IMPROVED SAFETY OF BICYCLISTS IN THE EVENT OF A COLLISION WITH MOTOR VEHICLES AND DURING SINGLE ACCIDENTS

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Paper Number 13-0180

ABSTRACT

Recent accident statistics from the German national database state bicyclists being the second endangered group of vulnerable road users besides pedestrians. With 399 fatalities, more than 14.000 seriously injured and more than 61.000 slightly injured persons on german roads in the year 2011, the group of bicyclists is ranked second of all road user groups (Statistisches Bundesamt, 2012). While the overall bicycle helmet usage frequency in Germany is very low, evidence is given that its usage leads to a significant reduction of severe head injuries.

After an estimation of the benefit of bicycle helmet usage as well as an appropriate test procedure for bicyclists, this paper describes two different approaches for the improvement of bicyclist safety. While the first one is focusing on the assessment of the vehicle based protection potential for bicyclists, the second one is concentrating on the safety assessment of bicycle helmets.

Within the first part of the study the possible revision of the existing pedestrian testing protocols is being examined, using in depth accident data, full scale simulation and hardware testing.

Within the second part of the study, the results of tests according to supplemental test procedures for the safety assessment of bicycle helmets developed by the German Federal Highway Research Institute (BASt) are presented.

An additional full scale test performed at reduced impact speed proves that measures of active vehicle safety as e.g. braking before the collision event do not necessarily always lead to a reduction of injury severity.

INTRODUCTION

Almost one out of ten fatally injured road users in Germany in 2011 was a bicyclist. Altogether, 76.750 bicyclists have been injured, thereof 399 fatally and 14.437 seriously (Statistisches Bundesamt, 2012). Despite this huge number of fatally and seriously injured bicyclists on german roads the average helmet usage frequency is at 6 percent only, whereas the helmet usage frequency of those bicyclists aged 10 years or younger is at 53 percent and thus significantly higher than the helmet usage frequency of the bicyclists aged 17 years or older (between 2 and 4 percent only) (Otte et al., 2008). Despite these facts, when using a bicycle helmet, the head injury severity can be reduced significantly.

After estimating the potential benefit of wearing a bicycle helmet as well as of introducing a test procedure for evaluating the passive cyclist safety potential of vehicle frontends, two different approaches for the improvement of the safety of bicyclists in the event of a collision with a motor vehicle are presented.

An additional full scale test at reduced impact speed is used for the investigation of the impact of vehicle braking before the collision event on the risk of head injuries.

BENEFIT ESTIMATION

Bicycle usage benefit estimation

Figure 1gives an overview of the distribution of the AIS head injury severity of bicyclists suffered due to a collision with a motor vehicle in Germany:

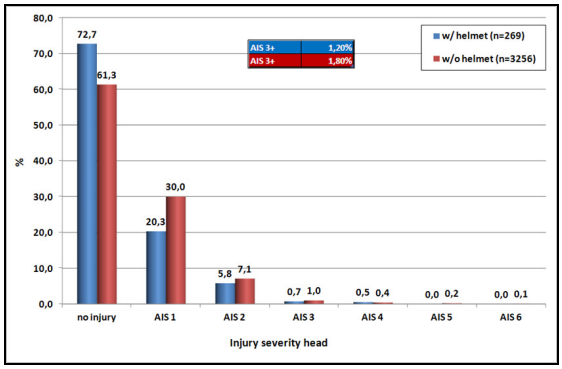

Figure 1. AIS distribution of bicyclist head injuries in Germany (Otte et al., 2008)

It can be seen that the proportion of bicyclists involved in accidents with motor vehicles not suffering any heard injury is significantly higher when wearing a helmet. Besides, the helmet usage leads to approx. 33 % reduction of the portion of AIS 3+ head injuries. Those facts indicate that bicyclists benefit in terms of both, less as well as more severe head injuries when wearing a bicycle helmet.

Test procedure benefit estimation

An investigation of the German In-Depth Accident Study (GIDAS, 2012) resulted in 3804 bicyclists involved in collisions with motor vehicles, thereof 3104 not wearing a helmet. Altogether, 9133 injuries were recorded, thereof 2451 injuries (27 percent) within vehicle zones addressed to a certain extent by the current pedestrian test procedure according to Euro NCAP (2013), and to another portion by a lateral and longitudinal extension of this test zone, having the first contact of the cyclist between -85 and +85 cm along the lateral vertical vehicle plane as shown in figure 2.

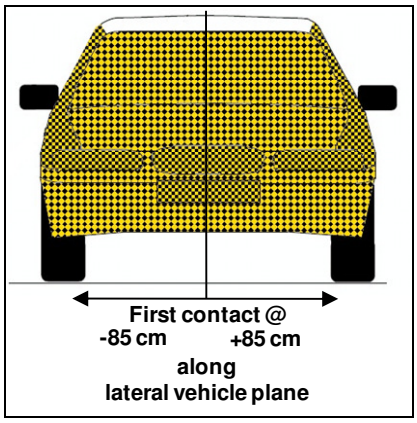

Figure 2. Definition of addressed zones on vehicle front.

442 of the detected injuries were head injuries (18 percent), thereof 424 (96 percent) suffered while the head of the cyclist being unprotected (figure 3).

