IMPACTOR DEVELOPMENT FOR THE ASSESSMENT OF ACTIVE PEDESTRIAN PROTECTION SYSTEMS

Edmund Marx
Werner Bieck
Thierry Mousel
IEE S.A.
Luxembourg
Paper Number 11-0177

ABSTRACT

Although pedestrian protection regulation does not yet cover the complete testing of active protection systems, Euro NCAP introduced in 2011 a pop-up hood test protocol [1]. Part of this assessment is a physical impact of a leg impactor against the vehicle front-end at the system's lower deployment threshold speed to test the sensing systems' response.

As the leg impactors used for injury assessment are not suitable for sensor testing, some first generation "sensor assessment impactors" were developed. Three of them can be selected within the Euro NCAP testing: IEE lower limit impactor, PDI, TRL SensorLeg. But as each of these impactors has certain limitations, further research was needed to develop an impactor reproducing a representative human impact.

This paper describes the development of an enhanced impactor with the highest possible level of abstraction, representing an appropriate effective mass not depending on the vehicle front-end geometry, showing human-like material properties and suitable for testing the "lower limit" case. The "lower limit" is defined as the lowest possible impact imprint that a sensing system must detect in a pedestrian-vehicle collision.

A first step in the development is based on LS-DYNA MADYMO coupled simulations where collisions between various MADYMO model statures (six-year-old child, 5% female, slim tall male, 50% male) and a variable test rig are evaluated. The test rig consists of variable load paths representing hood leading edge, lower bumper stiffener and the crossbeam area. In a second step, calculations are performed with an IEE in-house finite element human pedestrian model that is based on a driver knee-thigh-hip model which was further developed to a pedestrian model. This model was also scaled to represent the same adult pedestrian statures as mentioned above. Both simulation results were cross-checked and resulting differences were elaborated in a sensitivity analysis regarding knee-joint bending, knee-joint shear stiffness and contact stiffness of the MADYMO models.

The resulting impactor with a mass of approximately 6.6 kg at maximum abstraction level represents the lower limit against a wide range of different vehicle front-end designs. Omitting the knee joint allows the representation of the lower limit stature, which can be the 5th percentile female, the slim tall male or the six-year-old child, depending on the front end geometry. The impactor has a flexible robust core and the tissue is made of PU material replicating human tissue characteristics. The impactor can be shot with a propulsion system or used in driving tests.

The applicability of the impactor may be restricted for low bumper vehicles with a sensor mounting height below 400 mm above road level.

As the development of active protection systems including A-pillar airbags is ongoing, there is a pressing need for defining procedures testing the sensors triggering these systems. A "lower limit" impactor properly reproducing pedestrian-bumper interaction in a realistic way is a crucial element within such tests.

INTRODUCTION

The first pedestrian protection regulations that became effective in 2005 in the European Union and in Japan initiated a novel kind of vehicle safety technology: pop-up hoods.

These deployable hoods were an answer to the legislative needs on head protection, helping to realize compliance without having to compromise on aesthetic design. Especially for sports cars or sporty limousines it would have violated the design philosophy if the necessary clearance between hood and rigid engine bay components would have been created by simply raising the hood line. Pop-up hoods allow for a sporty design, and the energy absorbing clearance is provided only if a vehicle-to-pedestrian collision occurs. A sensing system in the vehicle front-end analyses the impact characteristics and decides whether hood lifting actuators need to be triggered or not.

While the initial pedestrian protection regulation as well as the upcoming Global Technical Regulation (GTR Nr. 9) [2] precisely define the tests and the criteria for the injury risk assessment of the human leg and head, little attention has so far been given to the specificities of pop-up hood systems. Regulation has not yet defined performance criteria for the sensors that trigger the hood lifting actuators. Current head protection assessment of pop-up hood vehicles is done with the hood by default in a deployed position, assuming that the sensing and triggering system works as intended in a real-life situation.

Early 2011, Euro NCAP started addressing this loophole by introducing a test procedure for deployable hood systems. As a first step, the protocol requires to simulate collisions between the vehicle and pedestrians of various statures in order to define the "hardest-to-detect" pedestrian also called the "lower limit" case. The impact speed corresponds to the lower deployment threshold speed, i.e. the minimum driving speed at which the systems are activated, typically around 20-25 km/h. Four parameters have to be simulated: effective mass, energy, force and intrusion. Whether the six-year-old child, or the 5% female or the 50% male corresponds to the "hardest-to-detect" pedestrian depends, to a certain extent, on bumper height and the height of the pedestrian's centre of gravity. In a second step, physical tests are made with an "appropriate" impactor, representing the "hardest-to-detect" pedestrian. The impact speed again corresponds to the lower deployment threshold speed. The head injury assessment impacts will only be made on the deployed hood if the hood is actuated during these tests. If the hood is not actuated, it will remain in the undeployed position for the head impactor tests.

The leg impactor currently used for the leg and knee injury assessment (EEVC WG17 lower legform impactor) as well as the future impactor (FlexGTR) are not suitable for testing the sensitivity of sensors of deployable hood systems. These impactors represent an "upper limit" with regards to the above mentioned impact parameters, which makes them suitable for injury risk assessment, but they are not able to represent a "lower limit" pedestrian. In addition, the material properties of their outer skins differ from the characteristics of human tissue and muscles. Therefore, their interaction with the bumper in the crucial early impact phase (~20 ms) is unlikely to be pedestrian-like.

In order to reliably reproduce a human impact, various stakeholders developed a new impactor type, "sensor assessment impactors". Due to different approaches, the resulting impactors show some significant differences. Three of these impactors can be selected within the Euro NCAP testing: the IEE lower limit impactor (6 kg), the Pedestrian Detection Impactor (PDI) (9.9 kg) and the TRL SensorLeg (13.4 kg). As each of these first generation impactors has certain limitations, IEE decided to conduct extensive simulations and research, in order to further improve the existing "lower limit impactor" concept in view of developing an impactor that reliably reproduces a "real-life" lower limit human impact.

MOTIVATION FOR IMPACTOR DEVELOPMENT

When IEE started to develop the pedestrian detection sensor system Protecto, the self-evident question that came up was how the sensor could be properly tested. One would require an impactor able to reproduce the interaction of muscles and tissue of a real human leg with the vehicle front bumper in the early phase of the impact. At the same time, the impactor should be able to reproduce a "worst-case" scenario in which the energy transfer into the bumper would be at the lower end of what could be expected in real pedestrian-to-vehicle collisions. IEE analyzed the leg impactors which were available or under development for the leg and knee injury risk assessment tests, but found them not suitable. The weight of these impactors was too high (representing the leg of a 50% male) and the characteristics of their outer materials differed from the ones of human muscle and tissue. Therefore IEE decided to develop its own impactor, the "IEE lower limit impactor".

The IEE lower limit impactor – 1st generation

Simulations of a large range of pedestrian-vehicle collisions and extensive research for an appropriate "tissue" material led to an impactor with following characteristics:

- weight 6 kg
- steel core surrounded by PU resin
- diameter 76 mm
- length 334 mm
- PU thickness 18 mm

This lower limit impactor as shown in figure 1 can be used in driving or propulsion tests. A second variant was designed to be used in pendulum tests (impactor weight reduced to 4.19 kg to compensate for pendulum mass). A Finite-Element model (LS-DYNA) of the leg impactor was also created. In impact tests, the vertical alignment of the impactor relative to the bumper shall be such that the centre of gravity of the impactor hits the bumper leading edge. The impactor can be used in a speed range from 20 km/h up to 55 km/h.

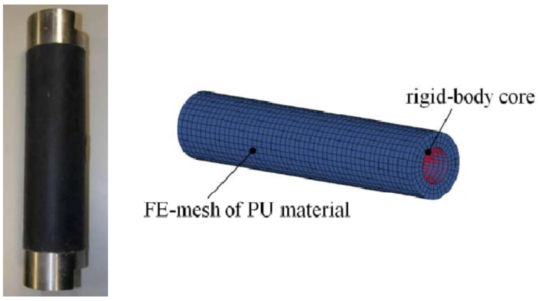

Figure 1. The lower limit impactor and its FE-model.

