ABSTRACT

Since the beginning of the testing activities related to passive pedestrian safety, the width of the test area being assessed regarding its protection level for the lower extremities of vulnerable road users has been determined by geometrical measurements at the outer contour of the vehicle. During the past years, the trend of a decreased width of the lower extremity test and assessment area realized by special features of the outer vehicle frontend design could be observed. This study discusses different possibilities for counteracting this development and thus finding a robust definition for this area including all structures with high injury risk for the lower extremities of vulnerable road users in the event of a collision with a motor vehicle.

While Euro NCAP\textsuperscript{1} is addressing the described problem by defining a test area under consideration of the stiff structures underneath the bumper fascia, a detailed study was carried out on behalf of the European Commission, aiming at a robust, world wide harmonized definition of the bumper test area for legislation, taking into account the specific requirements of different certification procedures of the contracting parties of the UN/ECE\textsuperscript{2} agreements from 1958\textsuperscript{3} and 1998\textsuperscript{4}.

This paper details the work undertaken by BASt, also serving as a contribution to the TF-BTA\textsuperscript{5} of the UN/ECE GRSP\textsuperscript{6}, towards a harmonized test area in order to better protect the lower extremities of vulnerable road users. The German In-Depth Accident Database GIDAS is studied with respect to the potential benefit of a revised test area. Several practical options are discussed and applied to actual vehicles, investigating the differences and possible effects. Tests are carried out and the results studied in detail. Finally, a proposal for a feasible definition is given and a suggestion is made for solving possible open issues at angled surfaces due to rotation of the impactor.

The study shows that, in principle, there is a need for the entire vehicle width being assessed with regard to the protection potential for lower extremities of vulnerable road users. It gives evidence on the necessity for a robust definition of the lower extremity test area including stiff and thus injurious structures at the vehicle frontend, especially underneath the bumper fascia.

The legal definition of the lower extremity test area will shortly be almost harmonized with the robust Euro NCAP requirements, as already endorsed by GRSP, taking into account injurious structures and thus contributing to the enhanced protection of vulnerable road users.

\textsuperscript{1} Euro NCAP: European New Car Assessment Programme
\textsuperscript{2} UN/ECE: United Nations Economic Commission for Europe
\textsuperscript{3} Agreement concerning the adoption of uniform technical prescriptions for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles and the conditions for reciprocal recognition of approvals granted on the basis of these prescriptions
\textsuperscript{4} Agreement concerning the establishing of global technical regulations for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles
\textsuperscript{5} TF-BTA: Task Force Bumper Test Area
\textsuperscript{6} GRSP: Working Party on Passive Safety
After finalization of the development of a torso mass for the flexible pedestrian legform impactor (FlexPLI) it is recommended to consider again the additional benefit of assessing the entire vehicle width.

INTRODUCTION

Since the year 2000, the Japan Automobile Research Institute (JARI) has been developing a new flexible pedestrian legform impactor (FlexPLI) with the purpose of properly assessing the protection potential of vehicle frontends in terms of passive pedestrian safety. From the year 2005 on a Technical Evaluation Group\(^7\) had evaluated the impactor towards introduction within legislation related to pedestrian safety. Subsequently, since 2011 an Informal Group\(^8\) of the Working Party on Passive Safety has been working on a framework and the preconditions for including the flexible pedestrian legform impactor within the global technical regulation on pedestrian safety (GTR No. 9) as well as the UN regulation on pedestrian safety (UN-R 127). The impactor with humanlike kinematic behaviour and biofidelic human responses in the knee and the tibia area has been found ready for legislation by working party 29\(^9\) of UN/ECE. Subsequently, the FlexPLI has been introduced within the 01 series of amendments of UN-R127 (UN/ECE, 2015). Due to an amendment of framework Directive 2007/46/EC of the European Parliament and of the Council (European Union, 2007), pedestrian protection requirements for the purpose of european type approval can be either tested according to Regulation (EC) No. 78/2009 in conjunction with Commission Regulation (EC) No. 631/2009 (European Union, 2009) or according to UN-R 127 in conjunction with UN-R 13H, latter one ruling the type approval provisions of passenger cars with regard to braking. Therefore, since 22 January 2015 and during a transitional period that lasts until 1 September 2017 all new vehicles to be type approved according to UN-R127 can be subjected to tests with the FlexPLI instead of the lower legform impactor according to EEVC\(^10\) (UN/ECE, 2015). After the expiration of this transition period the FlexPLI is to be used mandatorily for type approval tests according to UN-R 127.