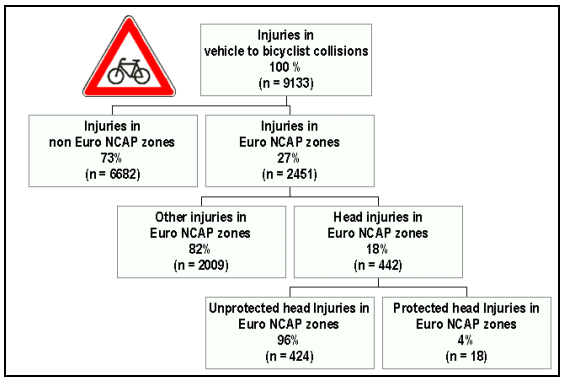

Figure 3. Portion of bicyclist head injuries covered by Euro NCAP pedestrian test zones.

Figure 4 demonstrates that 50 percent or more of all AIS 3 and AIS 4 bicyclist head injuries where the head being unprotected occurred within zones addressed by the described extended Euro NCAP testing protocol.

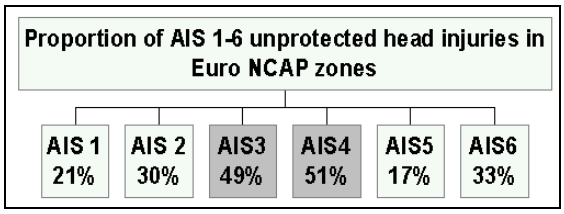

Figure 4. Portion of bicyclist head injuries covered by Euro NCAP pedestrian test zones.

APPROACHES FOR THE IMPROVEMENT OF BICYCLIST SAFETY

Within the following chapter two different approaches towards an improvement of the safety of bicyclists in the event of a collision with a motor vehicle are described. While the first one is based on the assessment of the protection potential of vehicle frontends, the second one is dealing with an enhanced safety assessment of bicycle helmets.

Vehicle based safety assessment

As a starting point for a possible introduction of a test procedure for the assessment of the safety of vehicle frontends, a comparison of pedestrian and cyclist accidents should figure out the principal differences in the impact behavior of those two groups of vulnerable road users. This can be done by means of in-depth accident data, human modeling and virtual testing as well as within full scale tests.

In-depth accident data The investigated GIDAS sample (2012) consists 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. Figure 5 illustrates the cumulative wrap around distances (WAD) for the pedestrian and cyclist head impacts at all collision speeds.

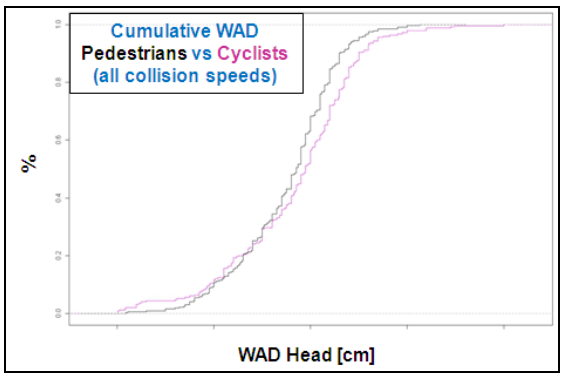

Figure 5. Cumulative wrap around distances (WAD) of pedestrians and cyclists head impacts at all collision speeds.

It can be seen that the head of the cyclists tends to generally impact the vehicle front rearwards of the pedestrian head.

Figure 6 is focusing on accidents at a collision speed of 40 kph or lower. 1032 pedestrian accidents and 1699 cyclist accidents with motor vehicles having the first contact between -85 and +85 cm along the lateral vertical vehicle plane emphasize the observation of pedestrian heads impacting more rearwards on the vehicle frontend than those of cyclists.

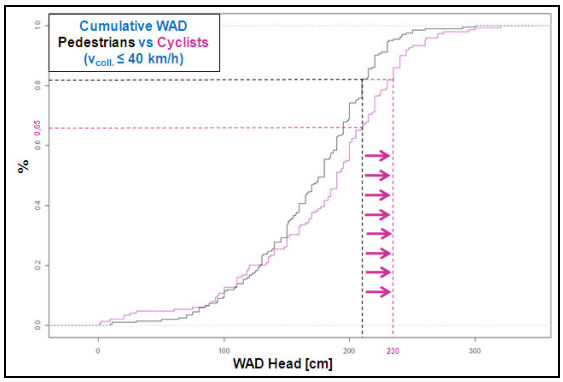

Figure 6. Cumulative Wrap around distances (WAD) of pedestrians and cyclists head impacts at collision speeds up to 40 kph.

Here, WAD 2100 covers 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. Although the definition of the wrap around distances taken from GIDAS and used within this dataset differs from the one according to the pedestrian test procedures (Euro NCAP, 2012), the trend of cyclist head impacts generally taking place rearward of the pedestrian head impacts is obvious.

Human modeling and virtual testing Within the FP6 project APROSYS (Advanced Protection Systems) funded by the European Commission, the impact conditions of pedestrians and cyclists have been studied in detail, using human model simulations and virtual test methods. Here, it has been found that independent from the vehicle shape the cyclist head impact is generally located further back on a vehicle, often beyond WAD 2100 (figure 7).

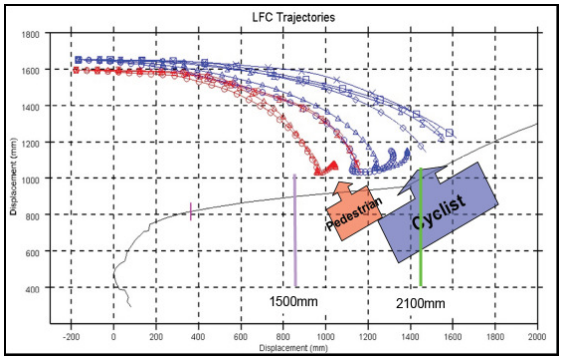

Figure 7. Head impact locations of cyclists vs. pedestrians on large family cars derived from human model simulations (Watson et al., 2009).