During testing, the impactor has proven to be very robust, and reproducibility of impacts and sensor signals was very good.

The weaknesses of the impactor

In the course of time, more enhanced simulations have shown that the impactor weight is still slightly too high to represent a worst case "lower limit" impact case, a weight of 5 kg would be more appropriate for such an impactor concept.

The initially chosen concept of aligning the centre of gravity of the impactor to the bumper leading edge aimed at reproducing the "lower limit" case independently from the vehicle bumper height. A disadvantage of this concept is that the impactor does not interact with the front-end's so-called lower bumper stiffener due to its limited length. This can be of concern for vehicles where the lower bumper stiffener's x-position is similar to the one of the main bumper. For such front end geometries, interaction with the lower bumper stiffener can initiate additional rotation into the collision object and thus reduce the energy transfer into the bumper. As a consequence, the signal then measured by a pedestrian impact detection sensor can be lower than the one that would be measured without lower stiffener interaction with the collision object. Another disadvantage is using a rigid core tube for bone/ligament representation, which leads to overestimation of human impact energy when applying the impactor at velocities higher than 20 km/h.

The new impactor concept aims at rectifying these weaknesses in order to be a suitable "lower limit" impactor for a broad range of vehicle front end geometries and designs.

HUMAN MODELING

Appropriate pedestrian models are crucial in order to realistically simulate and reproduce a pedestrian-to-vehicle collision. Special attention has to be given to the capability of the model to simulate the early phase of the leg-bumper interaction.

Currently, a wide range of human models is proposed for analyzing vehicle pedestrian collisions. The selection includes Rigid Multi Body Models as well as Finite Element Models (see Appendix I of [1]). The RMB- and FE-model types have a few advantages and disadvantages either related to their characteristics or to their computing needs.

Table 1.
Comparison of Rigid Multi Body and Finite Element pedestrian models

Model	Advantages	Disadvantages
Rigid Multi Body	- handling/complexity - calculation time	- low local resolution - poor representation of bone geometry - poor contact reproduction (no tissue)
Finite Elements	- high local resolution - good representation of bone geometry - good contact reproduction (tissue model included)	- handling/complexity - calculation time

Existing human models

One of the best known RMB models is the MADYMO model [3], which is available in various pedestrian statures. The MADYMO pedestrian model was developed to reproduce the kinematics of a pedestrian during the impact with a vehicle as well as during the "throw-off" phase. While the model is very well validated for this area of application, its suitability for reproducing pedestrian-vehicle bumper interaction in the very early phase of the collision is quite limited.

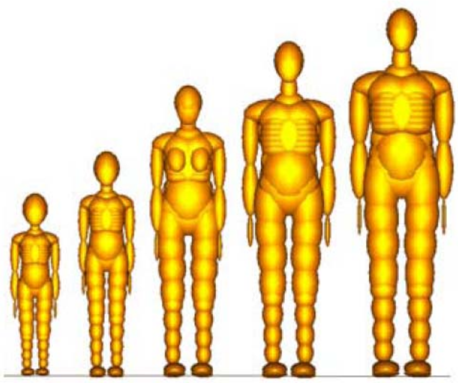

Figure 2. The MADYMO family [3].

Pedestrian-bumper interaction can be reproduced much more precisely with FE-models. Figure 3 shows a selection of existing pedestrian FE-models.

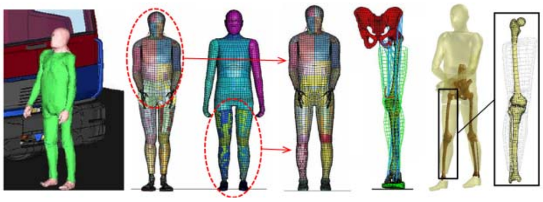

Figure 3. Human FE models from left to right: HUMOS [4], THUMS [5], H-Model [6], JAMA/JARI [6], A-LEMS [7], HONDA [8][9].

These are full FE models, except the Honda model, which is a hybrid model with a rigid upper body. While THUMS may have some shortcomings in leg geometry (legs too close together), the JAMA/JARI model appears to be the most advanced model, as it combines the upper body of THUMS with the lower body of the H-model, and has an adequate leg distance.

A Hybrid model, like the one developed by Honda, is likely to offer the best compromise: lower limbs with detailed FE bones, tissue and ligaments to guarantee an appropriate leg-bumper interaction, and a simplified upper body to reduce computational needs.

The IEE-WPI FE-Model

IEE developed a hybrid pedestrian model, based on the work of C. Silvestri and M. H. Ray [10, 11] which resulted out of a NHTSA research project. The original WPI injury model represents a driver sitting in a vehicle. IEE modified the model in the following areas:

- Repositioning: standing upright
- Discrete knee ligament modeling was replaced by shell element modeling using correct material definitions [12]
- Integration of additional shell elements representing tissue and knee capsule, ensuring necessary overall knee joint stabilization
- The solid femur model approach was replaced by shell elements
- Human skin and tissue was modeled using shell and solid elements, using correct material definitions [13]
- Some additional muscles were implemented
- The upper body is represented by rigid multi body elements

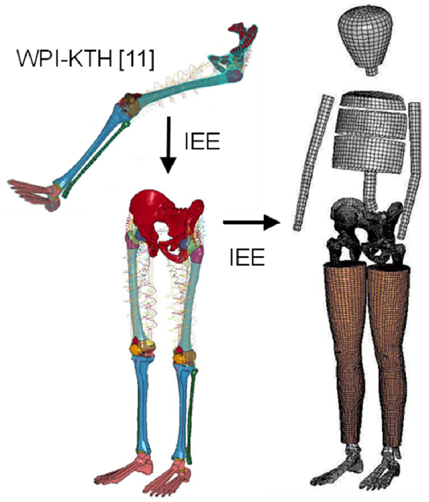

Figure 4. Development steps from the WPI model to the IEE-WPI hybrid pedestrian model.

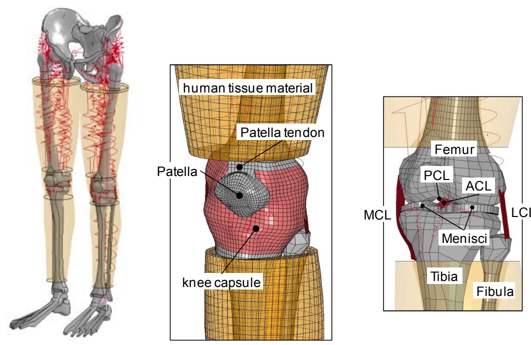

Figure 5. Detailed FE-model for leg, hip and knee area showing muscle, tissue and ligament definitions.

The IEE-WPI models' overall kinematic was validated comparing the impact response with the MADYMO pedestrian model, while the response for several best known load cases regarding lateral impact on lower limbs was validated using literature. For details on the validation methods, see the references:

- Kinematics [14]
- Knee Ligaments [12]
- Femur/Tibia [15]
- Knee [15] [16] [17] [18]
- Tissue [13]
- Muscles [19]

Figure 6 shows the first 250 ms of a simulated vehicle collision against a 50% male MADYMO model as well as against the IEE-WPI model. The good overlap of the movements over time of both models shows that the IEE-WPI can appropriately reproduce pedestrian kinematics.

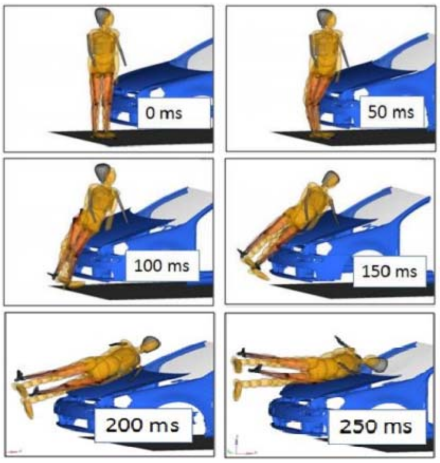

Figure 6. Lateral vehicle impact against the 50% male MADYMO and IEE-WPI model.