In parallel to the work performed by the Informal Group, the Task Force Bumper Test Area, chaired by the European Commission, was established under the umbrella of the Informal Group. Aim of this Task Force was to re-define the bumper area that is subjected to tests with the lower legform impactor according to UN-GTR 9 or UN-R 127 respectively, in order to avoid small bumper test areas that prevent large zones of the bumper from being tested, and to counteract some manufacturer’s practice of downsizing the width by design means of the outer vehicle contour.

This paper details the investigations performed by the Task Force and in particular the contributions of BASt that finally led to the proposal for the supplement 1 of the 01 series of amendments to UN-R 127 (UN/ECE, 2014) that was endorsed by GRSP at its December 2014 session.

In case of angled test areas a rotation of the lower legform impactor may occur which is, to some extent, not always coincident with the behavior of the human leg, possibly leading to unrealistic test results. In order to limit this possible rotation a pedestrian torso mass may be applied to the lower legform impactor. However, the ongoing validation of the torso mass still needs to be finalized, including tests to a broad variety of vehicle frontend designs.

PROBLEMS RELATED TO UN-GTR9 (PHASE 1) AND UN-R 127 (00)

The UN Regulation on pedestrian safety as transposition of the Global Technical Regulation No. 9 into national legislation entered into force in November 2012 (UN/ECE, 2013). The Regulation defines performance requirements for passenger cars with regard to the protection potential of their frontends when subjected to impactor tests with the adult and child headform impactors against the bonnet and the upper or lower legform impactor against the bumper fascia.

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\(^7\) Flex-TEG: Flexible Pedestrian Legform Impactor Technical Evaluation Group

\(^8\) IG GTR9-PH2: Informal Group on phase 2 of GTR No. 9

\(^9\) WP.29: Working Party 29 / World Forum for Harmonization of Vehicle Regulations

\(^10\) EEVC: European Enhanced Vehicle-safety Committee
The test area defined for the legform to bumper test is described by the part of the bumper fascia that is limited by two points 66 mm laterally inboard of the corners of bumper, see Figure 1a. The corners of bumper are defined as the vehicle’s points of contact with a vertical plane making an angle of 60 degrees with the vehicle vertical longitudinal centerplane.

In the past years, the application of specific vehicle design features resulted in a limitation of the bumper test area defined by legislation, as can be seen in Figure 1b. It is obvious that the definition of the corner of bumper which in the end defines the bumper test area rather depends on the outer contour of the vehicle than on the underlying hard structure that is responsible for the occurrence of lower leg injuries that should be mitigated by fulfilling the requirements described in the Regulation.

**Figures 1a (left) and b (middle and right). Bumper test area according to GTR9 / UN-R 127 and its limitation by design means.**

To counteract the phenomenon of misrepresenting the bumper test area by means of the current procedure, based on the outer vehicle design, the task force bumper test area elaborated different options for an appropriate revision that will be described in the following.