On the other hand, large bonnet leading edge heights tend to prevent cyclists sliding up the bonnet so that the corresponding head impact locations are more frequently within the current pedestrian head impact zones (Watson et al., 2009).

In terms of head impact angles, partly significant differences between pedestrian and cyclist head impacts were found. For multi-purpose vehicles, supermini vehicles and large family cars the cyclist head impact angles were found being shallower than those of the pedestrian. The fourth vehicle category, sports utility vehicles, produced the highest head impact angles for both, pedestrians and cyclists (figure 8):

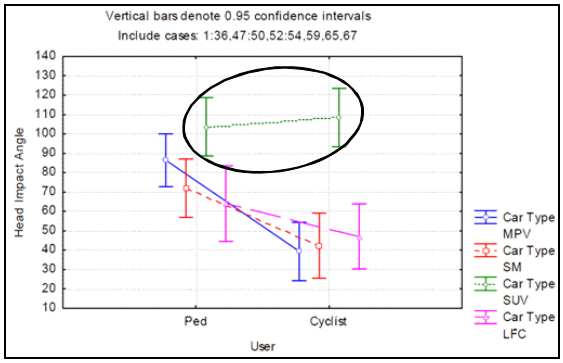

Figure 8. Head impact angles of cyclists vs. pedestrians on four different vehicle categories derived from human model simulations (Watson et al., 2009).

APROSYS also investigated possible modifications of currently available pedestrian impactors for the purpose of improving the pedestrian test procedures towards a consideration of the protection of cyclists. The current pedestrian head impactors were seen as a suitable basis for cyclist safety enhancement, but it was also stressed that the partly greater rotational motion of the cyclist head needs to be taken into account (Deck et al., 2008). Thus, new criteria for the risk of diffuse axonal injuries (DAI), subdural haematomas (SDH) and skull fractures were proposed by Deck et al. and modified head impactors, such as shown in figure 9, were developed by Brüll et al. (2009), considering amongst others the rotational aspects of head impacts of pedestrians as well as of cyclists.

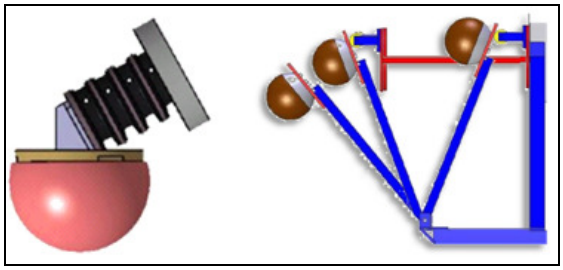

Figure 9. Head neck impactor and pendulum impactor (Brüll et al., 2009)

Full scale tests A series of five full scale tests with a sedan shaped car against an adult and a child dummy seated on an adult bicycle was carried out at BASt. While the head of the Hybrid II 50th percentile adult dummy placed on the bicycle seat was unprotected, the three years old Q3 child dummy in the child seat was wearing a bicycle helmet during all tests. Five different bicycles of different frame and wheel sizes as well as two different child seats were used. The repeatability of the test setup in terms of upmost points of the HII dummy head and the bicycle helmet was acceptable, as can be seen in figure 10. The vehicle speed was 40 kph in all tests, the aimed first point of contact of the adult dummy was at vehicle longitudinal centerline.

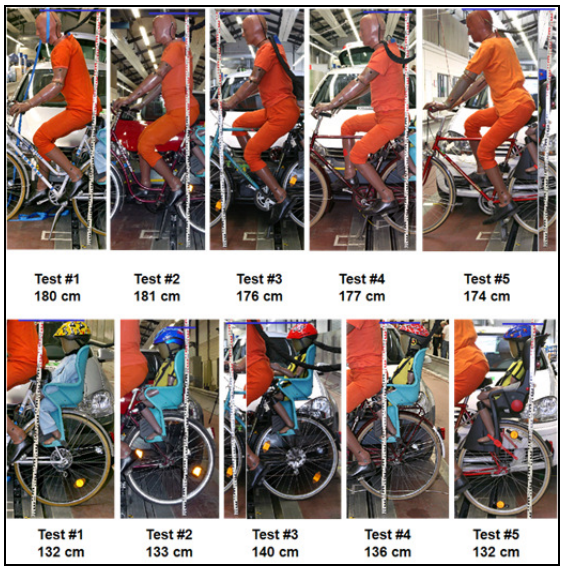

Figure 10. Test setups and HII head and Q3 helmet upmost points.

While the impact of the HII adult dummy took place on the windscreen, the Q3 child dummy impacted the car always on the bonnet (figure 11).

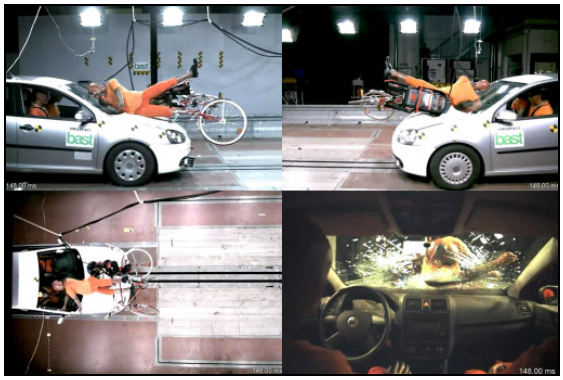

Figure 11. Different views and timing of the head impact of HII and Q3 dummy on windscreen and bonnet.