VEHICLE TO PEDESTRIAN COLLISION

Besides the pedestrian model, it is important to use a vehicle model which is representative of a vehicle that complies with the legislative passive safety requirements regarding leg and knee injuries.

Vehicle front-end model

The vehicle is represented by a variable test rig made up of the elements which interact with the pedestrian in the early impact phase. It consists of an upper, middle and lower load path corresponding to the bonnet leading edge, the bumper/crossbeam area and the lower bumper stiffener of a vehicle front-end. All three elements can be varied in x- and z-direction in order to represent various front-end geometries as well as vehicle types. A crossbeam foam with a density of 30 grams/liter is chosen as this corresponds with the foams used in modern vehicles with "pedestrian-friendly" bumpers (older vehicles typically used harder foams). The forces versus time values are measured at crossbeam level, where the contact sensors are usually located. The whole setup is assumed to be rigid behind the foam parts and is moving at constant velocity into the object.

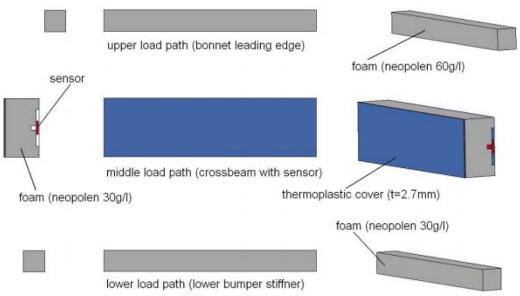

Figure 7. Variable test rig: side-, frontal- and isometric view.

Test rig vs. real vehicle front-end structures

Impact simulations of the IEE lower limit impactor with the test rig model are compared with simulations on existing vehicles. All of these vehicles have a "pedestrian friendly" bumper.

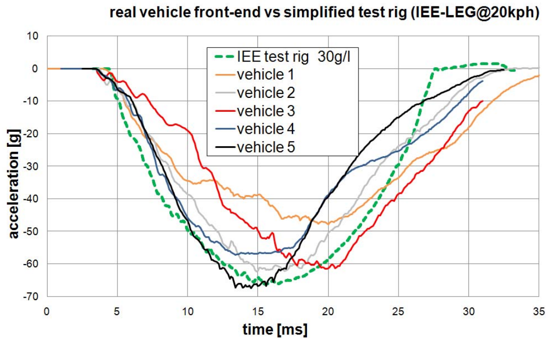

Figure 8. Impactor acceleration data comparison for test rig and vehicle impacts.

The curves show that the chosen test rig appropriately reproduces the front end of modern vehicles

Usage of a reverse engineered PDI model

As the Pedestrian Detection Impactor (PDI) is widely used in the development and testing of pedestrian sensing systems, it has been included in a few comparative simulations.

IEE made use of a reverse engineered PDI-model, validated according to [20], where an ECE R21 pendulum test is performed hitting the impactor at a height of 470 mm above ground level.

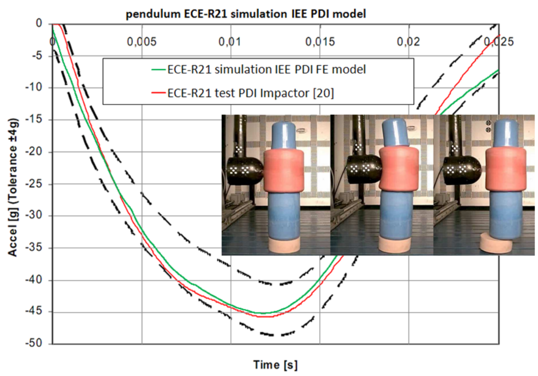

Figure 9. Validation of the reverse engineered PDI-model [20].

The pedestrian-to-vehicle interaction

In view of reproducing a "worst case scenario" from the impact sensing point of view, it is important to make sure that there is only a single leg interacting with the front-end in the early stage of the collision. Whether a standing pedestrian model with parallel legs is reproducing a single leg interaction in the first 20-25 ms of the lateral impact (at 20 km/h) depends on the implemented representation of leg geometry, especially on the defined knee distance.

For some pedestrian models there is very early interaction between the impacted leg and the 2nd leg, which then immediately leads to a double leg impact, while for other models interaction with the second leg only takes place after more than 20 ms after first contact with the bumper.

For simulation models where early interaction of the 2nd leg is an issue, it is recommended to position the model in a distinct walking stature.

The impact of pedestrian model type and walking posture

When comparing a 50% male IEE-WPI model with a 50% male MADYMO model, both in a standing posture with the legs in parallel, significant geometrical differences between both models can be observed (figure 10).

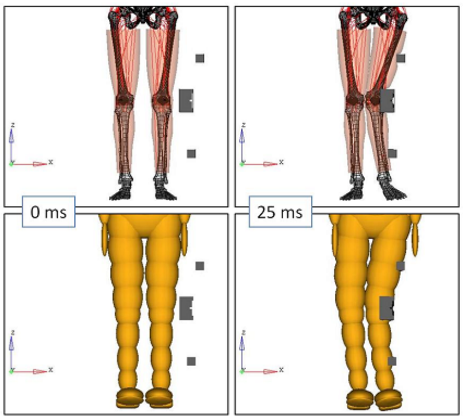

Figure 10. 50% male IEE-WPI (top) vs. MADYMO (bottom), 20 km/h, 0-25 ms.

The simplified leg geometry of the MADYMO defines a significantly smaller knee distance, and the rigid elements of the upper legs are almost in contact. Therefore both legs of the MADYMO interact very early in the collision (within the first 5 ms), which leads to a rather severe impact scenario representative of a "two leg collision" but not of a less severe single leg collision. For the IEE-WPI model, interaction with the 2nd leg is only observed after about 22 ms due to a better representation of the hip-leg anthropometry. At this point in time, the sensing system should already have taken a fire/no-fire decision.

Figure 11 shows force over time simulation curves for a selection of collision partners. For the IEE-WPI model the influence of leg muscle activation is also shown. Activation of the muscles leads to a higher force peak. For the MADYMO models it can be observed that a standing posture creates a much higher impact severity than a walking posture. The difference is especially significant for the 50% male (red curves), but also for the 6-year-old a notable difference can be observed (blue curves). The curves are compared to the 1st generation IEE "lower limit" impactor and also to the PDI impactor (the development of which was based on a standing 6 year MADYMO model).

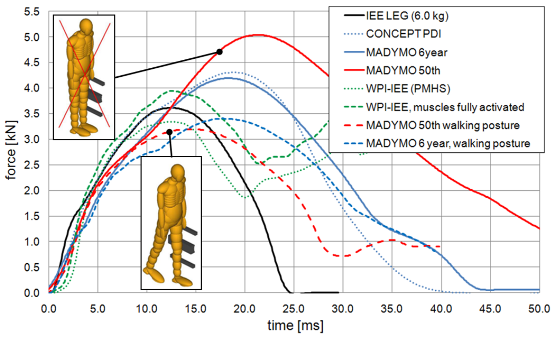

Figure 11. F(t) comparison of various collision partners, 20 km/h.

Some research has already been made to improve the biofidelity of the MADYMO leg model by implementing a more human-like knee. The figures below compare the initial MADYMO knee characteristics to the modifications applied by the University of Virginia (UVa) [21].

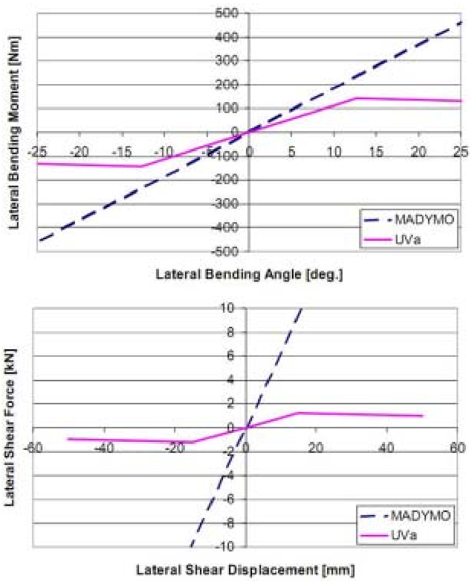

Figure 12. Modified knee bending and shear stiffness according to [21].