**EURO NCAP MARKUP PROCEDURE**

The problem of defining the bumper test area using vertical contact planes was already recognized by the technical working group of the European New Car Assessment Programme (Euro NCAP) in 2008. Until version 4.2 of the pedestrian testing protocol the width of the bumper test area was, also in line with the European legislation, in principle limited by the corners of bumper. Only in case of potentially injurious structures outboard of the described area Euro NCAP reserved the right of performing tests to those structures (Euro NCAP, 2008). However, an assessment of the results was not explicitly foreseen. An ad hoc group of Euro NCAP discussed the problems related to this procedure and concluded that, in principle, injurious structures outboard the corners of bumper shall be tested and the results shall be used for the final vehicle assessment. Additionally, the minimum distance requirements of 66 mm from the corners of bumper to define the bumper test area were removed from the protocol from its version 4.3 onwards (Euro NCAP, 2009). The bumper test area was then defined as the area limited by the corners of bumper or the outermost ends of the bumper beam/lower rails/cross beam structures, whichever area was wider. Figure 2a illustrates the markup of the bumper test area that was further divided into thirds, each of them subdivided into halves, until the end of 2013. As from 2014 onwards, along with the introduction of the FlexPLI, a homogeneous grid markup procedure for the legform area was introduced. However, the width of the test area basically remained unchanged. Additionally, since the introduction of the grid markup, in case of the distance between the outermost grid points and the end of the test area being greater than 50 mm, an additional grid point is to be marked at a lateral distance of 50 mm to the last grid point onto the upper bumper reference line. One example for the current Euro NCAP lower legform markup is depicted in Figure 2b.
Figures 2a (left) and b (right). Euro NCAP worst point and grid markup.

**USE OF WHOLE VEHICLE WIDTH**

Already during the discussions within the Euro NCAP ad hoc working group, BASt brought up a proposal to modify the bumper test area in a way that, in principle, the possibility is given to test, where appropriate, the entire width of the vehicle frontend. At that point in time, passenger cars were still tested according to the principle of worst point selection. Therefore, despite the provisions changed according to protocol version 4.3, the selection procedure of injurious points outside the bumper corners remained unclear. It was not further defined how far outboard a point was allowed to be selected; furthermore, no advice was given which point finally to be selected in case of the outermost point being equally but not more injurious as the remaining points. Also, the assessment procedure in case of selecting impact points outside the corners of bumper was not yet further specified, e.g. whether these points to be additionally assessed or to replace adjacent points, whether manufacturers were given the option to additionally nominate the adjacent sixths or whether the maximum number of points would increase. BASt concluded that an extension of the test area using the entire vehicle width (without mirrors) while sustaining the remaining markup procedure would be the most pragmatic way forward. The proposal would give Euro NCAP the possibility of testing, where appropriate, outside a test area described by the outer vehicle contour without further essential changes to the test and assessment procedure. However, it was also suggested that in cases where the tangential vertical plane making an angle of less than 60 degrees to the vehicle longitudinal centerplane a test could possibly lead to unrealistic test results due to a high rotation around the yaw axis and the physical limitations of the impactor.

In the course of the work performed by the TF-BTA, the description of the bumper test area based on the entire width of the vehicle was examined again in detail by Zander et al (2014).

**Accident data**

Passenger car to pedestrian accidents with maximum two parties involved were the starting point for a study of German in-depth road accident data from the years 2000 until 2012 using GIDAS. The study focused on accidents with pedestrian impact locations between the most forward vehicle part and 20 percent of the total vehicle length rearward under consideration of injury causing vehicle parts being located on the vehicle frontend only, i.e. bumpers, grilles, headlamps, front spoilers, license plates and indicators. In total, 567 cases were found fulfilling the given prerequisites, with an equal distribution of first pedestrian contact along the passenger car front in crashes with at least one injury suffered from contact with a part of the vehicle frontend, as depicted in Figure 3:
Altogether, the study gives no indication for neglecting outboard areas of passenger cars being less impacted by pedestrians during accidents.

**Test data**

Besides the impact distribution in real world accidents, the significance of the impacted areas in terms of injury causation was examined in more detail. Within the Euro NCAP test programme, injurious points, reflected by impactor readings beyond the limits for the introduced injury criteria, have been continuously found outside the test area described by the corners of bumper. It was thus concluded that the area to be considered should include all injurious structures underneath the bumper cover which are in most cases not indicated by the outer design. Therefore, a consideration of those structures, e.g. by dismantling of the fascia was found indispensable for a detection of hard structures.

