DEVELOPMENT OF A STANDARD FOR DEPLOYABLE PEDESTRIAN PROTECTION SYSTEMS (DPPS) FOR AMENDMENTS TO UN GLOBAL TECHNICAL REGULATION NO. 9 AND UN REGULATION NO. 127

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ABSTRACT

World-wide test and assessment procedures for passive pedestrian protection have been in place for many years. Passive safety requirements within global technical regulation no. 9 (UN-GTR9) are prescribed through tests to the front ends of stationary vehicles with instrumented impactors representing the pedestrian's head, pelvis and lower extremities. However, no specific requirements are included for vehicles equipped with active bonnets and other deployable pedestrian protection systems (DPPS). This paper describes the work of the UN informal working group (IWG) to develop procedures on DPPS that are intended to be incorporated into UN-GTR9 and UN-R127 as amendments.

DPPS must work as intended during actual vehicle-to-pedestrian accidents. Therefore, test methods and conditions need to reflect the challenges DPPS are facing during actual and representative accident scenarios, but without being design restrictive. Several prerequisites need to be met in order to assure that DPPS operate properly and offer at least the same level of pedestrian protection as conventional passive pedestrian protection systems. These prerequisites include system requirements providing pedestrian detection and the timely and safe DPPS deployment. Also, headform tests are run at impact speeds below the DPPS deployment threshold on the undeployed system to confirm the undeployed bonnet is sufficiently safe.

Draft amendments intended for UN-GTR9 and UN-R127 are being finalized by the IWG on DPPS to harmonize testing under the agreements of 1958 and 1998 while preserving contracting parties' options for domestic standards. Results reported herein include IWG investigations of: (1) An appropriate impactor to assure a pedestrian is detected by the front-end sensing system; (2) Real world pedestrian accidents to determine the needed width of the detection test area; (3) Qualification procedures for Human Body Models (HBM) for use in simulations to determine head impact times (HIT) and impact locations; (4) An empirical formula to determine HIT in lieu of HBM computer simulations; (5) Experimental determination of the total response time of the DPPS. Altogether, the amendments provide for headform impact test conditions on deployable systems against established performance requirements to reduce head injury risk.

A DPPS is expected to offer a sufficient level of pedestrian protection while preserving vehicle design freedom. Several shortcomings of the developed procedure are discussed and limitations are identified which could reduce the actual pedestrian protection during a crash: The FlexPLI does not mimic the hardest to detect pedestrian. The detection test area does not fully account for all pedestrian impact trajectories. The bonnet clearance afforded by a DPPS could be compromised by the upper body load. The deployment height and the oncoming speed of the

deploying bonnet could differ between testing and real-world scenarios. A valid HIT determination using a HBM simulation on a given vehicle model requires good CAE correlation with the actual vehicle. The alternatives, experimental testing or an empirical formulation to determine HIT, could increase objectivity.

The draft procedures are being developed by the IWG for consideration as amendment to UN-GTR9 and UN-R127. It will offer an approach for compliance testing of vehicles equipped with DPPS. Since UN-R127 and the European New Car Assessment Programme (Euro NCAP) have extended their scopes to the head protection of bicyclists, the DPPS head protection potential should be investigated accordingly in future studies.

INTRODUCTION

Test and assessment procedures for vehicle-related passive pedestrian protection have been in place internationally for many years. These procedures evolved from Working Groups 10 and 17 of the European Enhanced Vehicle-safety Committee (EEVC, 2002) and the pedestrian working group within the International Harmonization of Research Activities (IHRA) (Mizuno, 2001). Then, the European Directive 2003/102/EC introduced the first mandatory requirements with effect from October 2005 (European Union, 2003). These were followed by Regulation (EC) No 78/2009 on pedestrian protection in January 2009 (European Union, 2009). The global technical regulation on pedestrian safety (UN-GTR9) under the parallel agreement of 1998 was published in January 2009 (UNECE, 2009) and United Nations Economic Commission for Europe Regulation on pedestrian safety (UN-R127) under the umbrella of the agreement of 1958 entered into force in November 2012 (UNECE, 2013).

More recently, since July 2022, Regulation (EU) 2019/2144 on type-approval requirements for motor vehicles as regards their general safety and the protection of vehicle occupants and vulnerable road users governs the legal passive pedestrian protection requirements for obtaining a European whole vehicle type approval (European Union, 2019).

Deployable Pedestrian Protection Systems (DPPS)

The most common type of DPPS to date is an active bonnet. It incorporates actuators and lever arms to automatically lift the bonnet upon detecting that a pedestrian has been struck by the front-end of the vehicle. The system acts to pre-position the bonnet before the secondary impact takes place with an oncoming pedestrian. In doing so, space is created between the bonnet and rigid components in the engine bay, thus reducing the risk of injury to the pedestrian. A second type of DPPS is an airbag e.g. deploying from the cowl area and partially covering hard structures of the windscreen periphery (e.g. lower frame, A-pillars).

DPPS are not directly addressed in UN-GTR9 or UN-R127. The GTR9 regulatory text merely states that “all devices designed to protect vulnerable road users when impacted by the vehicle shall be correctly activated before and/or be active during the relevant test” and furthermore adds the manufacturer’s responsibility to demonstrate any devices acting as intended during a pedestrian impact.

The current preamble of UN-GTR9 offers a guideline to Contracting Parties for performing headform tests on vehicles with DPPS. The “Certification Standard for Type Approval Testing of Active Deployable Systems of the Bonnet/Windscreen Area” (UNECE, 2005), prepared by the International Organization of Motor Vehicle Manufacturers (OICA), provides a broad overview for determining whether a headform test on the deployed system, on the deploying system, or another type of test should be carried out. It contains a decision tree analysis devised for a type approval system of compliance in which the vehicle manufacturer and a type approval authority agree on the test parameters. However, the guidelines serve only to specify terminology for defining the timing of a launch as provided by the manufacturer, without specifying the timing itself. They do not cover requirements for the deployment threshold or the detection test area.

IWG on DPPS

Soon after UN-GTR9 was adopted, Euro NCAP introduced more sophisticated test provisions and requirements for deployable bonnets (Euro NCAP, 2010). Similar to those provisions, the IWG on DPPS is developing amendments to UN-GTR9 and UN-R127 with regards to the prerequisites and modified test provisions that are indispensable for assessing the safety level provided to pedestrians' heads by deployable systems during accidents. The prerequisites mainly comprise of (1) sufficient protection of a pedestrian at vehicle speeds below the deployment velocity threshold of the system, (2) the capability to detect a pedestrian during an impact, and (3) appropriate timing for a DPPS to be in the correct position for providing head protection during the impact. Each of these prerequisites is discussed in this paper. Depending on the degree of fulfillment of those prerequisites, the draft amendment will require headform tests to be performed either statically on the fully deployed DPPS, dynamically on a deploying DPPS, or statically on the DPPS in fully stowed position. A certain level of head protection also at vehicle speeds beyond 40km/h and the actual protection level of the DPPS during real world pedestrian accidents being sufficiently reflected by experimental impactor tests are further aspects for a proper functionality of the system and may be additionally considered in the future.

PROTECTION AT SPEEDS BELOW THE DEPLOYMENT THRESHOLD

DPPS are technical systems which are designed to increase head protection for a pedestrian in the event of an impact by a four-wheeled power-driven vehicle. This safety benefit is usually implemented by means of additional clearance between the bonnet and the underlying structure for sufficient energy absorption before any possible hard contact. Since DPPS do not activate below the "lower deployment velocity threshold," head protection at an impact velocity corresponding to this vehicle speed must be demonstrated to an equal level of protection of a passive, non-deployable system. This is done by performing a number of component tests with the headform impactors at the defined velocities.

Previous studies have suggested that head impact velocities of a pedestrian may correspond to not more than in average 0.9 times the vehicle speed (UNECE, 2003). However, wide variations of head impact velocities can be observed depending on the position of the pedestrian prior to impact, the pedestrian's stature, shape of the vehicle, random effects of different body parts and the chosen surrogate (Hardy et al., 2007). A range of head impact velocities with k-factors (the ratio between head velocity and vehicle speed) between 0.68 and 1.5 for a car impact speed of 40km/h were reported by Lawrence et al. (2004). Since those estimations were also taken into account when defining the test provisions for the legal headform tests at 35km/h, the same factor of 0.9 has been applied by the IWG for head impacts below the lower deployment threshold.

For UN-R127, the draft amendment calls for three headform tests, one to each third of the headform test area, are to be performed at an impact velocity of 0.9 times the corresponding vehicle's lower deployment velocity threshold. The GTR draft amendment will not place restrictions on the number of headform tests. The markup for the performance zones where the head performance criterion (HPC) must not exceed values of 1000 or 1700 may differ from that for the headform tests at the nominal impactor velocities of 35km/h.