The tests showed that the 50th percentile male head impact is only partly covered by the currently defined adult head impact area. Figure 12 demonstrates that in two cases the impact locations of the adult head were significantly beyond WAD 2100. Only in one test WAD 2100 covered the adult head impact completely.

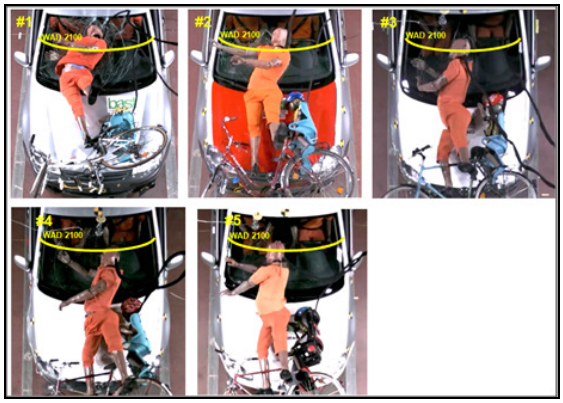

Figure 12. Head impact location of HII dummy on the vehicle front.

While WAD 2100 was shown as not being the appropriate rearward limitation for the adult head impact of bicyclists, the impact of the Q3 head occurred in four cases below WAD 1500 which was used within previous test protocols as the rearward limitation for the child head impact. In the fifth case, the child head impact was covered by WAD 1700 which is the current rearward limitation:

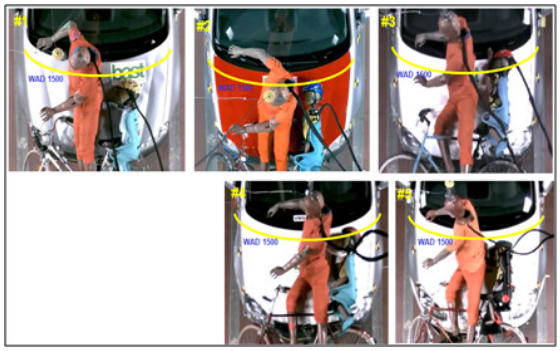

Figure 13. Head impact location of Q3 dummy on the vehicle front.

Thus, in terms of the 3 YO child, a rearward extension of the child head test area seems not necessary. On the other hand, further information on the impact conditions of other statures such as a 6YO bicyclist is needed.

<u>Summary of vehicle based assessment</u> In depth accident data, virtual testing with human body models as well as full scale dummy tests indicate that in case of a collision with a motor vehicle the bicyclist head impacting the vehicle front rearwards of the pedestrian. Furthermore, the head impact angles between bicyclists and pedestrians partly differ significantly.

Safety assessment of bicycle helmets

For the purpose of assessing the protection potential of bicycle helmets, corresponding test procedures are described amongst others within the European Standard EN 1078 (CEN, 2006-2). Modified procedures as well as more stringent requirements can be found within consumer test programmes as e.g. from ADAC (2010), Stiftung Warentest (2005) or Öko Test (2010). Supplemental test procedures, representing more realistic impact conditions, have been developed by BASt.

<u>European Standard EN 1078</u> The European Standard EN 1078 "Helmets for pedal cyclists and for users of skateboards and roller skates" contains requirements and test methods for bicycle helmets regarding their

- material
- helmet construction
- field of vision
- shock absorbing properties
- durability
- retention system properties
- labelling
- manual / information

Obviously of highest interest for the protection of cyclists in the event of a collision is the assessment of the shock absorbing properties. For that purpose, a pre-conditioned bicycle helmet impacts under a guided free fall a flat as well as a kerbstone test anvil at test speeds of 5,42 m/s and 4,57 m/s respectively, see figure 14:

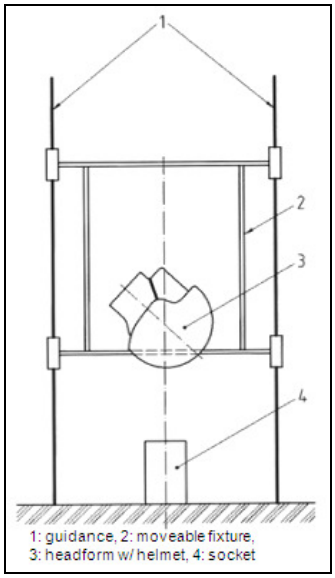

Figure 14. Test setup for the assessment of shock absorbing properties (CEN, 2006-2).

The acquired maximum peak acceleration of the headform to be used within these tests according to the European Standard EN 960 (CEN, 2006-1) must not exceed 250 g.

Consumer testing Various consumer test programmes for the assessment of bicycle helmets contain a broader variety and also more stringent requirements than the European Standard. Amongst others, within the tests according to ADAC the raised impact speed for the kerbstone test (5,42 m/s instead of 4,57 m/s) leads to higher loadings on the helmet during the test. When just fulfilling the requirement for the maximum acceleration of the headform according to the European Standard, the helmet is ranked comparatively poor within the assessment of ADAC. In order to score full points in that category, the maximum acceleration must not exceed 120 g.