Furthermore, a comparative test that was conducted outside the corners of bumper was examined with respect to the validity of the kinematics, see Figure 4. High speed film analysis revealed that until the timing of maximum readings the kinematic behaviour was comparable to the one during the baseline test on a location inside the corners of bumper.
MODIFICATION OF DEFINITION OF CORNERS OF BUMPER

Apart from assessing the entire vehicle width by testing injurious structures of the vehicle frontend, TF-BTA discussed possibilities for modifying the corners of bumper definition.

The first option investigated was related to changing the angle between the vertical tangential planes and the vehicle vertical longitudinal centerplane from 60 to 45 degrees and thus enlarging the test area to a certain extent. This option that was investigated in detail within a study on behalf of the European Commission by Carroll et al. (2014) was already brought forward by the Transport Research Laboratory TRL during their studies for the Working Group on Pedestrian Safety (WG 17) of the European Enhanced Vehicle-Safety Committee in 2002. At that point in time, the proposal was justified with actual vehicles partly having very small bumper test widths, just between the inner ends of the headlights. It was noted that the performance of the legform at impact points with these tangential surface angles could be limited due to spinning of the impactor; however, the legform was expected to still be able to indicate particularly dangerous structures. Not testing these areas would open the door for putting bumper supports, longitudinal members or other hard structures in a non-evaluated area. (TRL, 2002)

The second option was evolved from the current corner of bumper definition described in US bumper standard 49 CFR part 581 (NHTSA, 2011). Instead of a vertical plane, a vertical corner gauge with the dimensions of the face of the impact device as described in part 581, making an angle of 60 degrees to the vehicle vertical longitudinal centerplane, is contacting the vehicle frontend with its vertical centerline while its horizontal centerline is moved between heights of 75 mm and 1003 mm above ground level, representing the lower and upper end of the FlexPLI during an impact, but not falling below the lower bumper reference line and not exceeding the upper bumper reference line. The outermost contact point between the corner gauge and the fascia is then defining the corner of bumper. In the end, the test area is limited by the corners of bumper minus a lateral distance of 42 mm on both sides of the car, taking into account half of the width of the FlexPLI femur and tibia section. This distance requirement was meant to avoid as far as possible any rotation or sliding of the impactor possibly leading to unrealistic test results during an impact against angled surfaces.

In a final stage, the second option was further modified, changing the original corner gauge dimensions to a 236 mm * 236 mm square.

BASt investigated the consequences in case of modifying the markup procedure by just using the corners of bumper defined by the modified corner gauges. When checking the robustness of the procedure against any changes in the outer contour, BASt found that by simple design features the test area could still be narrowed in future design concepts, as illustrated in Figure 5:
Although the example given shows a comparatively small difference between the definition using the end of the bumper beam and the corner of bumper (12 mm plus 42 mm as distance requirement on each side), this design exemplarily demonstrates that in case of an inboard movement of the intake for the daytime running lights (DRL) the width of the test area could be easily minimized significantly. BASt concluded again the indispensability of defining the bumper test area using the underlying injurious structures. In a first step, addressing nowadays vehicle frontends, it seems reasonable to define the test area using the width of the bumper beam. A robust definition of the bumper beam is given by the Research Council for Automobile Repairs (RCAR). In the RCAR bumper test procedures it is described as the structural cross member under the bumper fascia protecting the front or rear of the vehicle, not including foam, cover support or pedestrian protection devices. The bumper beam width is to be measured from the outermost left to the outermost right section of the bumper beam, but only taking into account outer ends meeting the qualifying bumper beam heights. Latter ones are to be measured from a vertical plane contacting the beam up to a distance of 10 mm in direction of the profile (RCAR, 2010):