PEDESTRIAN DETECTION

In order to take into consideration the safety benefit provided by a DPPS in the event of a collision, the pedestrian must be appropriately detected. To account for a range of real-world accident scenarios covering the most common and frequent cases, the draft amendment requires tests with a pedestrian surrogate representing a broad variety of pedestrian statures and stances. According to the draft amendment, the tests have to be carried out on the area of the vehicle front where a pedestrian impact can be expected. It is assumed that a vehicle-to-pedestrian impact at the vehicle speed corresponding to the lower deployment threshold of the DPPS represents the most challenging case to be detected (referred to as "hardest to detect", or HTD) by the sensing system.

Pedestrian surrogate

During the discussions among members of the IWG on DPPS, it was recognized that most of the currently available impactors show several shortcomings when acting as pedestrian surrogates for the purpose of detection and sensor activation. The pros and cons of available pedestrian legform impactors were investigated in terms of scope, certification procedures, contact biofidelity, representativeness, and applicability during component or full-scale tests (see Table 1.

Table 1.
Comparison of candidate Sensing Impactors (Zander et al., 2020)

	EEVC WG 17 Lower Legform Impactor	**EEVC WG 17 Upper Legform Impactor**	**Flexible Pedestrian Legform Impactor**	**Pedestrian Detection Impactor 2**
State of the art / Current Usage	Tool for homologation in Regulation (EC) No. 78/2009 50th percentile Pedestrian surrogate in Euro NCAP Pedestrian Testing Protocol (++)	Tool for homologation in Regulation (EC) No. 78/2009 and UN-R127/UN-GTR9 (+++)	Tool for homologation in UN-R127/UN-GTR9 50th percentile Pedestrian surrogate in Euro NCAP Pedestrian Testing Protocol (+++)	Tool for HTD Pedestrian surrogate in Euro NCAP Pedestrian Testing Protocol (+)
Dynamic Certification (Injury Criteria)	Procedure and verification of 3 criteria (internal biofidelity) (+)	Procedure and verification of 5 criteria (internal biofidelity) (+)	2 procedures and verification of 7 criteria each (internal biofidelity) (++)	Not available (-)
Contact Biofidelity	not verified (-)	not verified (-)	not verified (-)	verified (+)
Mass	13.4kg	9.5-18kg	13.2kg	6.7kg
Representativeness	50th male	50th male	50th male	Various statures (++++)
Applicability	Yes (moving car) Feasibility in low speed testing with propelled impactor (+)	No (needed mass reduction to 7.4kg for HTD approximation not feasible. New guiding system would be needed) (-)	Yes (moving car) Feasibility in low speed testing with propelled impactor (+)	Yes (moving car) Feasibility in low speed testing with propelled impactor (+)
Summary	+++	++	+++++	++++++

According to the summary table, the pedestrian detection impactor 2 (PDI-2) would be the first choice as pedestrian representative. However, while its very conservative and demanding requirements seem appropriate for consumer tests, it sometimes underestimates the loads that are emanated from a pedestrian onto a sensing system.

Figure 1 shows that the mean intrusions, forces, and energy levels (i.e. the internal energy of the expanded polypropylene foam block at the middle loadpath, considering intrusions and horizontal and vertical deformation) induced by the PDI-2 (evaluated only at the approximate height of the sensor system, i.e. in the middle loadpath) are very often at the lower end of the scale when being compared to Human Body Model simulations, the FlexPLI, and the EEVC WG 17 pedestrian legform impactor (Pauer et al., 2018).

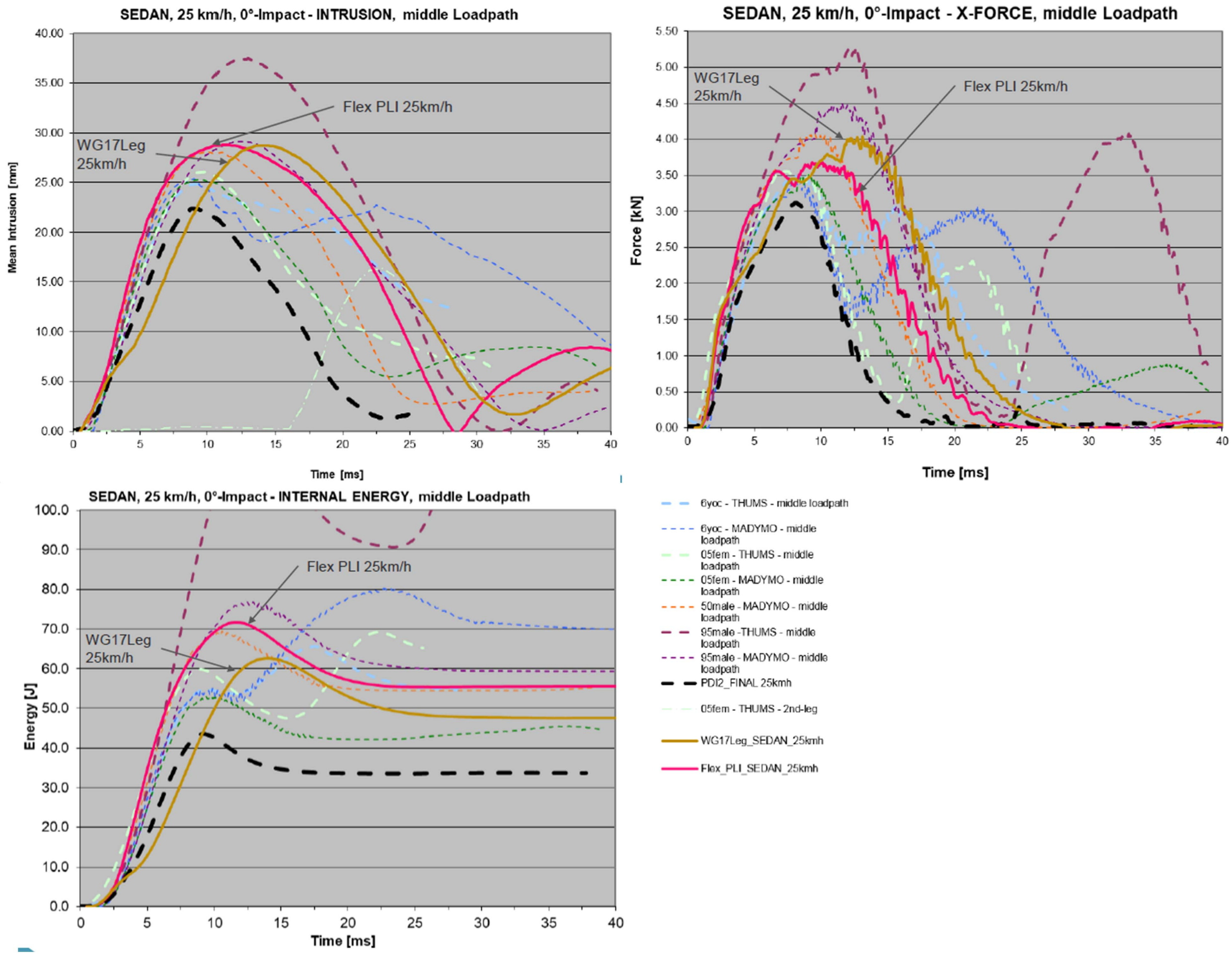


Figure 1. Loadings from pedestrian Human Body Models, PDI-2, FlexPLI and EEVC WG17 PLI on the vehicle frontend – Example Sedan 2D test frame, 25km/h, perpendicular impact at mid loadpath (Pauer et al., 2018).

The FlexPLI, on the other hand, provides good representativeness and contact biofidelity. Furthermore, it has already been established as a tool for injury assessment in UN-GTR9, UN-R127, as well as consumer tests. It was demonstrated to have good repeatability for injury assessment. Dynamic certification tests were established to assure the reproducibility of the device and repeatability during testing. The device is fully specified within UNECE Mutual Resolution No. 1, including a complete set of engineering drawings (UNECE, 2020).

For a validation of its contact biofidelity, properties of the FlexPLI that are relevant for the sensor signals need to stay within defined tolerances. When meeting the tolerances as defined within the impactor specifications (UNECE, 2018), its total mass, the mass distribution, moments of inertia, centers of gravity, lateral dimensions for all load paths and the bending stiffness around the y axis can be considered very robust. Furthermore, the stability of the impactor local stiffness / compression behavior in the longitudinal direction at height of the vehicle mid cross beam were evaluated by the intrusion which can be approximated by integrating twice the channel filter class (CFC) 180-filtered (to account for the test specification) acceleration signal. The double integral then needs to stay within a narrow range.