Supplemental test procedures Aim of the development of additional test procedures for the safety assessment of bicycle helmets based on more stringent requirements than those described in the European Standard and consumer test programmes was the definition of more realistic accident situations of bicyclists during collisions with motor vehicles and during single accidents. Impactor tests based on the current pedestrian test procedures were carried out against a sedan shaped vehicle front. During lateral upset tests a 6YO HIII child dummy seated on a bicycle impacted with his head a simulation of road surface and kerbstone. Pendulum tests were performed as means of simulation of an overturn over the handlebar and subsequent head impact against the road surface or an obstacle. Full scale tests were performed to validate the results of the impactor tests on the one hand and to simulate a real situation as it can be actually found during vehicle to cyclist collisions. Altogether, 16 comparative tests were performed with and without applied bicycle helmet. An overview of the tests and corresponding setups is given in table 1.

Table 1.
Overview of tests according to supplemental test procedures.

# Test	Test No.	Description	Vehicle
1 Pos 1	BVGFH-C1C	Ped Pro Component Test Pos 1	Sedan
2 Pos 1 - Helmet	BVGFH-C1C-H	Ped Pro Component Test Pos 1 - Helmet	Sedan
3 Pos 2	BVGFH-C2A	Ped Pro Component Test Pos 2	Sedan
4 Pos 2 - Helmet	BVGFH-C2A-H	Ped Pro Component Test Pos 2 - Helmet	Sedan
5 Pos 3	BVGFH-C4B	Ped Pro Component Test Pos 3	Sedan
6 Pos 3 - Helmet	BVGFH-C4B-H	Ped Pro Component Test Pos 3 - Helmet	Sedan
7 Road Surface	UV6YH3F1	Lateral Upset Road surface	
8 Road Surface - Helmet	UV6YH3F2	Lateral Upset Road surface - Helmet	
9 Kerbstone	UV6YH3F3	Lateral Upset Kerbstone	
10 Kerbstone - Helmet	UV6YH3F5	Lateral Upset Kerbstone - Helmet	
11 Pendulum upright	PV6YH3-1	Overturn upright	
12 Pendulum upright - Helmet	PV6YH3-2	Overturn upright - Helmet	
13 Pendulum declined	PV6YH3-3	Overturn declined	
14 Pendulum declined - Helmet	PV6YH3-4	Overturn declined - Helmet	
15 Bonnet	GV6YH3F3	Full Scale Test Bonnet Impact	Sedan modified
16 Bonnet - Helmet	GV6YH3F4	Full Scale Test Bonnet Impact - Helmet	Sedan modified
15 Road Surface	GV6YH3F3	Full Scale Test Secondary Impact	Sedan
16 Road Surface - Helmet	GV6YH3F4	Full Scale Test Secondary Impact - Helmet	Sedan

Prior to the comparative study the following expectations were defined:

1) An increasing protection potential of bicycle helmets with increasing impact severity
2) A decreasing protection potential of bicycle helmets in combination with already improved, "vulnerable road user friendly" vehicle frontends

Impactor tests The assessment of the potential of pedestrian head protection is currently based on tests with the adult and the child/small adult head impactor described within various test procedures as e.g. the European Legislation on Pedestrian Safety (European Commission, 2009) and the Euro NCAP Pedestrian Testing Protocol (2012). Comparative tests under identical impact conditions were performed with the child/small adult head impactor with and without bicycle helmet against three different impact locations on a pedestrian three star rated vehicle according to a previous version of the Euro NCAP assessment protocol (2004):

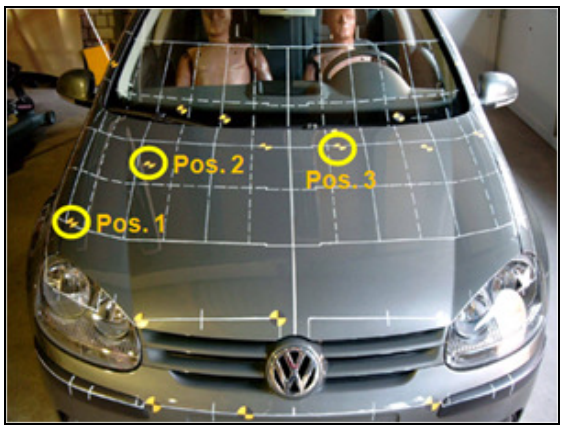

Figure 15. Impact locations for headform testing.

The tested structures were

- Position 1: bonnet support
- Position 2: gas spring support
- Position 3: fire wall

In total, six headform tests were performed so that each location was impacted with the child/small adult headform without and with applied bicycle helmet.

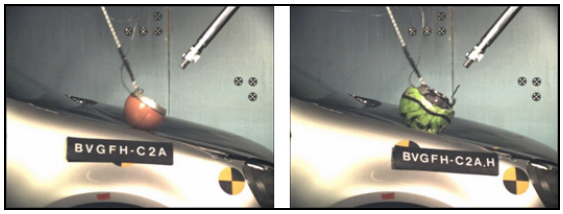

Figure 16. Headform testing without and with helmet.

The test results in terms of the resultant peak acceleration are shown in figure 17, the Head Performance Criteria (HPC) results are given in figure 18:

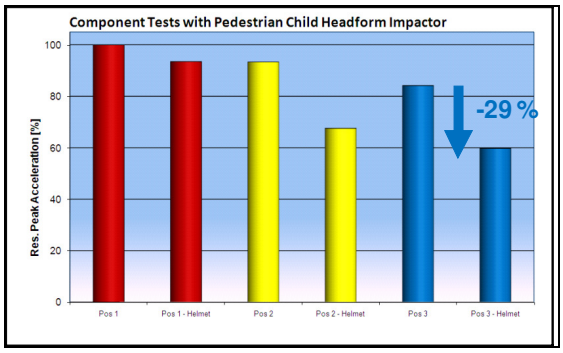

Figure 17. Peak acceleration results of component tests with child/small adult head impactor.