The orange spotted curve in figure 13 shows the effect of these modifications, and the additional effect of an adapted contact stiffness is illustrated by the solid orange line. This most biofidelic variant shows higher peak force, while the contact duration is reduced compared to the original MADYMO model. The obtained MADYMO force transient F(t) versus collision time is close to the one of the IEE-lower limit impactor.

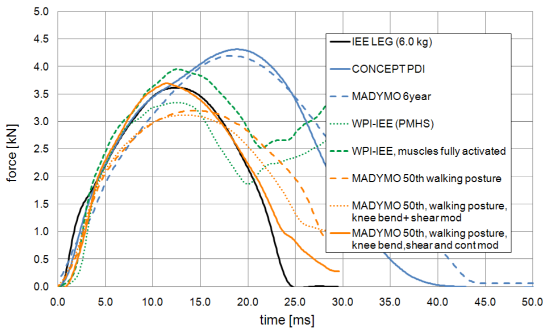

Figure 13. Influence of knee shear, knee bending and contact modification on MADYMO's F(t) curves, 20 km/h.

Momentum transfer and effective impact mass

In order to identify the "hardest to detect" pedestrian, the effective impact mass is considered as a representative parameter. Its calculation is based on the conservation of momentum, neglecting inelastic processes during the constitution phase of the impact. In general, this assumption is only valid for low speed impacts which have to be considered anyway in order to determine the “lower limit” pedestrian. Other parameters like energy transfer or intrusion can be helpful to increase the precision of the evaluation, but they require a more careful evaluation of the overall impact scenario.

A more simplified analytical approach is schematically described in figure 14. When the vehicle front-end gets into contact with a walking pedestrian, the leg-bumper interaction mechanism can be seen as a (non-linear) dual-spring system. The overall compression **α** of two colliding objects with relative speed $\mathbf{v_0}$ in the centre-of-mass system CM can be described by following differential equation [22]:

$$\mu \cdot \ddot{\alpha} = -k(v_0, Y, T) \cdot \alpha^n \qquad (1)$$

with non-linear total spring constants **k**, an exponent **n** to be quantified experimentally and the so called reduced mass $\mu = m \cdot M/(m+M)$. **k** depends on impact location **Y**, impact speed $\mathbf{v_0}$ and ambient temperature **T**.

Integrating equation (1) provides a simple relationship between maximum compression α_{max} and the corresponding collision time τ_{max}:

$$\frac{\alpha_{max}}{\tau_{max}} = \frac{v_0}{\sqrt{\pi} \cdot c(n)} \qquad (2)$$

with integration constant c(n).

In the same way the effective impact mass m << M of the colliding object can be determined according to equation (1) taking the force peak as the integration end point, an approach also proposed in the EURO NCAP protocol.

$$m \cdot v_0 = \int_0^{\tau_{max}} F(t) \cdot dt \qquad (3a)$$

The value depends on front-end stiffness and geometry as the leg cannot be treated as simple rigid body due to inelastic processes (injury effects) and energy absorption limits of the front-end at higher impact speed.

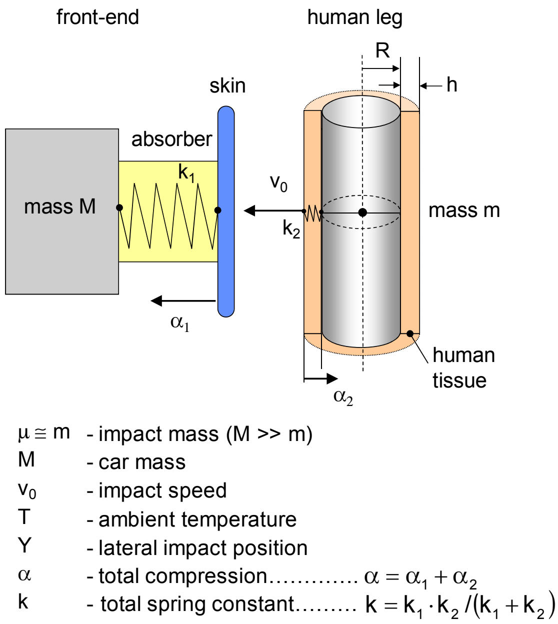

Figure 14. Schematics describing the collision between a car front-end and an impacting object in the centre-of-mass system.

An alternative approach not based on the absolute peak force defines the corresponding effective impact mass as follows:

$$m' \cdot v_0 = \int_0^{\tau_{trigger}} F(t) \cdot dt \qquad (3b)$$

This approach is more aligned with the way pedestrian contact sensors operate. The sensors have a certain trigger level followed by a certain sensing time before the algorithm has to take the decision to fire or not to fire the hood actuators. The available sensing time depends on the total system response time TRT (TRT = sensing time + actuator triggering + plus hood lifting time), and TRT must be smaller than the most critical head-to-impact time HIT for the 6-year-old child. The minimum TRT required by pop-up hood systems typically allows for a sensing time of 20 ms before an actuator trigger decision has to be taken.

In the following all force versus time plots have been evaluated on the basis of a 1 kN sensor trigger level as a starting point and then integrating F(t) for a duration of $\tau_{trigger}$ = 20 ms as maximum sensing time at 20 km/h impact speed.

It has to be pointed out that a typical single-leg bumper collision at 20 km/h lasts about 15-20 ms for common absorbers fulfilling passive safety requirements. Thus, depending on the applied leg model, almost twice the momentum **p** will be transferred within 20 ms sensing time (e.g. IEE leg with τ_{max} at 12 ms) while other impactors representing more severe impacts will introduce only **p** or even less than that (c.f. figure 15). A physically correct evaluation of the impact strength (independent from any sensing system) requires a comparison of specific impact related parameters like $\boldsymbol{\tau_{max}}$ or **p** as defined by equation (3a).

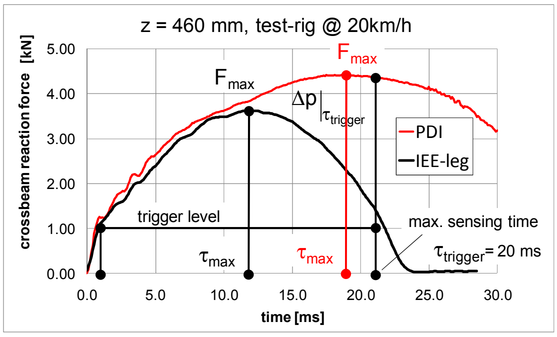

Figure 15. Typical F(t) transient curves for two different types of impactor models (taken from Fig.31) exemplifying the effective mass concept described in the text.

This kind of evaluation can be done straightforward in case of impactors but it might be more difficult for complex pedestrian models at high impact speed due to double-leg collisions. Table 2 compiles the momentum transfer in case of no time limits and shows the related effective impact mass which can be detected. For comparison, the data for 20 ms sensing time is also included.

Table 2.
Effective mass and momentum transfer comparison

Evaluation Method	**IEE-LEG 20 km/h**	**PDI 20 km/h**
Peak force (eq. 3a) Δp @ F_{max} **[Ns]**	32.9	54.3
effective impact mass [kg] resulting from (3a)	5.9	9.8
TRT dependent Δp @ 20ms **[Ns] (eq. 3b)**	55.4	69.7

TEST RIG TO PEDESTRIAN COLLISION SIMULATION

The subsequent graphs and charts show simulation based relative comparisons of various impactor and human-model collisions against a variable test rig. The analysis is performed at 20 km/h, the lowest threshold speed at which sensors should detect a car-to-pedestrian collision

Test results for standard human models

The following graphs show the crossbeam reaction force versus time for the following pedestrian models:

- 50% male and 5% female using IEE-WPI
- 6 year MADYMO with changed contact stiffness, walking posture

The crossbeam height is varied in steps of 20 mm, from 400 mm to 500 mm above the ground.

