle is 20°. The requirements to be fulfilled on the bonnet are in line with the European Pedestrian Safety Regulation. On the windscreen, one third of the assessable area needs to fulfill HIC 1000 and the remaining two thirds HIC 1700, as summarized in table 2.

**Table 2.**
**Requirements for the combined vulnerable road user test procedure.**

| Surface | Test area | HIC |
|---|---|---|
| **Bonnet** (WAD 1000 - 2500/BRRL) | **Child head area** (WAD 1000 - 1700/BRRL) | 1000 (1/2) 1700 (1/2) |
| | **Child & Adult head area** (WAD 1000 - 2500/BRRL) | 1000 (2/3) 1700 (1/3) |
| **Windscreen** (BRRL - WRRL/ WAD 2500) | **Assessable area** (BRRL - WMRL) | 1000 (1/3) 1700 (2/3) |
| | **Monitoring area** (WMRL - WRRL/WAD 2500) | 1000 monitoring |

All described impact parameters and requirements are applicable for passenger cars. Also OneBox vehicles could be tested accordingly.

## DISCUSSION

In the present study, based on accident investigations, full human body model simulations and pedestrian full scale as well as component testing, the existing pedestrian test and assessment procedures have been revised and modified to include the protection of bicyclists as the second big group of vulnerable road users. Since a standalone passive bicyclist test procedure in parallel to the established pedestrian test procedure would require a huge amount of additional test effort, it seems more convenient to combine both sets of parameters and requirements to a combined vulnerable road user test procedure, taking into account both road user groups likewise.

For the headform procedure, comparatively limited modifications of pedestrian test parameters according to European Regulation lead to a combined procedure with manageable efforts on the one hand but with remarkable additional benefit for bicyclists while not neglecting the safety needs of the pedestrians on the other hand. Additionally to the bonnet area, an assessable windscreen area ensures a better protection of both vulnerable road user groups in case of a windscreen impact while abstaining from the pure assessment of the sometimes unpredictable glazing behaviour. However, in order to holistically protect vulnerable road users during head impacts against rearward locations of the vehicle front, a rearward limitation to the windscreen only should be suspended, including the hard and injurious areas of the roof pillar to the test area.

Investigations of the legform test procedure have revealed significantly different ambient conditions such as impact height, impact angle and also impact speed along with limited capabilities of the currently used flexible pedestrian legform impactor. For the assessment of actual knee bending or ligament elongation, a pre-bending of the legform would be necessary. The bending moments of the tibia on the other hand are in most cases in line with or below the results in pedestrian tests. The reduced vehicle speed in case of bicyclists further contribute to reduced loadings of the leg, always significantly below the currently used impactor limits. Altogether, no additional benefit is to be expected from an introduction of modified legform impactor test conditions when using the FlexPLI.

Recent accident investigations resulted in the thorax area being the third body region that should be considered in future test procedures. A study of the German In-Depth Accident Study GIDAS showed pedestrians as well as bicyclists involved in accidents with passenger cars as from model year 2006 onwards with a high portion of AIS 2+ and AIS 3+ injuries in the thorax area (Zander et al., 2016), see figure 22.

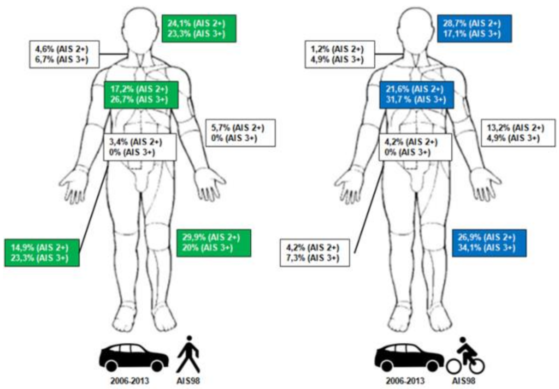



***Figure 22. AIS2+ and AIS3+ pedestrian and bicyclist injuries in accidents with modern passenger cars (Zander et al., 2016).***

A possible development of a prediction tool for injuries to the thorax of vulnerable road users is currently being investigated within the EC-funded research project SENIORS (Safety ENhanced Innovations for Older Road userS) under the HORIZON 2020 framework programme (Zander et al., 2016-2). However, a test tool ready for implementation within legislation or consumer programmes will most likely need several years of further development.

## CONCLUSIONS

Subsequent to a revision of the pedestrian safety legislation, current plans of the European Commission include, amongst other things, an extension of the pedestrian headform test area towards a better protection of bicyclists. A possible extension of the pedestrian test procedures towards an inclusion of cyclists is also reviewed by Euro NCAP. A combination of accident data, human body model simulations and full scale tests with dummies show, in principle, a need for a rearward extension of the head impact area until a wrap around distance of 2500 along with a modification of head impact angles. Since a standalone bicyclist test procedure in parallel to the existing pedestrian protocols would result in huge additional testing efforts, a combined vulnerable road user test procedure including the protection of both, pedestrians as well as cyclists, is proposed. Slight modifications of the pedestrian testing boundary conditions in combination with a rearwards extension of the head impact area and a corresponding cyclist-related impact angle of the adult headform are expected to result in the highest possible safety benefit for both vulnerable road user groups that can be contributed by means of passive vehicle safety. It is therefore suggested to introduce the modified headform test procedure within type approval procedures as well as consumer programmes. In terms of other highly affected body regions further research is needed. For lower extremities, the study showed that with the current test tool FlexPLI a simulation of a pre-bended knee as actually occurring in bicyclist impacts is not feasible. For the thorax area, the development of an injury prediction tool is currently being investigated.

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