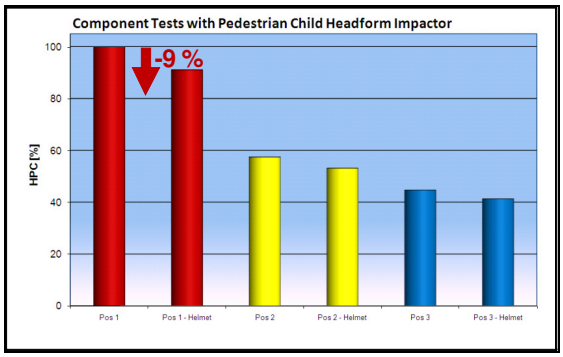

Figure 18. HPC results of component tests with child/small adult head impactor.

The diagrams demonstrate that the bicycle helmet used for these tests provided a reduction of the resultant peak acceleration up to 29 % related to the unprotected headform. The calculated HPC of the headform equipped with bicycle helmet could be reduced up to 9 % related to the HPC of unprotected headform.

The following time history curves (figure 19) show that the resultant peak acceleration was mainly derived from the acceleration in z-direction, latter one distributed more homogeneously along the entire duration of the impact in the tests with bicycle helmet:

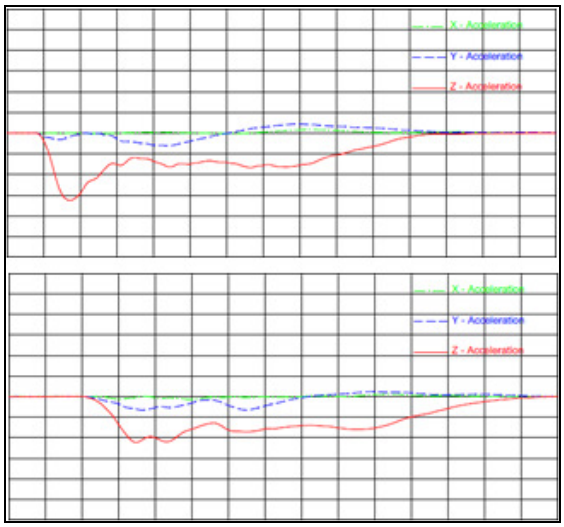

Figure 19. Acceleration time history curves of unprotected (top) and protected (bottom) headform in component tests against impact position #3.

<u>Lateral upset</u> Lateral upset tests were conducted as simulation of a bicyclist ground impact against the road surface and a kerbstone. The tests were performed with a 6 YO HIII dummy positioned on a bicycle with a rim size of 20 inches, with its head being protected with a bicycle helmet and also unprotected (figure 20).

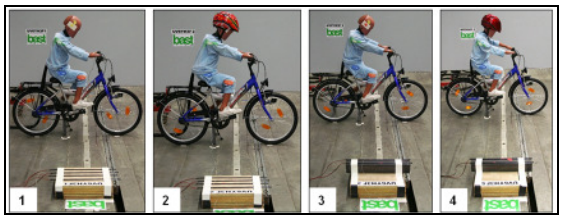

Figure 20. Test setups for lateral upset tests**.**

The test setup was chosen in a way providing the first ground contact of the dummy with its head (figure 21).

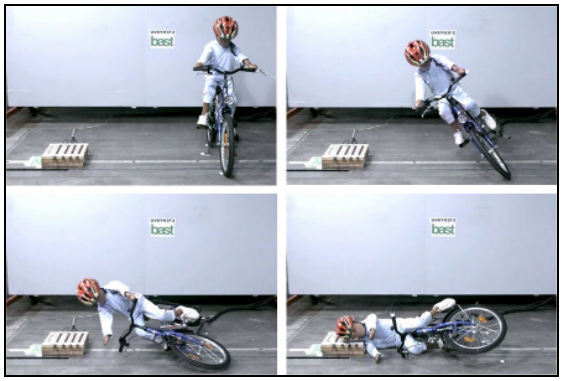

Figure 21. Dummy trajectory within lateral upset tests.

Figures 22 and 23 show the test results in terms of HPC and peak head acceleration during the impact tests against the road surface and kerbstone simulation with protected and unprotected head.

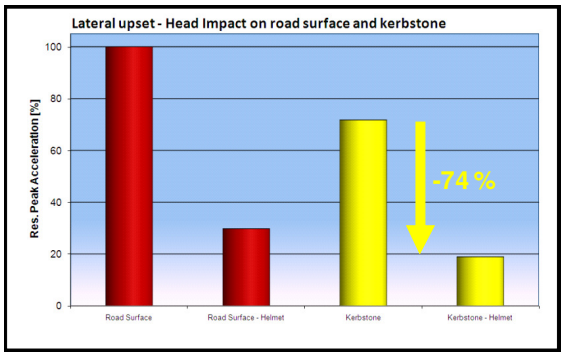

Figure 22. Peak acceleration results of lateral upset tests with HII 6YO dummy.

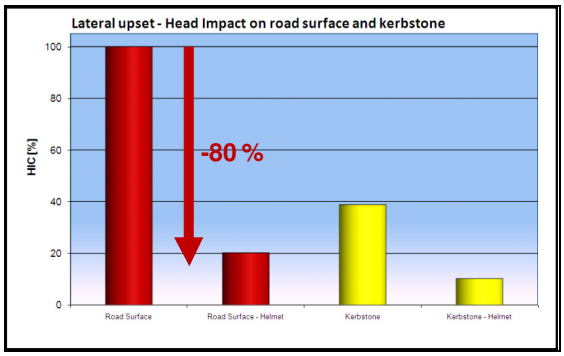

Figure 23. HPC results of lateral upset tests with HII 6YO dummy.