The smaller the pedestrian, the more the curves diverge for varying crossbeam levels. The data for the 6-year-old child is most sensitive to changing crossbeam heights followed by the 5% female, while the data for the 50% male is quite robust against crossbeam height variations.

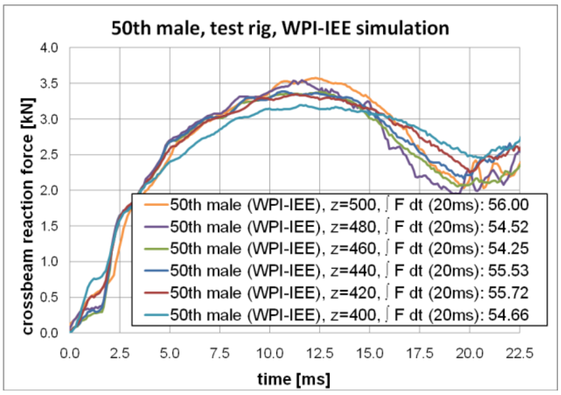

Figure 16. F(t) and ∫ F dt (Ns@20 ms) variation for 50% male as a function of crossbeam height z (mm).

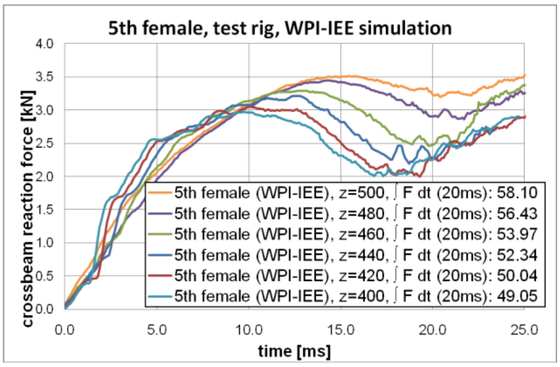

Figure 17. F(t) and ∫ F dt (Ns@20 ms) variation for 5% female as a function of crossbeam height z (mm).

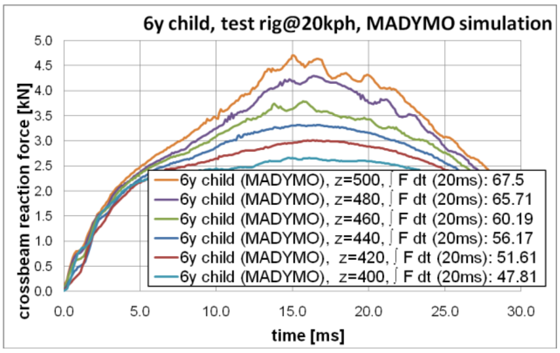

Figure 18. F(t) and ∫ F dt (Ns@20 ms) variation for 6-year-old child (walking posture) as a function of crossbeam height z (mm).

This effect can be explained by the change of the impact point relative to the pedestrians centre of gravity and hip joint, respectively. For the small pedestrian the relative change between the varying impact point height and the centre of gravity height is more important than for a tall pedestrian where the same crossbeam height variation leads to a less substantial relative change.

In the next step, the calculated momentum transfer is used to identify the "hardest to detect" pedestrian for various crossbeam heights. In addition, the data generated for the 1st generation IEE leg impactor is compared to the other pedestrian models.

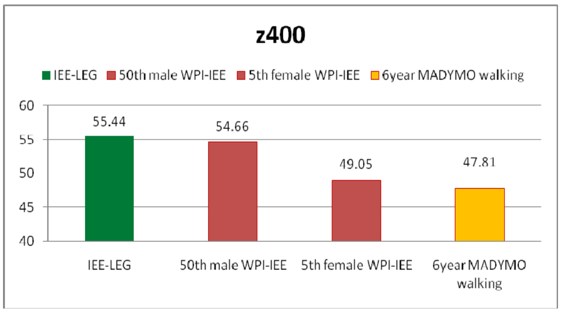

Figure 19. Momentum transfer comparison for crossbeam height of 400 mm, Δp in [Ns@20ms]

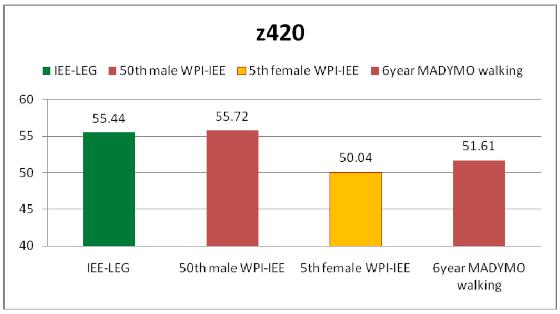

Figure 20. Momentum transfer comparison for crossbeam height of 420 mm, Δp in [Ns@20ms]

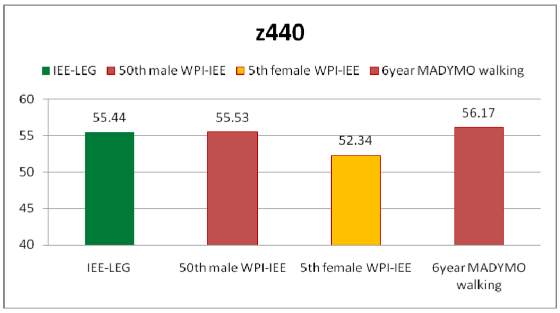

Figure 21. Momentum transfer comparison for crossbeam height of 440 mm, Δp in [Ns@20ms]

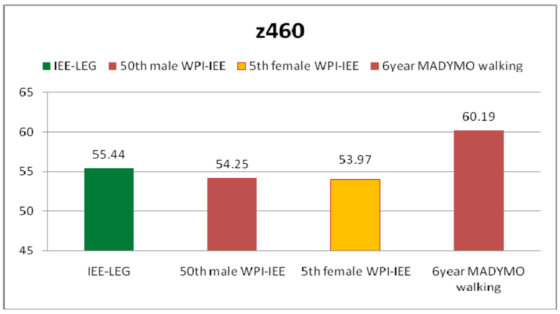

Figure 22. Momentum transfer comparison for crossbeam height of 460 mm, Δp in [Ns@20ms]

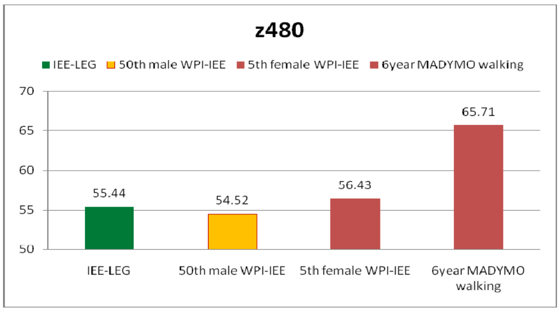

Figure 23. Momentum transfer comparison for crossbeam height of 480 mm, Δp in [Ns@20ms]

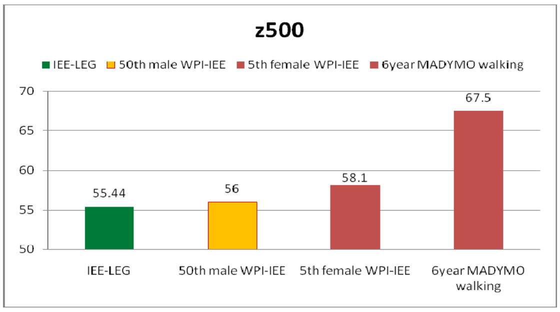

Figure 24. Momentum transfer comparison for crossbeam height of 500 mm, Δp in [Ns@20ms]

For a crossbeam height of 400 mm, the 6-year-old child is the "worst case" pedestrian. For the bumper height range from 420 mm to 460 mm the 5% female is the hardest to detect pedestrian, and for a crossbeam height of 480 mm and 500 mm the situation changes again with the 50% male being the "lower limit" case.