The results of a number of dynamic inverse tests, derived from the inverse test as described in UN-GTR9 and UN-R127, were evaluated with regards to the repeatability of the acceleration signal. Acceleration, as described above, is the most convenient criterion for ensuring high quality contact biofidelity. The acceleration measurement needs to be done at the impactor itself, and not on the impacting aluminum honeycomb, as specified in Figure 2, in order to get the full path of travel of the impactor and to damp the effect of scatter of the folding honeycomb. The tests were performed at a common DPPS lower deployment velocity threshold of 25km/h. Two inverse tests, each with halved honeycombs, were carried out with ten certified FlexPLI impactors (UNECE, 2018). One impact height matched the inverse certification test at the knee, the second one was 64mm lower on the tibia, altogether representing “worst case” heights of typical cross beam structures around the requirement of the Research Council for Automotive Repairs (RCAR, 2010), see Figure 2. The accelerations were measured with the standard accelerometer positioned at the knee location, 523mm above ground level, and an additional accelerometer positioned at the uppermost tibia segment, 459mm above ground level:

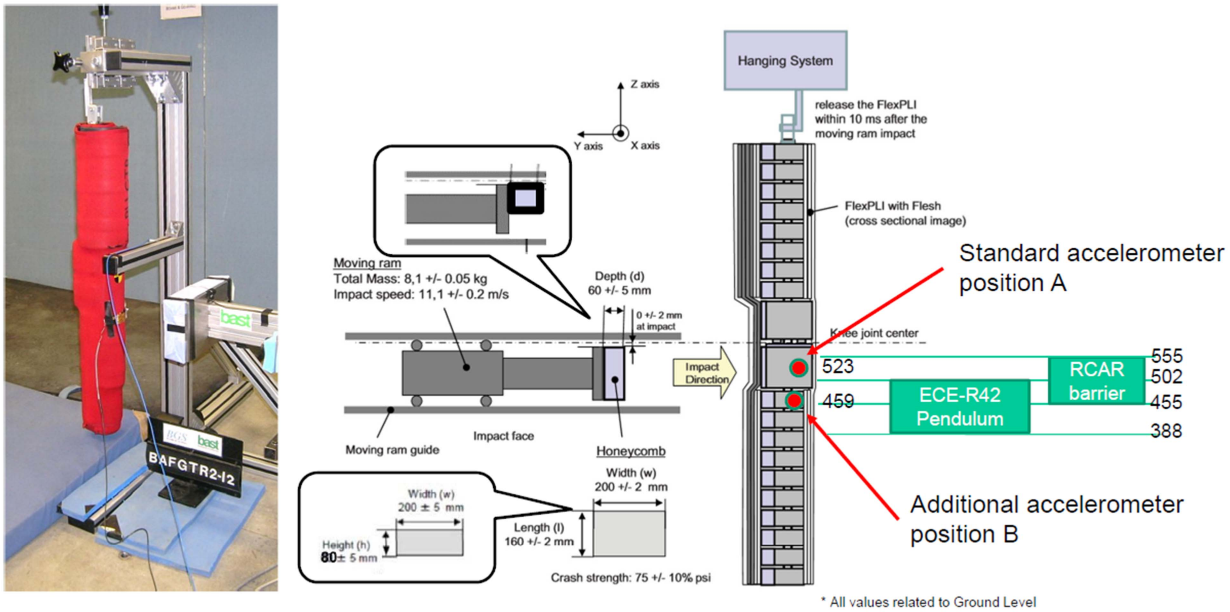


Figure 2. Test setup and positioning of the accelerometers for FlexPLI contact biofidelity check (Zander et al., 2020-2).

The determined displacement vs. time results of the inverse tests are plotted in Figure 3 for the honeycomb alignment with the knee (left) and with the tibia (right). The coefficients of variation were calculated at different time steps at 20, 25, 30 and 35ms after the impact with 2.4-2.8% for the knee impact and 5.7-6.2% for the tibia impact. Altogether, the repeatability of the displacement was good or acceptable.

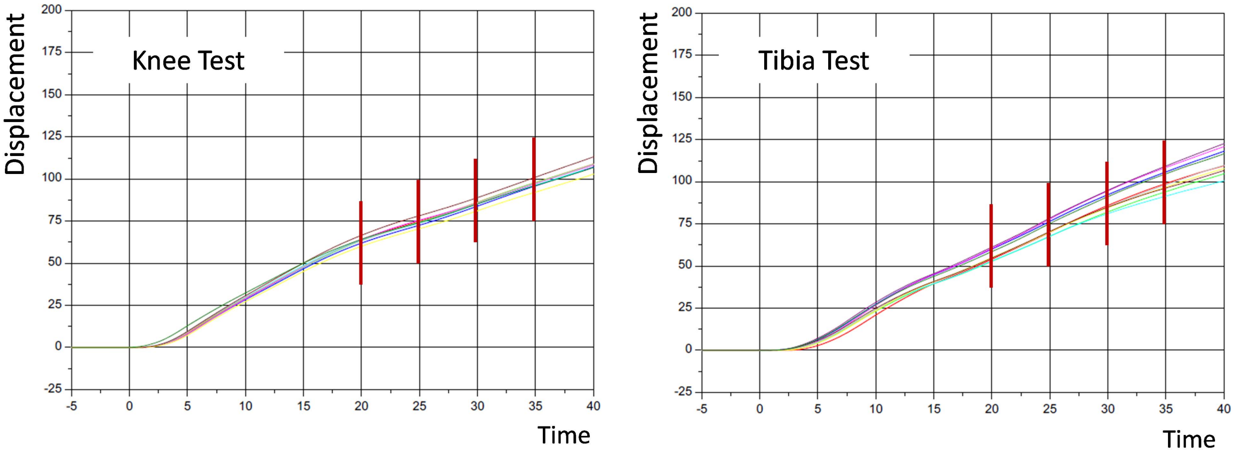


Figure 3. Displacement vs. time for the knee test (left) and the tibia test (right) (Gehring et al., 2021).

Altogether, it could be demonstrated that the FlexPLI represents a pedestrian surrogate that can be used for the sensing verification of a DPPS. However, the impactor can only represent a limited range of typical load cases. The authors recommend including the corresponding language within the preamble of UN-GTR9 and in UN-R127.

Detection test area

As one of the fundamental prerequisites to account for the potential safety benefits of a DPPS, any pedestrian needs to be detected during an accident prior to head impact on the vehicle. The IWG discussed the required width of the area on the vehicle front where a pedestrian needs to be detected in order to purposefully initiate the DPPS. The area definition should balance the zone where a pedestrian contact with the vehicle front could occur as well as the technical feasibility and limitations of an impactor test.

In a study of the German In Depth Accidents (GIDAS), Zander et al. (2014) found that first contact of pedestrians take place, in principle, over the entire width of the vehicle, where thus a detection would be needed. A Laboratory of Accidentology and Biomechanics (LAB) study of the In-Depth Database of only injured or fatal accidents in France (LAB, 2022) revealed no head impacts to the bonnet for cases in which a pedestrian was struck outside the longitudinal frame rails of the vehicle, while approximately 1/3 of cases resulted in a pelvis impact to the bonnet. The LAB study found that the area outside the frame rails accounts for approximately 15-20% of the vehicle width.

A pedestrian may tend to spin off at the outer widths of typical angled or V-shaped vehicle front end surfaces, without a head-to-bonnet impact. This effect may be even more pronounced when using a leg impactor as pedestrian surrogate without attaching additional mass representative of the pedestrian’s hip, torso, arms, neck and head. The lower mass reduces the load on the sensing system and is therefore not representative of a pedestrian.

Several possible definitions for a detection test area were discussed by the IWG. Based on the laboratory results from post-mortem human subject (PMHS) tests, HBM simulations and full-scale dummy tests, there was mainly a longitudinal wrap-around of the pedestrian, with low lateral offset, and thus a detection area with lateral dimensions identical to the width of the activated part of the DPPS was suggested (JASIC, 2021). On the other hand, GIDAS data showed a number of real-world cases with a significant lateral offset between the first leg impact and the subsequent pedestrian head impact (Zander et al., 2021). Among the proposals for the detection test area were:

(a) to use the existing lower leg bumper test area (BTA) as defined in UN-R127 and UN-GTR9;

(b) to use the corner reference points (CRPs) as specified in UN-R127 (the intersections of the side reference lines (SRLs) and the bonnet leading edge reference line (BLERL)) as outer boundaries;

(c) to use a percentage of the relevant vehicle width (RVW), where RVW is defined as the width at the cross-section of the front axle, without rear view mirrors or rear-view mirror substitute systems. Under this setting, the detection test area is taken from reference points on the vehicle front-end that are (12.5% * RVW) inboard from the outer boundaries of the RVW. Thus, all vehicles would be equally treated, regardless of their effective width;

(d) in addition to (c), to account for wider vehicles, a subtraction of no more than 250mm on either vehicle side would be allowed;

(e) to exclude any structure-based criterion such as the cross beam with possible additional structures which are appended to fulfill crash test requirements for different markets.