The comparative tests on both impact locations demonstrate the high protection potential of the bicycle helmet. According to the lateral upset tests, when impacting the kerbstone simulation, the helmet provided a maximum reduction of the resultant peak acceleration of 74 % compared to unprotected dummy head. A maximum HPC reduction of 80 % compared to the HPC value of the unprotected head is achieved during the road surface impact.

Handlebar overturn The simulation of an overturn over the bicycle handlebar and subsequent impact against the road surface or a rigid obstacle was simulated during pendulum tests. Those tests were again performed with a 6 YO HII dummy with protected and unprotected head in upright and declined position (figures 24 and 25).

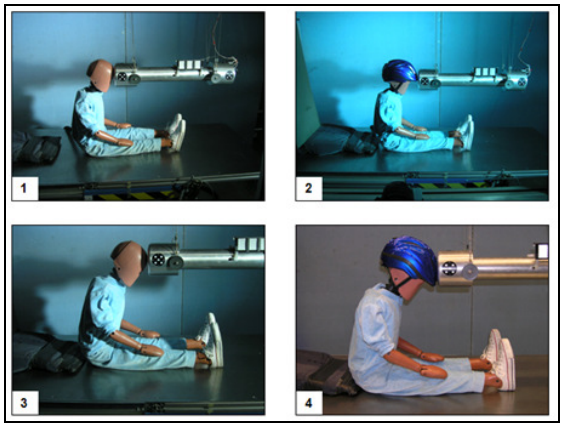

Figure 24. Test setups for pendulum tests.

Figure 25. Pendulum tests – example declined and protected head.

As during the lateral upset tests, the high protection potential of the bicycle helmet is underlined also within the handlebar overturn tests (figures 26 and 27).

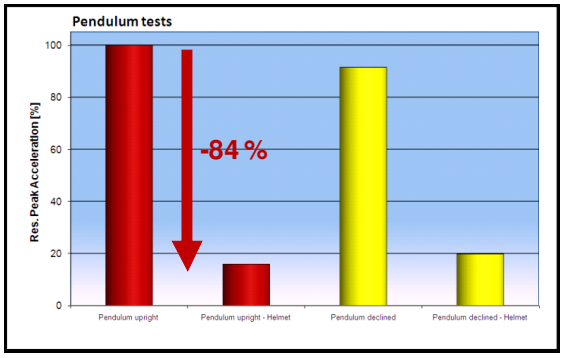

Figure 26. Peak acceleration results of handlebar overturn tests with HII 6YO dummy.

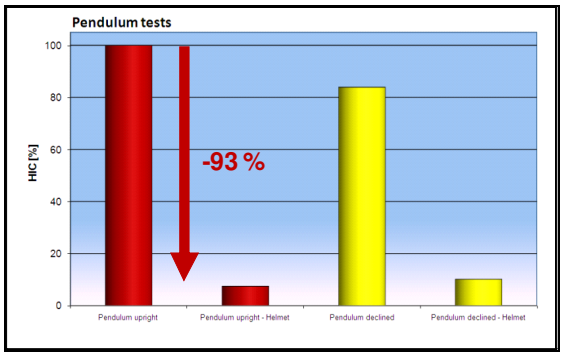

Figure 27. HPC results of handlebar overturn tests with HII 6YO dummy.

While the maximum acceleration could be reduced by up to 84 % when using a bicycle helmet during the accident, the calculated HPC was reduced by up to 93 % compared to the HPC of the unprotected head.

Full scale vehicle to dummy tests In addition to the impactor tests according to the procedures described within legislation and consumer test programmes and the lateral upset and handlebar overturn simulations, two full scale vehicle to dummy tests were performed. The 6YO HIII dummy positioned on a bicycle with a rim size of 20 inches was impacted by a modified sedan shaped vehicle with bonnet reinforcements at an impact speed of 40 kph. The aimed impact location was at the longitudinal vehicle centre plane. Besides the loadings of the head during the primary impact on the bonnet, those due to the secondary ground impact were recorded and assessed as well (figure 28).

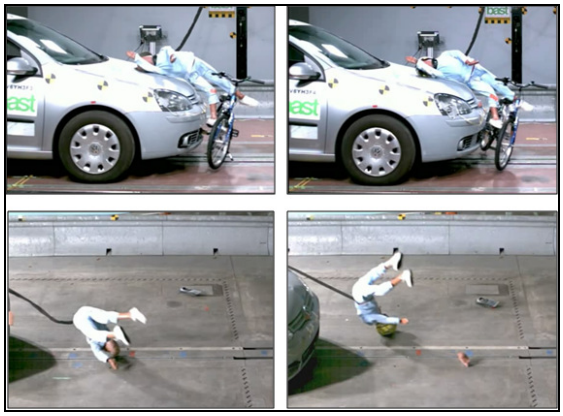

Figure 28. HIII 6YO dummies primary impact on the vehicle front and secondary impact on the ground.

The comparative tests were performed with protected and unprotected dummy head. Wrap around distances of 1280 mm and 1260 mm respectively and lateral impact positions at 60 mm and 150 mm provided an acceptable repeatability of test and impact conditions for full scale vehicle to dummy tests.