Table 3.
Overview on the "hardest to detect" pedestrian relative to the crossbeam height

Height z	Minimum momentum transfer [Ns @ 20ms]	Hardest to detect pedestrian
400 mm	47.81	6-year-old child
420 mm	50.04	5% female
440 mm	52.34	5% female
460 mm	53.97	5% female
480 mm	54.52	50% male
500 mm	56.00	50% male

The 1st generation IEE lower limit impactor is appropriately applicable for bumper heights from 460 mm to 500 mm, while for lower bumper heights it creates an impact severity above the "hardest to detect" pedestrian.

The VC-COMPAT research project [23] analysed the crossbeam heights of 55 vehicles. The mean crossbeam height was 469 mm. Almost all vehicles (except 4WD and Light Commercial Vehicles) had a significant part of their crossbeam surface in the height range between 400 mm and 500 mm. As the crossbeam is a typical location for a pedestrian detection sensor, the above impact simulations are representative of a major part of the "real-life" vehicles.

Test result for non-standard human model

In addition to the standard human model sizes, a further set of simulations was realised by using an IEE-WPI "slim tall male". The size of the model corresponded to a 50% male, while the weight was reduced to the one of a 5% male.

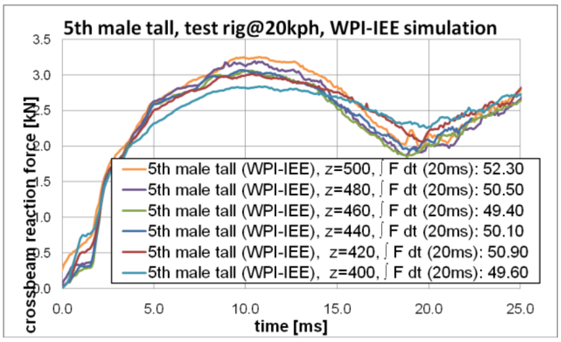

Figure 25. F(t) and ∫ F dt (Ns@20 ms) variation for 5% tall male (weight =5th size=50th) as a function of crossbeam height z (mm).

When comparing the momentum transfer values to the ones of table 2, it appears that this slim tall male would represent a "hardest to detect" pedestrian for bumper heights from 440 mm to 500 mm.

This result is consistent with the above discussed findings as the slim tall male has a comparatively high centre of gravity (similar to the 50% male), but with a significantly lower mass. Due to these proportions it even beats the 5% female with regards to a "lower limit" case for a bumper height of 440 mm.

These results indicate that also non standard pedestrian sizes have to be considered when searching for a "worst case pedestrian". Further investigations with other models may be necessary to confirm these findings.

Therefore the subsequent impactor development and the related analysis are mostly based on findings realized with standard pedestrian statures.

THE IEE LEG IMPACTOR GENERATION 2

As discussed and shown above, the 1st generation IEE "lower limit" leg impactor has some small, but in certain cases non-negligible weaknesses:

- As it is not positioned on the ground but rather used as a "center-of-gravity to bumper" impactor, there is no interaction with the vehicle's lower bumper stiffener which might be relevant for certain sensor systems.

- The impactor has a very rigid core defining much too strong impacts at high speed.
- It is not a realistic "lower limit" for bumper heights below 440 mm

These issues are successfully addressed by the new impactor design.

Concept of the IEE G2 impactor

The illustration below shows a schematic representation of the IEE leg impactor Generation 2 (G2), in the following called the IEE G2 impactor.

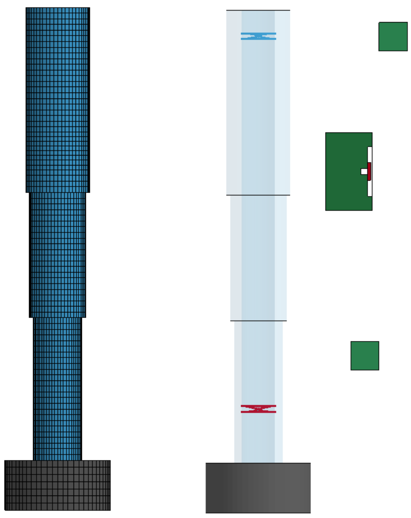

Figure 26. The IEE G2 impactor model positioned in front of the test rig.

The core of the IEE G2 impactor consists of a carbon fiber reinforced tube with two concentrated masses, one towards the top of the impactor (blue) and one towards the lower end (red) (see figure 26). The core is surrounded by a Wevo PU material for human muscle and tissue representation. This material guarantees a humanlike interaction with the bumper in the early contact phase. The diameter of the core is 45 mm, and the total impactor diameter varies from 70 mm at the lower end to 90 mm at the upper end, with a center segment of 80 mm. The impactor weighs 6.6 kg and can be positioned on a 70 mm high base to ensure reproducible friction in driving tests. Including the base, the impactor has a total standing height of 700 mm.

Table 4.
Comparison of the IEE impactors

	IEE lower limit	IEE G2 impactor
Year	2006	2011
Weight	6 kg	6.6 kg
Length	334 mm	630 mm
Diameter	76 mm	70-90 mm
Core	massive steel	carbon fiber tube
Conc. masses	no	Yes

The impactor itself has a height of 630 mm. When used with a propulsion system, the ground clearance has to correspond to the height of the base plate.

The geometry of the G2 impactor has changed significantly compared to the 1^{st} generation lower limit impactor. The length has doubled and the diameter increases from bottom to top, while the weight has only slightly increased. The flexible core and the two concentrated masses are meant to allow for a cerain impactor bending and a more realistic rotation, depending on the point of impact.

IEE G2 impactor test results

A simulation series was performed with the IEE G2 impactor, in line with the previous simulations using the same test rig configuration.

The following graph shows the crossbeam reaction force versus time and momentum transfer values for the IEE G2 impactor for crossbeam height variations from 400 mm to 500 mm.

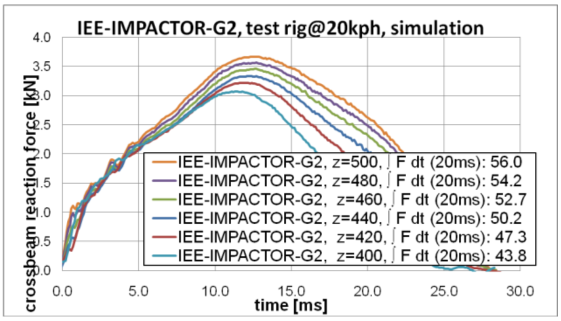

Figure 27. F(t) and ∫ F dt (Ns@20 ms) variation for the IEE G2 impactor as a function of crossbeam height z (mm).

Peak pulse and pulse duration vary with the impact location height and the momentum transfer ∫ F dt (20 ms) increases with impact height. This is a first solid indication that the impactor is able to address a shift in impact location relative to its centre of mass and the response is as intended.

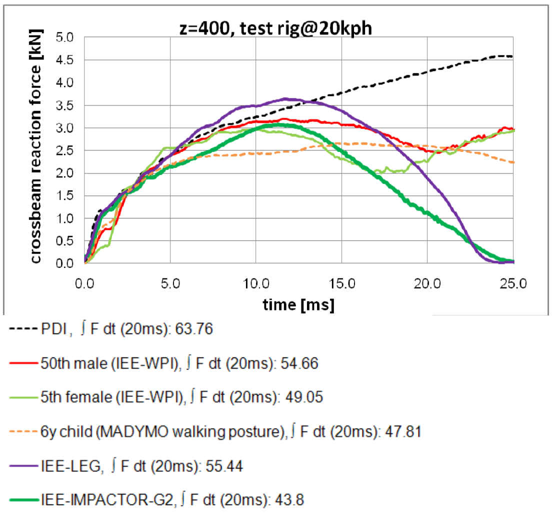

Figure 28. F(t) and ∫ F dt (Ns@20 ms) comparison for impact height of 400 mm.