**Figure 5. Corner point due to gauge contact with daytime running light intake.**

**Figure 6. Definition of the bumper beam width (RCAR, 2010).**
COMBINATION OF MARKUP REQUIREMENTS

BASt examined the test areas resulting from the different markup procedures and compared them with the markup according to GTR9 (Phase 1) or UN-R 127 (00) respectively. Figure 7 exemplarily illustrates the differences in width of test areas:

![Image of test area comparison]

**Figure 7.** Comparison of different markup procedures and resulting test area widths.

The example given in Figure 7 results in the different markups having a range of 530 mm just between the corners of bumper defined by 45 degree planes and the GTR9 (Phase 1) / UN-R 127 (00) markup. The difference between the bumper beam width and the markup with corner gauges is still 159 mm.

The Task Force Bumper Test Area concluded its work in forwarding two different proposals to GRSP for an amendment of GTR9 (Phase 2) and a supplement of UN-R 127.01. The first proposal reflects, while keeping the angle between vertical tangential plane and vehicle vertical longitudinal centerplane unchanged, the idea of defining the bumper test area by a revision of the bumper of corner definition only, using vertical 236 mm * 236 mm corner gauges and laterally moving 42 mm inboard on both sides, see Figure 8. The second proposal adds to the corner gauge definition a second definition of the bumper test area described by the width of the bumper beam. The maximum of both definitions is then to be used to describe the bumper test area:

![Image of bumper test area definition]

**Figure 8.** Definition of bumper test area endorsed by GRSP in December 2014 (UN/ECE, 2014).
It has to be noted that supplement 1 to the 01 series of amendments to UN-R127 relates to the FlexPLI only. Therefore, if tested in accordance with UN-R 127 in its original version, the tests conducted with the EEVC lower legform impactor will be limited to the bumper test area defined by the vertical 60 degree planes, whose contact points afterwards laterally moving 66 mm inboard on each side of the vehicle.

OUTLOOK

Real world accident data has shown that pedestrians are generally impacted by locations along the entire vehicle width. Test results with the FlexPLI have proven that in many cases injurious impact locations occur outside the test area described by the corners of bumper. However, technical services need to take care of the fact that on angled surfaces a rotation of the impactor can lead to sometimes unrealistic test results. The rotation of the impactor that is not reflected to that extent by lower extremity rotation as seen in road traffic accidents, is expected to be compensated by the application of an upper body mass, representing the mass of the pedestrians’ torso during an accident. An upper body mass for the FlexPLI has been developed within the European FP6 project APROSYS (Advanced PROtection SYStems) by Bovenkerk et al. (2009) and is being evaluated by Zander et al. (2011 and 2013). Subsequently, amongst other things, during the European FP 7 project AsPeCSS (Assessment methodologies for forward looking Integrated Pedestrian and further extension to Cyclist Safety Systems), BASt carried out comparative tests conducted with baseline FlexPLI and FlexPLI with applied UBM on angled vehicle frontend surfaces (Ferrer et al., 2014), see Figure 9:

![Figure 9. Influence of applied upper body mass during impact on oblique surface.](image)

The depicted screenshots demonstrate that the application of an upper pedestrian mass can significantly reduce the rotation around its yaw axis as well as the sliding of the FlexPLI during impacts on angled areas, leading to an improved simulation of the lower extremity kinematics of a pedestrian. This observation can be underlined by the test results especially in the knee area:
**DISCUSSION**

In depth accident data gives evidence of an equal distribution of first pedestrian contact at the front of passenger cars in crashes with at least one injury suffered from contact with a part of the vehicle frontend (Zander et al., 2014). For vehicles with market launch after 2006, a further study of the German In Depth Accident Data (GIDAS) showed an even distribution of the injury severities outside the current bumper test area while having a higher portion of uninjured or slightly injured pedestrians inside the current bumper test area. (Fries et al., 2014). Thus it can be concluded that vulnerable road user safety improvements are focused on the currently assessed areas. Also several stakeholders state the potentially injurious nature of hard structures outside the current bumper test area as defined in UN Regulation No. 127 and consequently confirm the need to assess the structural parts behind the bumper cover (Carroll et al., 2014).