Once again, the comparative tests demonstrated the high potential of the bicycle helmet especially when impacting rigid structures. Figure 29 shows a reduction of the resultant peak acceleration provided by the helmet at 40 % on the bonnet and at 90 % during the secondary impact, compared to the unprotected dummy head:

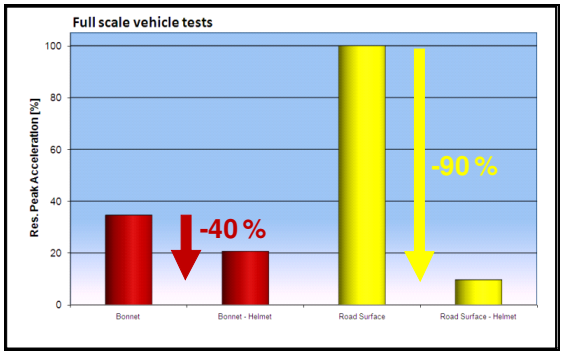

Figure 29. Peak acceleration results of full scale vehicle to HII 6YO dummy tests.

In terms of HPC, the reduction was at 15 % during the bonnet impact and at 98 % during the secondary impact compared to HPC value of the unprotected child head (figure 30):

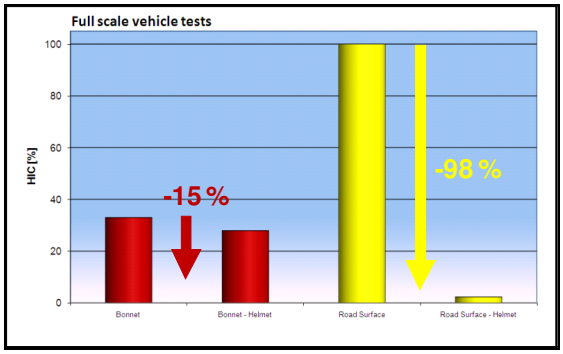

Figure 30. HPC results of full scale vehicle to HII 6YO dummy tests.

Contribution of active vehicle safety

An additionally performed full scale test at reduced impact speed was aimed for assessing measures of active vehicle safety as e.g. braking before the collision event towards injury mitigation. Therefore, the 6 YO HIII child dummy with unprotected head and positioned on the 20 inch rim sized bicycle was impacted at a reduced impact speed of 30 kph.

The reduced impact speed did not show any significant effect on the wrap around distance of the head impact, which was this time at 1290 mm and thus even further rearwards than during the tests at 40 kph. Besides, a secondary impact was noted on the bonnet.

Figure 31 shows the peak resultant head acceleration, HPC and 3 ms cumulative value of the unprotected 6 YO head during the tests at 40 kph and 30 kph.

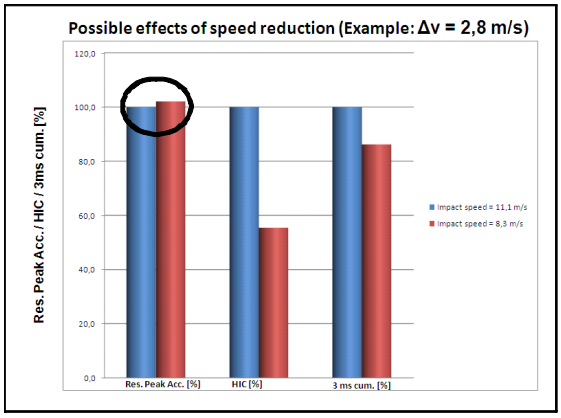

Figure 31. Influence of impact speed reduction.

As it could be expected, the calculated HPC was significantly higher within the test at higher impact speed. The 3 ms value was higher at 40 kph, too. On the other hand, a slightly higher peak resultant head acceleration at lower impact speed indicated that a different structure must have been impacted in the test at lower impact speed. This leads to the assumption that within tests at reduced impact speed the benefit of speed reduction might partly be compensated due to the different impact location and thus possibly harder structure.

DISCUSSION

Real world accident investigations result in the group of bicyclists being on rank 2 of casualties considering all injury severities in Germany. Bicycle helmets have been proved to always providing head protection in different accident scenarios. The supplemental tests beyond EN 1078 presented in this study demonstrated an increasing protection potential of bicycle helmets with increasing impact severity. In combination with optimized, i.e. „VRU friendly“ vehicle frontends the protection potential of bicycle helmets has been found to decrease, but still being significant.
Amongst other things, the helmet usage leads to approx. 33 % reduction of the portion of AIS 3+ head injuries. On the other hand, the overall bicycle helmet usage frequency has been found at 6% only in Germany.

A comparison of in depth cyclist and pedestrian accident data as well as simulation and test data suggested a rearward extension of the head impact area for the assessment of passive safety systems.
A further investigation of the German In-Depth Accident Study (GIDAS) showed that another 50 percent or more of all AIS 3 and AIS 4 bicyclist head injuries where the head being unprotected occur within zones that could be addressed by an extended Euro NCAP testing protocol.

An additional full scale test performed at reduced impact speed proved that measures of active vehicle safety as e.g. braking before the collision event do not necessarily always lead to a reduction of injury severity.

CONCLUSIONS

Improvement of bicyclist protection is suggested by either an enhancement of passive, active or integrated vehicle based cyclist protection, leading to accident avoidance or injury mitigation, or by cyclist self protection using a bicycle helmet, always focusing on mitigation only.

Within Euro NCAP, active safety will be initially implemented from the year 2014 on. Active pedestrian safety will follow two years later, introducing the assessment of AEB systems on top of state-of-the-art passive pedestrian safety. Bicyclists are expected to follow in a later stage. However, active safety is expected to never be able to target all accidents.

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