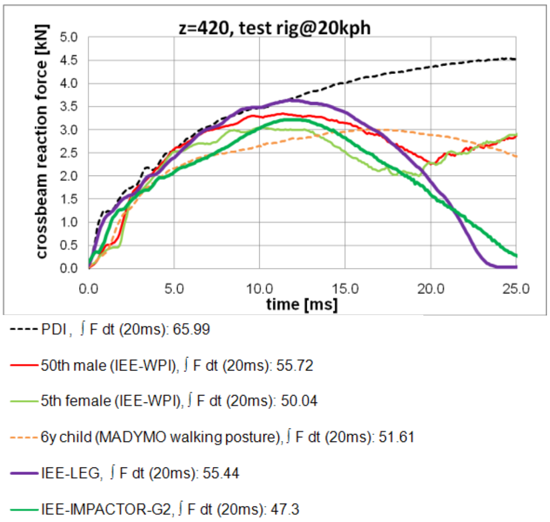

Figure 29. F(t) and ∫ F dt (Ns@20 ms) comparison for impact height of 420 mm.

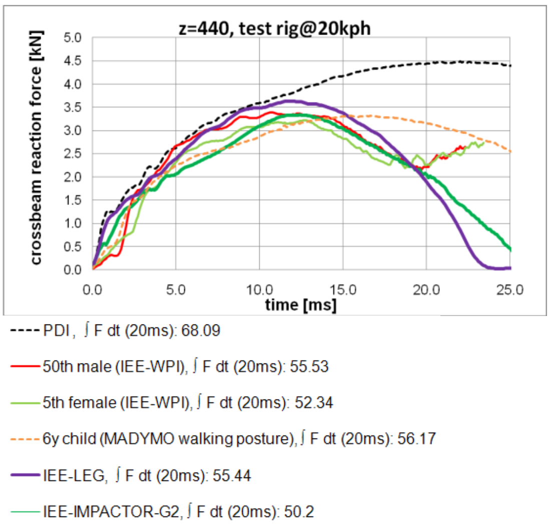

Figure 30. F(t) and ∫ F dt (Ns@20 ms) comparison for impact height of 440 mm.

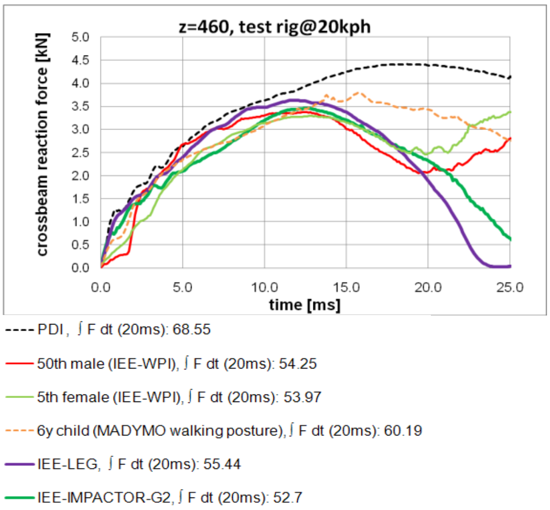

Figure 31. F(t) and ∫ F dt (Ns@20 ms) comparison for impact height of 460 mm.

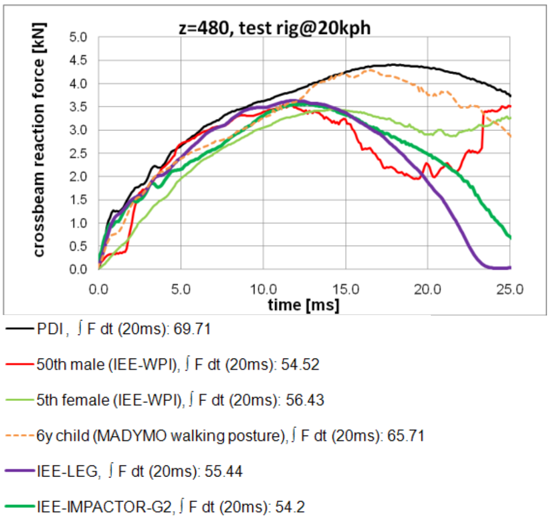

Figure 32. F(t) and ∫ F dt (Ns@20 ms) comparison for impact height of 480 mm.

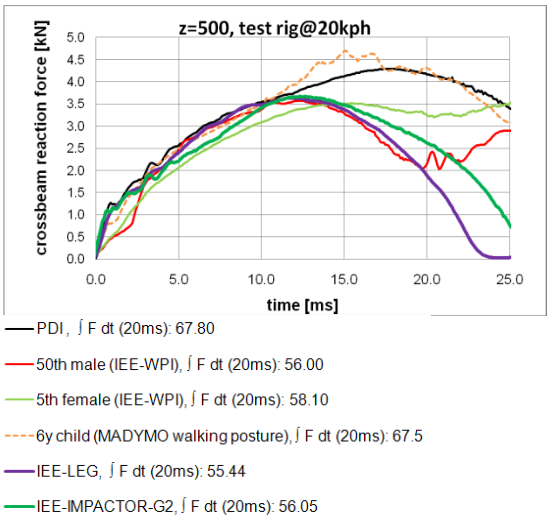

Figure 33. F(t) and ∫ F dt (Ns@20 ms) comparison for impact height of 500 mm.

In a next step the F(t) curves of the IEE G2 impactor are compared to the ones of the various previously simulated pedestrian models (6-year-old child, 5% female, 50% male) and impactors (IEE lower limit leg, PDI). This is again repeated for an impact height range from 400 mm to 500 mm.

The simulation results confirm that the IEE G2 impactor is suitable to address pedestrian collisions with vehicles having different crossbeam heights, while at the same time the impactor is a suitable representation of the "hardest to detect" pedestrian.

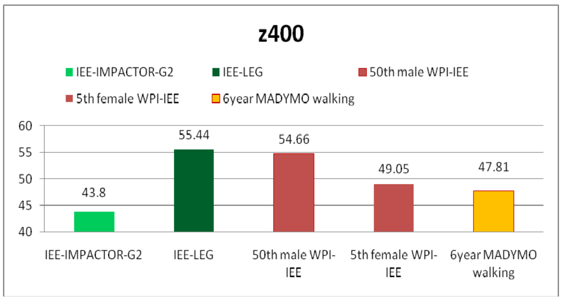

Figure 34. Momentum transfer comparison for crossbeam height of 400 mm, Δp in [Ns@20ms].

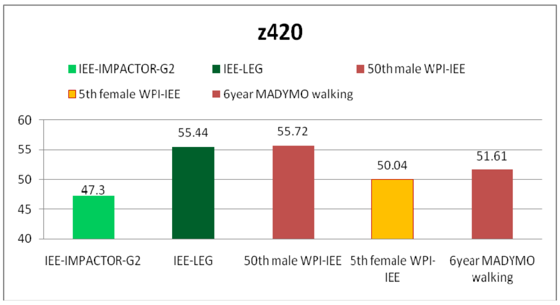

Figure 35. Momentum transfer comparison for crossbeam height of 420 mm, Δp in [Ns@20ms].

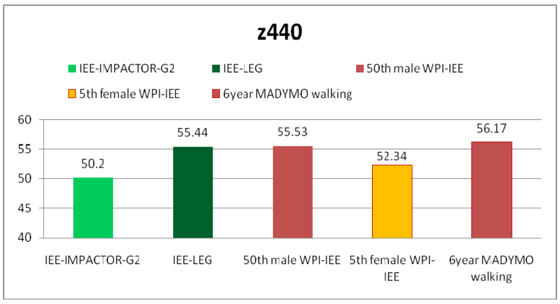

Figure 36. Momentum transfer comparison for crossbeam height of 440 mm, Δp in [Ns@20ms].