During testing, injurious points have been continuously found outside test areas defined by measurements depending on the outer contour, especially at the ends of the bumper beam (Euro NCAP, 2012). Thus, the assessment of injury risks for vulnerable road users should basically consider the entire vehicle width. However, if a limitation of the test area is necessary, at least no potentially injurious structures should be prematurely excluded from the test area.

The contractor of the European Union states that it would be entirely reasonable to expect that vehicle front-end designs would react to any definition only related to the outer contour and in the future the bumper test area widths return to something similar as todays. Thus, it could be imagined that the same issue may occur again in several months or years (Carroll et al., 2014). The presented study already gives an example of an actual vehicle where outer design features could be easily used for downsizing the bumper test area, see Figure 5.

As procedures based on the outer vehicle contour do not necessarily include the relevant injurious vehicle structures (e.g. bumper beam), at least the entire bumper beam should be included within the test area.

It has been proven that the flexible pedestrian legform impactor works outside the current bumper test area as defined in UN Regulation No. 127, e.g. within the width of the bumper beam (Zander et al., 2014-2). A robust definition for the bumper beam is provided by RCAR (2010).

The above mentioned issues show that the use of the bumper beam for defining the BTA is inevitable.
The work undertaken within the TF-BTA resulted in different options on how to define the vehicle bumper area to be subjected to tests with the lower legform impactor. All options are basically following two different philosophies, either describing the test area by means of the outer vehicle contour or by elements of the underlying stiff structures. Starting from leaving the area as it is described within current legislation, the consequences of a modification of the angles between the tangential vertical planes and the vertical longitudinal vehicle centerplane from 60 degrees to 45 degrees as well as the modification of the markup tool for the corner of bumper definition from planes to gauges were investigated as means of leaving the test area definition depending on individual single details of the outer vehicle contour. A new definition of the test area using the ends of the bumper beam, following and harmonizing with the procedure that had been already introduced within Euro NCAP in 2009, reflects the philosophy of assessing the underlying injurious structures rather than the bumper fascia. A third philosophy aims at addressing the real world accident data which results in a homogeneous lateral impact distribution of pedestrians over the entire vehicle width, which therefore is suggested to be assessed. It thus should be, in principle, left to the testing authority to test over the entire width, considering the applicability of tests on angled structures.

CONCLUSIONS

The present study gives evidence of the bumper test area of passenger cars currently assessed within the type approval procedures in terms of pedestrian safety not anymore adequately addressing the purpose of protecting the lower extremities of pedestrians involved in accidents with passenger cars, mainly due to the downsizing of the test area width by means of outer vehicle design in many cases. It was demonstrated that any proposed method for a revision of the test area using tools related to the outer contour will most unlikely be of a permanent effect in terms of avoiding small test areas. Requirements for passive pedestrian safety unconditionally need to include the stiff structures, mainly located under the bumper fascia, which are responsible for injuries to the lower extremities. Therefore, for the time being, the test area definition using the bumper beam is indispensible. However, in the long run, giving consideration to current accident data which shows an equal distribution of pedestrian impacts along the entire vehicle width, the technical services should be given the opportunity to assess the complete vehicle width. Following this procedure, in case of angled test areas a rotation of the lower legform impactor may occur which is, to some extent, not always coincident with the behavior of the human leg, possibly leading to unrealistic test results. In order to limit this possible rotation a pedestrian torso mass may be applied to the FlexPLI. However, further research is needed and the ongoing validation of the torso mass still needs to be finalized, including tests to a broad variety of vehicle frontend designs. It is recommended to introduce the test and assessment procedure for the entire vehicle width after final validation and evaluation of the upper body mass, limiting impactor rotation during impacts on angled surfaces.

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