In subsequent deliberations, the IWG decided against the use of the corner reference points. It was noted by IWG participants that when a vehicle has multiple or continuous intersections between the BLERL and the SLR, the most outboard point is used as the CRP. It was also noted that the distance between right and left CRPs can be narrowed easily by a minor, cosmetic redesign of the vehicle front end. Such a redesign would have no effect on the legform test zone, but could lead to large differences in CRP locations and thus greatly affect the DPPS detection test area.

The IWG also deliberated on the use of the BTA, which is defined as the wider of the width defined by the corners of the bumper (CoB, determined by contacting the vehicle front with a corner gauge maintaining an angle of 60° to the vehicle longitudinal centre plane) and the width of the underlying bumper beam. The IWG decided to exclude the bumper beam, reasoning this to be consistent with a performance-based standard. If a bumper beam requirement had been included, it would have partly acted to prescribe the currently prevalent sensing tube technology and the form of the bumper beam itself. A regulation should not prescribe a particular design nor stand in the way of new technologies, such as different sensing technologies or bumper beams that utilize different materials, shapes and functions.

While discussing the various definitions, the IWG also examined a survey of current vehicles with DPPS on the market, see Table 2 (VDA, 2022). The survey revealed the 12.5% stipulation would determine the width of the detection test area in all but one case. It also showed that the reported width of sensing of some (but not all) vehicles would exceed the width of the detection test area.

Additionally, the survey demonstrated that the width of sensing, i.e. the area in which a detection of a pedestrian is potentially covered, can also extend outboard into an area where the front-end is highly curved and a glancing blow of the impactor could occur. Furthermore, subtracting 12.5% of the relevant vehicle width at each side could also still result in an area with potential impactor spin-off. In general, new vehicles are expected to have a greater width of sensing relative to vehicles not fulfilling any of the requirements associated with a detection test area.

Table 2. Survey of current vehicles with DPPS (VDA, 2022).

OEM	RVW* (mm)	RVW - 2*12,5% (mm)	Corner gauge - 2*42mm	Width of Sensing (mm)	Type of sensing system	Vehicle Category
# 1	1985	1488.75	1108	1390	single pressure tube	SUV
# 3	1954	1465.5	1012	1544	pressure tube + 3 accel.	SUV
# 4	1922	1441.5	1452	1672	single pressure tube	Sedan
# 5	1880	1410	1110	1316	single pressure tube	Sedan
# 1	1878	1408.5	1328	1600	single pressure tube	SUV
# 3	1876	1407	1234	1380	single pressure tube	SUV
# 5	1871	1403.25	972	1472	pressure tube + 3 accel.	Sedan
# 1	1838	1378.5	1120	1400	7 accelerometers	Sedan
# 2	1820	1365	1258	1410	single pressure tube	Sedan
# 3	1798	1348.5	1304	1424	single pressure tube	Compact
# 4	1790	1342.5	1170	1430	pressure tube + 3 accel.	Compact
# 5	1777	1332.75	1200	1276	single pressure tube	Compact

*The 250 mm stipulation did not apply to any of the vehicles in the survey.
Dark green: Determination of the Detection Test Area
Light Green: Width of Sensing larger than Detection Test Area

The IWG finally agreed upon that the minimum width of the detection test area would be the relevant vehicle width minus 12.5% (but not more than 250mm) on each side. Additionally, the width must extend to at least 42 mm inboard of each corner of bumper (CoB), see Figure 4:

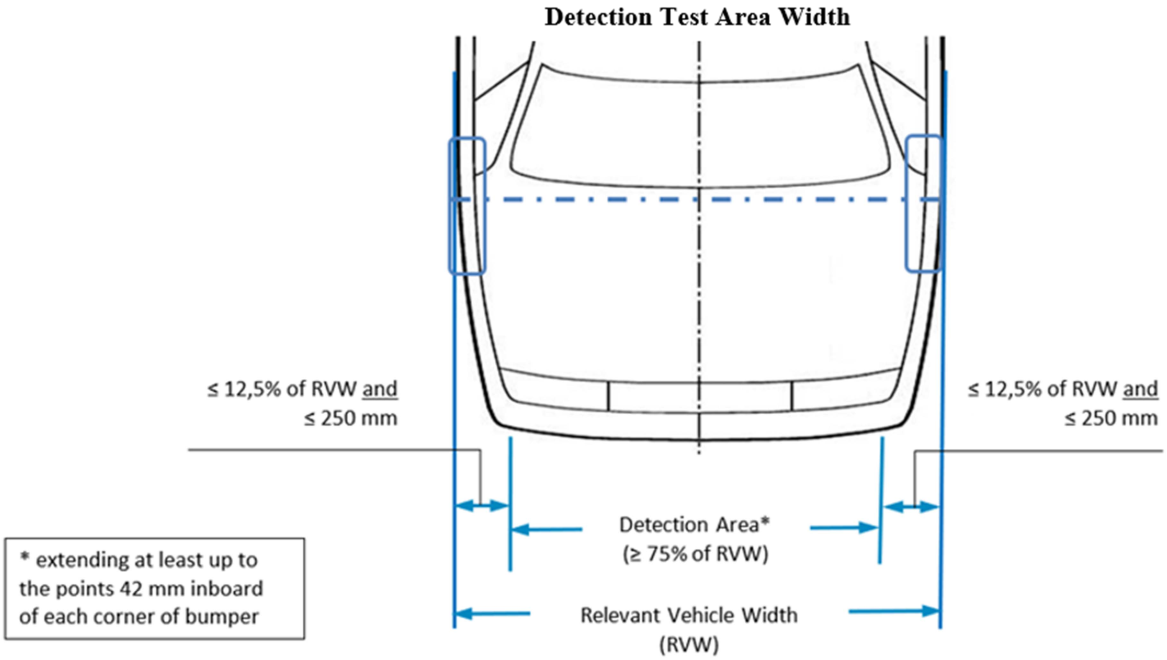


Figure 4. Definition of the Detection Test Area (based on Gehring et al., 2020).

Depending on the outer contour of the vehicle frontend, the detection test area is either determined by the CoB -42mm on either side (compare Figure 5 left), or the relevant vehicle width -12,5% on either side (Figure 5, right):

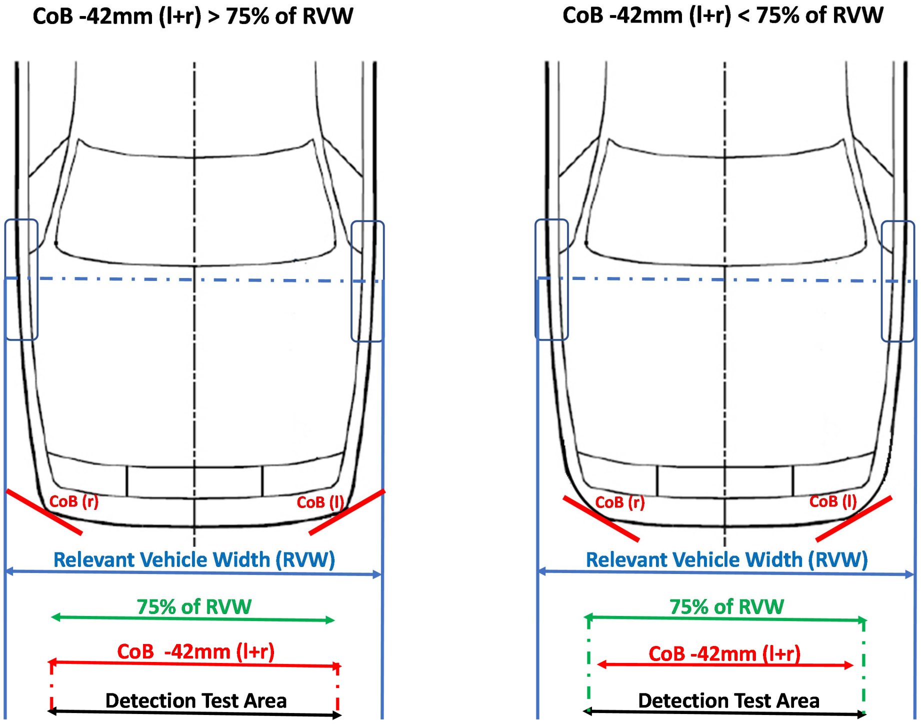


Figure 5. Factors for the determination of the detection test area.

Sensor activation tests

The draft amendment specifies sensor activation tests for UN-R127 and UN-GTR9. For UN-R127, the detection test area will be subdivided into thirds of equal width, measured with a flexible tape along the outer bumper contour at a height of the upper bumper reference line. A minimum of one test per third with the Flex-PLI, with a distance of at least 50mm to adjacent points, will be performed at the lower deployment velocity threshold. For UN-GTR9, there will be no mandates on the number of tests or where along the bumper reference line testing is carried out.

When tested with a moving vehicle against a stationary impactor, a vehicle velocity tolerance of ±0.6m/s and an impact accuracy of ±50mm must be met. During the inverse test with the FlexPLI propelled against the stationary vehicle, all tolerances on impact velocity and impact location specified in the UN-R127 / UN-GTR9 injury assessment tests must be fulfilled. Tests must be repeated if they do not meet the prescribed test specifications and the DPPS does not deploy. If the DPPS does not activate in any of the tests, the subsequent headform tests will be performed with the DPPS in the undeployed position.

TIMING OF DPPS DEPLOYMENT

As one of the indispensable prerequisites for consideration of the safety benefits provided by a DPPS, its position must be in its intended position during the pedestrian's head impact. For testing the DPPS statically in the fully deployed position, the total response time (TRT) of the system must be smaller or equal to the head impact time: $TRT \leq HIT$. If the $TRT > HIT$, the test is to be performed dynamically on a deploying DPPS or statically on a completely undeployed system. For contracting parties not considering static tests on the fully deployed system, the determination of the TRT is not necessary; however the sensing time (ST) as part of the TRT as well as the HIT must be determined in order to appropriately synchronize the firing times of the head impactor and the DPPS during dynamic headform tests.

Total response time

The total response time is the first benchmark for deciding upon the state of the DPPS during static headform tests. It is the sum of the sensing time (ST) and the deployment time (DT): $TRT = ST + DT$. The sensing time is understood as the duration from the time of first contact of the pedestrian (excluding forearms and hands) with the vehicle outer surface until the initiation of the deployment. The deployment time means the duration from the initiation of the deployment until the DPPS reaches its deployed position. The sensing time is experimentally determined during an impactor test with the FlexPLI at 40km/h. It starts with the first contact of the impactor with the vehicle frontend. As with the sensor activation tests, this test can be performed either as a driving test with a stationary FlexPLI or as an inverse test with the FlexPLI being propelled horizontally against the vehicle frontend. The same test specifications as for the sensor activation tests apply.

The IWG discussed several aspects that need to be taken into account when determining the TRT. The TRT can, in principle, be considered as the elapsed time from the point of first contact with the pedestrian until the operating condition of the DPPS. However, a full deployment is not necessarily equal to the required deployment height (RDH), i.e. the height which is required in order to provide sufficient clearance under the bonnet for head energy absorption. Furthermore, a full deployment / final state can differ from the maximum deployment height since, after having reached the maximum, the DPPS may oscillate and fade out around the final state. For each test point on the bonnet, the RDH, maximum deployment height (MDH), and final state and their corresponding timings will need to be compared with the HIT of the pedestrian. Figure 6 illustrates possible different states of the DPPS during its deployment:

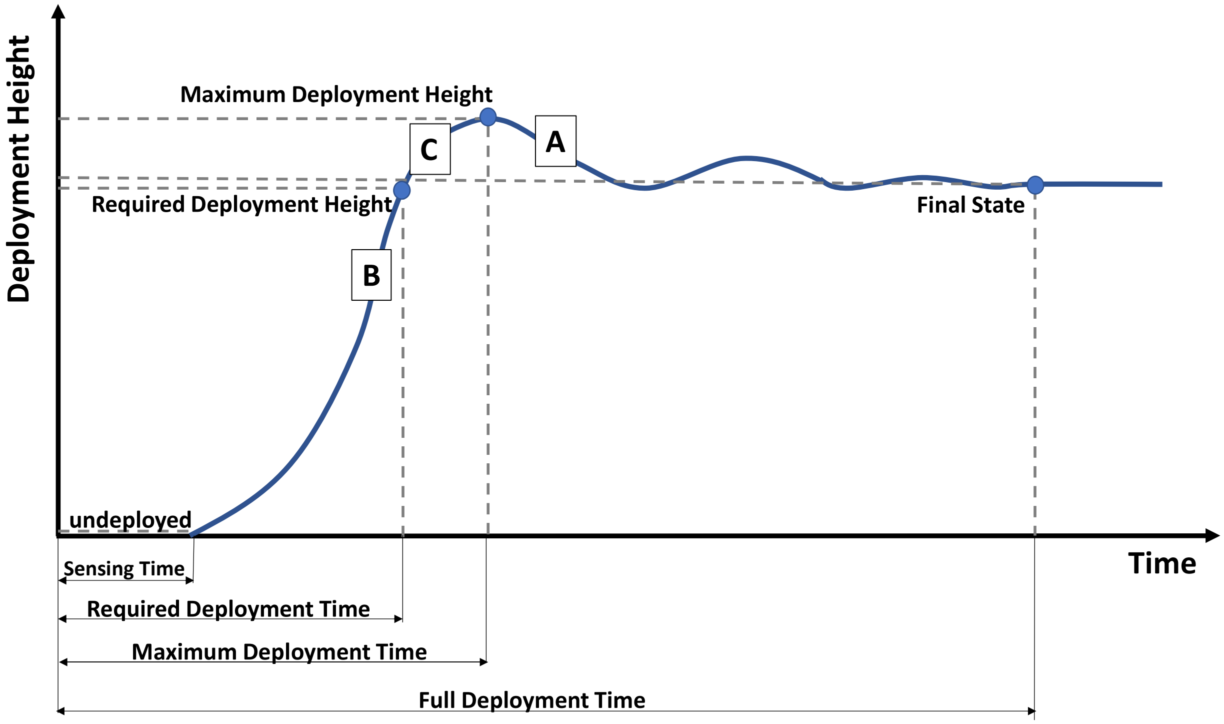


Figure 6. DPPS deployment height vs. time (Zander, 2022-2).

Subsequent to the required deployment time (RDT), i.e. the duration from the time of first contact of a pedestrian with the vehicle front until the DPPS reaches (stops at or passes) the RDH, the system may continue moving upwards until it has reached the MDH at the maximum deployment time (MDT). Afterwards, it may continue to oscillate around the full deployment height which will be the final state of the DPPS.

According to the draft procedure, depending on the HIT of the pedestrian, the DPPS may be tested in the fully deployed state (HIT ≥ MDT, in area "A") or in the dynamic mode while the DPPS is deploying (HIT < RDH, in area "B"). The test conditions for RDT ≤ HIT < MDT in area "C" depend on the effects of the oncoming, not yet fully deployed, DPPS on loads to the headform. If the effects are negligible, the DPPS may be tested statically at a height no more than the RDH. Otherwise, a dynamic test at the time of head impact must be performed. However, since a study of the possible effects of an oncoming DPPS did not result in unambiguous evidence for a neglectable influence, the draft test procedure tentatively specifies to perform all tests with HIT < MDT with the DPPS in the dynamic mode.

Head impact time

For a decision upon the boundary conditions of headform impact tests, the TRT is to be compared with the HIT of the pedestrian. The IWG discussed several alternatives for HIT determination: (a) by means of numerical simulations with HBMs on vehicle models, (b) by performing experimental full-scale tests using pedestrian dummies and the actual vehicle (c) by applying an empirical formula to calculate a generic HIT.

The IWG intends to present the draft procedures in multiple phases. For the first phase of legal DPPS testing, HITs are determined by means of numerical simulations, only. The method for including full scale dummy tests and the generic approach with empirical formula are being further evolved for subsequent phases of UN-GTR9 and UN-R127.

Simulation-based approach

A simulation-based determination of pedestrian HITs on vehicle frontends requires high quality HBMs and vehicle models. Euro NCAP already developed a procedure for the certification of HBMs with regular updates and revisions (Euro NCAP, 2021). The IWG transposed this procedure into the draft amendment's regulatory text for the HBM qualification, including the documentation of the validation of the reference HBMs. Figure 7 illustrates the process for determination of the HIT based on simulations with qualified HBMs:

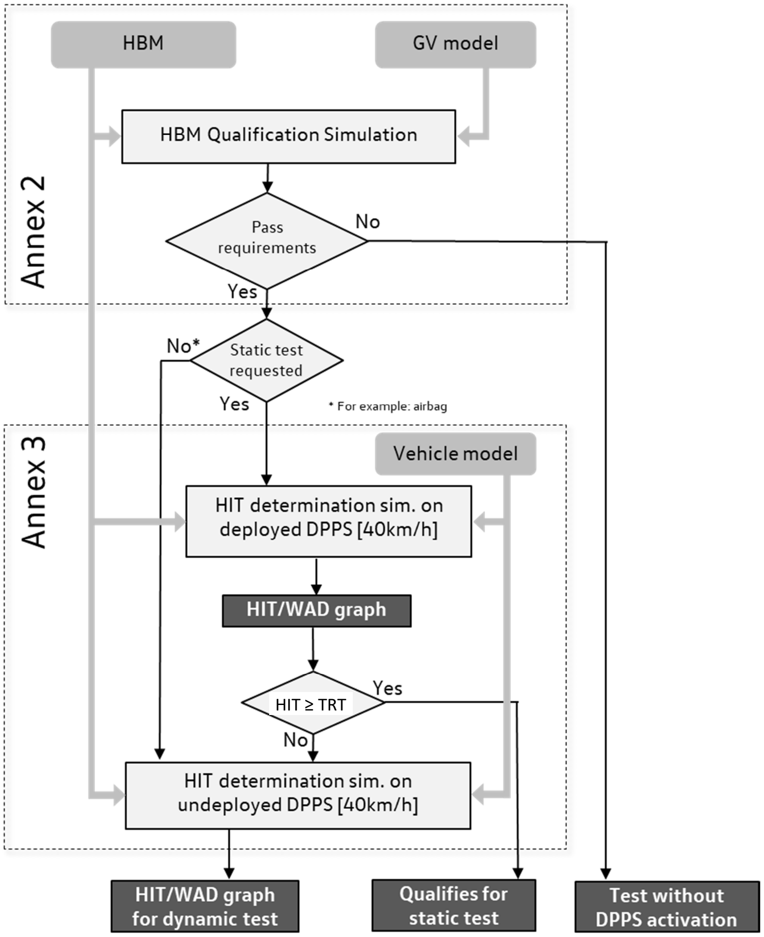


Figure 7. Flowchart for HIT determination based on numerical simulations (Besch, 2022).

Qualification of the HBM is performed on Generic Vehicle (GV) models representing a roadster (RDS), a family car (FCR) and a sports utility vehicle (SUV). A multi-purpose vehicle (MPV) had been evaluated and used for several years by Euro NCAP (2021). Since its shape was found to be represented by FCR and SUV, it was removed from the simulation matrix. Those findings were transposed to the legal procedure.

Vehicle speeds are 30km/h, 40km/h and 50km/h. All relevant HBM statures are used at predefined initial postures, with the Head Centre of Gravity (CoG) located on the vertical longitudinal vehicle centre plane. The static and dynamic coefficients of friction are 0.3 each.

During the qualification simulations, HIT values, the height of the centre of the left and right acetabulum centres (AC), the head CoG (HC) relative to the ground level and their relative horizontal distance at HIT need to fulfill the corridors drafted with reference values from HBMs that were validated against PMHS by Forman et al. (2015). The calculated HIT from the simulations is the elapsed time between the first time where the contact force deviates from 0 (neglecting shoulder and upper arm) and the contact time of the head to the vehicle.

The HBMs for the six-year-old child (6YO), the 5th female (AF05) and the 50th male (AM50) need to be specifically qualified. For the 95th male (AM95), no qualification simulations are needed because the AM95 HBM was derived directly from the AM50 HBM. The 6YO, AF05, and AM50 HBMs were developed independently. Only HBMs qualified according to the described procedure can be subsequently used to determine the HIT with simulations on the actual vehicle models.

If headform compliance tests are targeted to be run statically on a deployed DPPS, the HIT determination simulations are to be performed on the deployed DPPS. If the requirement HIT ≥ TRT is met, the headform compliance tests may be done statically on the deployed system; otherwise, further HIT determination simulations have to be performed on the undeployed DPPS for setting up the firing times and WAD values during dynamic compliance tests on the deploying DPPS.

If no static but only dynamic headform compliance tests on the deploying DPPS are requested, the HIT determination simulations will be altogether performed on the undeployed DPPS only, for firing times and WAD values (compare Figure 7, "Annex 3"). In either case, for simplification, the vehicle speed during all simulations is 40km/h.

All HBMs with their heads properly hitting the actual DPPS need to undergo HIT determination simulations. In case of only one HBM properly hitting the DPPS with its head, the next tallest HBM should also be used for the purpose of drawing a HIT vs. WAD graph. Based on the results of HBM simulations on the deployed DPPS, the HITs of all relevant HBMs are plotted as a function of the WADs and the connecting line (drawn by means of linear interpolation) is compared with the TRT of the DPPS, see Figure 8 (left):

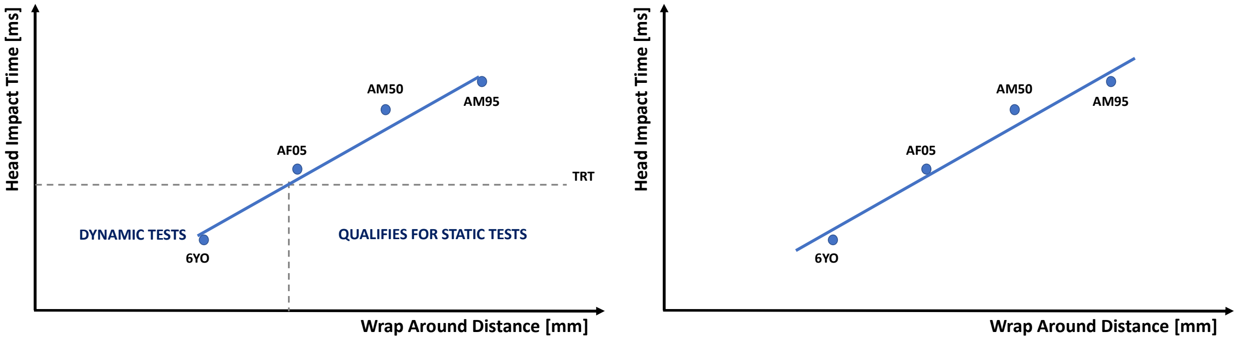


Figure 8. HIT vs. WAD graph for HBM simulations on deployed DPPS (left) and on undeployed DPPS (right).

If HIT ≥ TRT, compliance headform tests may be performed statically on the deployed DPPS. In case of HIT < TRT, compliance headform tests must be performed dynamically on the deploying DPPS. In some situations, only portions of a given DPPS may be tested in static mode since HIT varies depending on the point of impact.

For the determination of the firing times related to WAD of points to be tested dynamically, additional HBM simulations on the undeployed DPPS must be performed, the HIT for all relevant HBM statures plotted vs the corresponding WAD and the regression line marked in the diagram and extrapolated to all WADs within the DPPS (see Figure 8 (right)). To obtain the HIT for a dynamic test, the known WAD can be associated to the corresponding HIT by means of the regression line.

<u>HIT determination by experimental dummy testing</u>

As an alternative to finite element (FE) simulations, the IWG plans to develop a procedure wherein pedestrian head impact times can be determined with full scale vehicle crash tests against stationary pedestrian dummies. Specifications for a midsize pedestrian dummy are outlined in SAE J 2782 (2019), with focus on biofidelic whole body kinematics during a vehicle to pedestrian impact. It may be assumed that additional performance specifications for other pedestrian sizes will be developed in the future. Thus, at this point in time, the experimental determination of the HIT is possible for the 50th male, only. The applicability of alternative dummies such as the biofidelic dummy (Schäuble et al., 2019) needs to be further investigated. A full-scale testing procedure can be found in SAE J 2868 (2020), but it is understood to be a guideline rather than a mandatory set of requirements.

HIT determination by a generic approach

The IWG on DPPS is also planning on developing an option for HIT determination using an empirical formula. This formula will make use of geometry information of the vehicle with potentially significant influence on the pedestrian's impact kinematics: height of different load paths such as BLE, bumper, lower stiffener, bonnet angle etc. Geometry information such as BLE height, bonnet angle, WAD or HIT will be collated in a database. An algorithm will be developed in order to determine the HIT based on the available geometry information and WAD of the test point. A correction factor will account for possible inaccuracies. The database will be updated regularly for further improvement of the approximations. Due to its objectivity and independency, the generic approach seems advantageous, in particular, for self-certification.

ADDITIONAL PREREQUISITES TO BE CONSIDERED FOR FUTURE DPPS AMENDMENTS

The IWG discussed the need for two other system requirements that are not covered by the DPPS amendments: (1) Assurance that a DPPS system will deploy safely at pedestrian impact speeds above 40 km/h; (2) Certainty that pedestrian body loading to a DPPS will not compromise its effectiveness prior to head impact. These requirements are discussed below. Additionally, future accidentology may reveal a prominent safety need exists in current DPPS due to body loading and impacts at higher speeds. In either case, the GTR will be reviewed and adapted if and where necessary.

Protection at higher vehicle speeds

Headform compliance tests are means for representing head injury assessment during vehicle to pedestrian accidents at vehicle speeds of 40km/h. However, passive systems are expected to also provide some protection during accidents with higher vehicle speeds. Since DPPS are to provide at least the same level of protection as passive systems, they need to ensure measures to meet this requirement. For that purpose, its deployment should be at least initiated at vehicle speeds beyond 40km/h, or sufficient clearance be provided for energy absorption during head impacts at impact velocities higher than 35km/h.

Body loading: Actual DPPS protection level

In case of meeting the defined prerequisites, DPPS may undergo headform compliance tests in a deployed state or during deployment. The generated clearance underneath the bonnet provides for energy absorption of the impacting headform, decreased impactor accelerations and a lower head injury criterion, linked to a lower injury risk. However, provisions need to take care of the additional clearance not being reduced before pedestrian head impact. In the regulatory impact analysis conducted for the European Directive 2003/102/EC (European Union, 2003), a failure mode and effects analysis found that the actuators used to raise the bonnet pose one of the greater risks to failure of the entire active bonnet system (Hardy et al., 2006). Nuß et al. (2013) also investigated the effect of upper body contact on the deformation of the bonnet:

Figure 9 shows a passive vehicle front with undeformed (left) and with deformed (middle) bonnet due to loadings induced from the upper body of the pedestrian (right), at the location of and prior to head impact:

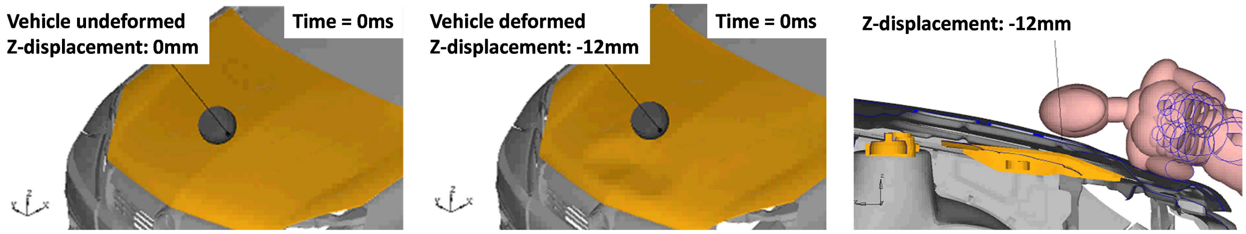


Figure 9. Deformation of the bonnet due to upper body prior to head impact (Nuß et al., 2013).

The influence of the deformation is depicted in Figure 10: The peak headform acceleration during head impact on the deformed bonnet exceeds the acceleration on the undeformed bonnet by approx. 40 percent; the HIC increases by almost 44 percent.

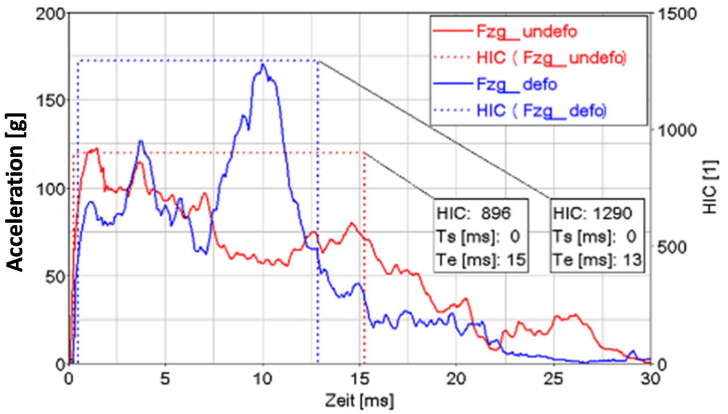


Figure 10. Head acceleration during impact on undeformed and deformed bonnet (Nuß et al., 2013).

Notwithstanding concerns with higher speeds and body loading, the IWG agreed that a regulatory need is not known with enough certainty to warrant the development of test procedures and requirements. However, further research or the development of future DPPS may result in insights for which the effect of pedestrian body loading and protection at higher speeds may require special attention. Test procedures may be needed to assure that the lifting linkages are strong enough for not only the initial lift but also to support the weight of the pedestrian's torso so that the bonnet does not collapse prior to head-to-bonnet impact. The IWG furthermore acknowledged that corresponding requirements have already been implemented within the Euro NCAP test procedures (Euro NCAP. 2010).

Non-contact pedestrian detection sensors

In current DPPS, only contact sensors are taken into consideration for pedestrian detection. Procedures for forward-looking and non-contact-based sensing systems that will contribute to a time shift of the initiation of the deployment and the TRT and allow for actuators with larger deployment times may need to be elaborated.

IMPACTOR COMPLIANCE TESTS

Prior to headform testing, the vehicle markup, including the allocation of the performance zones "HPC 1000" and "HPC 1700" and test point selection, is always done on the undeployed DPPS. UN-R127 specifies a minimum of 18 headform tests, thereof 9 to the child headform test area and 9 to the adult headform test area. Furthermore, UN-R127 prescribes that 3 impacts for each impactor be tested to each third of the bonnet (UNECE, 2013). UN-GTR9 does not define a number of tests.

With the introduction of the General Safety Regulation (EU) No 2019/2144, cyclists as the second big group of vulnerable road users will be protected by extending the head impact area up to a maximum of WAD 2500, adding a windscreen test area and a cowl monitoring area (European Union, 2019). Thus, according to the respective amendment to UN-R127, wherever possible, at least one out of the nine tests each with the child and the adult headform impactor should be performed within the windscreen test area and within the cowl monitoring area (UNECE, 2022).

Depending on the degree of fulfillment of the prerequisites, the compliance tests with adult and child headform impactor are performed on either the undeployed or the deployed DPPS, or dynamically on the deploying DPPS. The firing times for the headform impactor and the DPPS during dynamic tests are to be derived from the generated HIT vs. WAD regression line in Figure 8 (right). Head impact velocity is 35km/h. HPC values are calculated from the recorded headform accelerations. The HPC requirements remain unchanged.

PROCEDURE

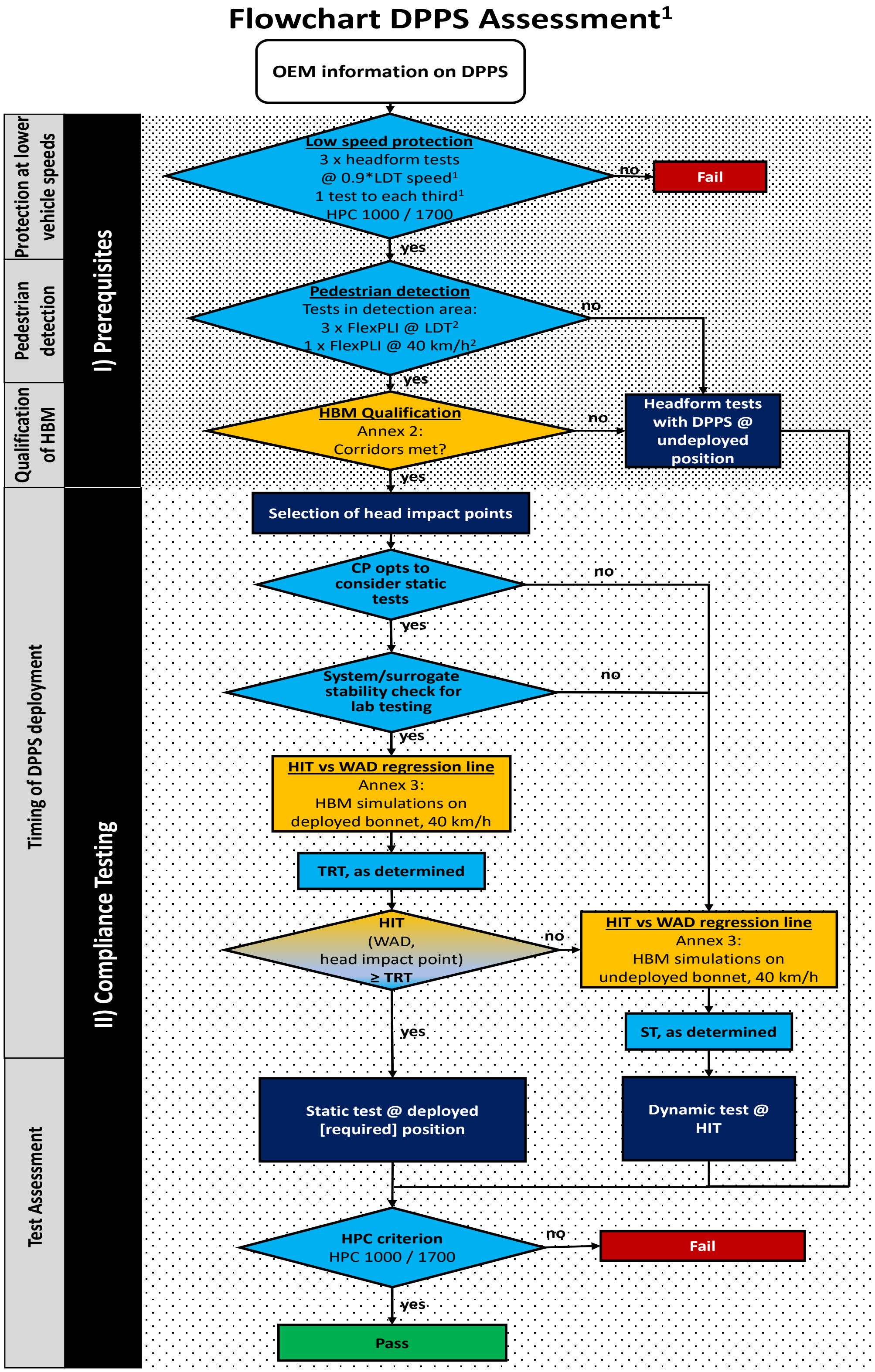
The flowchart in Figure 11 summarizes all steps that need to be passed for the assessment of DPPS according to the test procedures drafted by the IWG. The DPPS assessment is divided into the verification of the prerequisites, followed by the compliance testing.

Prerequisites

As first prerequisite the DPPS needs to demonstrate a pedestrian protection at vehicle speeds below the deployment threshold. There will be a slight difference in the draft amendments. For UN-R127, a minimum of three headform impactor tests are to be performed on the part of the vehicle front being affected by the DPPS, at headform impact velocities equivalent to the vehicle speed at lower deployment threshold. HPC 1000 must be fulfilled at 2/3 of the affected part of the vehicle front. For the remaining test area, HPC 1700 shall not be exceeded. For UN-GTR9, unlike UN-R127, the amendment does not specify a minimum number of tests, but it does maintain the HPC requirements. If those are fulfilled, the proper functionality of pedestrian detection is checked as second prerequisite, otherwise, the DPPS fails.

To demonstrate that a pedestrian is detected in case of an accident, UN-R127 will require three tests with the FlexPLI with an impact speed equivalent to the vehicle speed at lower deployment threshold and one test at 40km/h in the detection test area. UN-GTR9 will not specify a number of tests. If, during all tests, the FlexPLI is re-cognized by the sensing system of the DPPS and its deployment initiated, HBMs will be qualified to fulfill the third prerequisite; otherwise, all headform compliance tests are to be performed with the DPPS in undeployed position.

During numerical simulations of generic vehicle frontends, all HBMs that are used to determine HIT for the compliance testing must be qualified and fulfill reference corridors for AC, HC and HIT. In case of meeting the corridors, clearance provided by DPPS may be taken into consideration during compliance testing; otherwise all headform tests must be performed against the DPPS in undeployed position.



¹: Will be updated with DPPS Phase 2 (Generic approach)

²: Minimum number of tests specified for Contracting Parties of the 1958 Agreement, only

Figure 11. Flowchart for the assessment of DPPS under consideration for UN-R 127 and UN-GTR9 (Zander, 2022).

Compliance testing

Prior to headform compliance testing, the vehicle markup, allocation of the HPC 1000 and HPC 1700 performance zones and the selection of head impact points are done with the DPPS in the undeployed position. Based on the fulfillment of all prerequisites, the amendment will permit Contracting Parties (CP) to the agreements of 1958 and 1998 to perform headform compliance tests on a statically deployed (static tests) or on a deploying (dynamic tests) DPPS, see Figure 11.

For static tests, a stability check is needed to verify that the resisting force of the pre-deployed DPPS is equivalent to the force in a real-world situation when the DPPS deploys just before the head of a pedestrian makes contact with it. Depending on the outcome of the stability check, a time constraint may be needed, i.e. the test must be run within a certain time period after deployment. Otherwise, an unlimited period of time is allowed in which the test may be conducted on a static, pre-deployed DPPS.

As demonstration of HIT ≥ TRT of the DPPS, simulations with all relevant statures of the qualified HBMs are performed on the deployed DPPS of the actual vehicle model and the HIT vs. WAD regression line plotted (compare Figure 8, left). For all selected impact points with the HIT greater than or equal to the TRT, static tests on the deployed DPPS may be performed. For the remaining impact points dynamic tests on the deploying DPPS are conducted. In the latter case, prior to headform testing, for the correct timing of the DPPS and the headform impactor, additional HBM simulations with the qualified HBMs are performed on the undeployed DPPS of the actual vehicle model and the HIT vs WAD regression line plotted and extended to all relevant WADs within the DPPS (see Figure 8, right).

In case of the CP opting for dynamic tests only, the stability check, the HBM simulations on the deployed DPPS and TRT determination are not necessary. HBM simulations with the qualified HBMs are performed on the undeployed DPPS to create the HIT vs WAD regression line that is extended to all relevant WADs. For the determination of the correct timing during testing, the sensing time (ST) needs to be previously determined.

For the first phase of implementing the DPPS procedures, HITs will be determined by means of numerical simulations, only. The formerly described method for including full scale dummy tests and the generic approach with empirical formula are being further explored by the IWG for subsequent phases.

DISCUSSION

A draft procedure for assessing DPPS systems as part of whole vehicle type approval or self-certification is being developed by an informal working group of UNECE. Depending on the degree of fulfillment of several prerequisites, the procedure specifies that the DPPS may be tested statically in the deployed state or dynamically during deployment. The procedure is intended to enable authorities to fully integrate the DPPS within compliance testing according to UN-R127 and UN-GTR9.

However, several shortcomings and limitations of the procedure have been identified which could decrease the actual pedestrian protection during an accident. The FlexPLI has proven to be a robust test tool for the assessment of the sensing system with a high repeatability of the generated intrusions. However, it represents a typical rather than the hardest to detect pedestrian. For pedestrians that remain undetected, the DPPS does not offer any safety benefit. Since, due to feasibility reasons, the detection test area does not cover the entire vehicle width, not all pedestrian trajectories can be accounted for and not all head impacts can be mitigated.

Furthermore, the clearance between the surface of the DPPS and the underlying structure may be compromised due to upper body contact prior to head impact. Also, the deploying DPPS may have a negative influence on the pedestrian's head that differs from the laboratory test conditions with an isolated headform impact. The quality of the determined HITs as basis for DPPS conditions during compliance testing strongly depend on the correlation of the HBMs with actual pedestrians as well as the vehicle models with the actual vehicles. Experimental dummy tests and the generic HIT determination are expected to increase the objectivity of the procedure. Finally, procedures for forward-looking and non contact-based sensing systems that will contribute to a time shift of the initiation of the deployment and the TRT need to be elaborated.

CONCLUSIONS

A set of procedures and requirements for DPPS is in the final stages of development. These are intended to enable authorities to approve and certify systems with a deployable unit for head protection. Including a generic approach for HIT determination in the future is expected to increase objectivity of the procedure. However, further research is needed to also consider the influence on, and possible injury mitigation to body parts other than the head. The upcoming scope extension of UN-R127, taking into account the head protection of cyclists, will bring new challenges to the sensing system and possibly require modifications of the sensing impactor and the simulation procedures for HBM qualification and HIT determination.

DISCLAIMER

The authors of this paper are members of the IWG on DPPS who have helped to create the draft procedures. IWG members (including the authors) do not have the authority to approve the procedures for regulatory use. Although the authors may represent their respective contracting parties within the deliberations of the IWG on DPPS, the views expressed in this paper are not necessarily those of the contracting parties to which they belong. Authorship of this paper does not guarantee that a contracting party will completely agree with the positions taken or will vote to affirm adoption of the DPPS procedures into GTR9 or UN-R127.

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