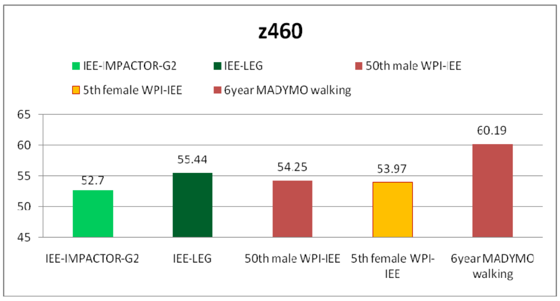

Figure 37. Momentum transfer comparison for crossbeam height of 460 mm, Δp in [Ns@20ms].

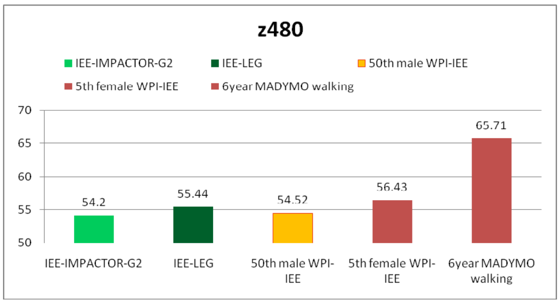

Figure 38. Momentum transfer comparison for crossbeam height of 480 mm, Δp in [Ns@20ms].

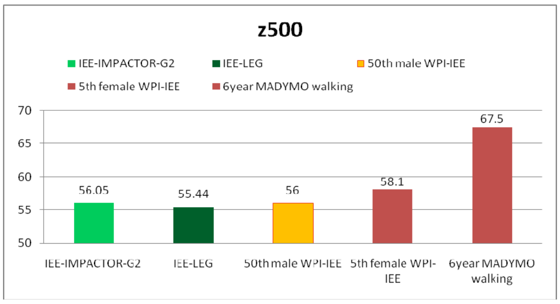

Figure 39. Momentum transfer comparison for crossbeam height of 500 mm, Δp in [Ns@20ms].

The figures 34 to 39 draw a direct comparison of the momentum transfer in order to better illustrate the "lower limit" capability of the IEE G2 impactor.

For any impact location height, the IEE G2 impactor represents a "lower limit" relative to the specific "worst case" standard pedestrian model, no matter if it is the 6-year-old child (for z = 400 mm), the 5% female (for z = 420 – 460 mm) or the 50% male (for z = 480 - 500 mm). The new impactor concept sucessfully meets all the challenges that had to be tackled.

Limitations of the applicability

While the IEE G2 impactor can be successfully applied as a "lower limit" for collisions between "standard pedestrian statures" and vehicles with bumper heights between 400 and 500 mm, there might nevertheless be some limitations in its applicability.

These limitations can be related to more extreme front end designs, with higher or lower bumpers than the investigated ones.

On the other side, non-standard pedestrian models can also lead to impact scenarios where the human model can generate momentum transfers that are even below the ones of the IEE G2 impactor. Table 5 gives an overview on how well the IEE G2 impactor can represent the lower limit case. When including the investigated non-standard pedestrian model (slim tall male), the IEE G2 covers very well the "hardest to detect" pedestrian model for bumper heights from 400 mm up to 440 mm.

Table 5.
Comparison of momentum transfers

Height z	IEE G2 impactor [Ns@20ms]	Hardest to detect, excl. non-standard model [Ns@20ms]	Hardest to detect, incl. non-standard model [Ns@20ms]
400 mm	43.80	47.81	47.81
420 mm	47.30	50.04	50.04
440 mm	50.20	52.34	50.10
460 mm	52.70	53.97	49.40
480 mm	54.20	54.52	50.50
500 mm	56.05	56.00	52.30

For the evaluated bumper heights in the range of 460 mm to 500 mm, the slim tall male generates a momentum transfer which is about 6.5% below the one of the IEE G2 impactor. This appears to be an acceptable underestimation, especially when taking into consideration the major improvements that have been achieved compared to the 1st generation impactor.

OUTLOOK

During the generation and evaluation of the findings presented in this paper, a few subjects were identified which would deserve to be covered by subsequent research.

IEE plans to extend the IEE-WPI pedestrian model family to the 6-year-old child. This would allow us to cover the full range of "hardest to detect" pedestrians and to run all future evaluations based on a hybrid FE-model.

The test rig simulations were conducted with a test rig geometry setup that was representative of "normal" vehicle front end geometries. As the test rig allows to shift the three elements in x-and z-direction, more extreme configurations can be realized and analyzed in future investigations.

Actually, a real IEE G2 impactor is in construction in order to be able to run physical tests as done with the original IEE 1st generation impactor. It reflects correct pedestrian impact physics and is meant to be a test tool at varying velocities.

CONCLUSIONS

The paper has given an overview on the various steps that were taken in order to realize an improved impactor which aims at representing the "hardest to detect" pedestrian for a broad range of vehicle front-end configurations. The impactor can be used as a test tool to evaluate the detection performance of pedestrian detection sensors used to trigger pop-up hood systems or, in the future, windscreen or A-pillar airbags.

The simulation results have shown that a significant improvement could be achieved with the new IEE G2 impactor compared to the 1st generation lower limit impactor. The concept of the impactor has been optimized in order to guarantee interaction with all vehicle front end elements that can also interact with a real pedestrian.

The IEE G2 impactor is a very suitable "lower limit" impactor for all evaluated bumper heights. The deviations the impactor shows when including the slim tall male to the analysis are within an acceptable range.

The impactor also appears to be a very good compromise regarding the level of abstraction compared to a real leg, and the expected robustness of a real physical impactor model.

REFERENCES

[1] Euro NCAP pedestrian testing protocol, Version 5.2.1 (www.euroncap.com)

[2] Global Technical Regulation No. 9 Pedestrian Safety (http://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29registry/gtr9.html)

[3] TNO:
MADYMO, Human Models Manual;
Release 7.1, June 2009

[4] INRETS FRANCE
http://humos2.inrets.fr/

[5] TOYOTA Motor Corp.:
THUMS,Total Human Model for Safety;
TMC press release, May 2010

[6] T.Sugimoto, K.Yamazaki:
First Results of the JAMA Human Body Model Project; JAMA/JARI; Paper 05-0291, 19th ESV 2005

[7] A.Soni, A.Chawla, S.Murkherjee:
Effect of Muscle Contraction on Knee Loading for a Standing Pedestrian in lateral Impacts;
Paper 07-0458, 20th ESV 2007

[8] Y. Takahashi, Y. Kikuchi, F. Mori, A. Konosu:
Advanced FE Lower Limb Model for Pedestrians;
Paper 03-0218, 18th ESV 2003

[9] Y. Takahashi, Y. Kikuchi, F. Mori:
Full-ScaleValidationb of a Human FE Model for the Pelvis and Lower Limb of a Pedestrian; SAE International 2008-01-1243,2008

[10] M.H.Ray, private communication

[11] C.Silvestri, M.H.Ray: Development of a Finite Element Model of the Knee-Thigh-Hip of a 50th Perc Male including Ligaments and Muscles; International Journal of Crashworthiness, Vol.14, No.2,pp:215-229,2009

[12] J.A.W. van Dommelen, B.J. Ivarsson, M.M. Jolandan, S.A. Millington, M. Raut, J.R. Kerrigan, J.R. Crandall, D.R. Diduch: Characterization of the Rate-Dependent Mechanical Prpoerties and Failure of Human Knee Ligaments; SAE International 2005-01-0293,2 005

[13] C. Untaroiu, K. Darvish, J. Crandall, B. Deng, J.-T. Wang: Characterization of the Lower Limb Soft Tissue in Pedestrian Finite Element Models; Paper 05-0250, 19th ESV 2005

[14] J. van Hoof, R. de Lange, J. S. H.M.Wismans:
Improving Pedestrian Safety Using Numerical Human
TNO, Stapp Car Crash Journal Vol.47, 2003-22-0018

[15] J. Kerrigan, K. Bhalla, N. Madeley, J. Funk, D. Bose, J. Crandall: Experiments for Establishing Pedestrian-Impact Lower Limb Injury Criteria; SAE International 2003-01-0895,2003

[16] D. Bose, K. Bhalla, L. Rooij, S. Millington, A. Studley, J. Crandall: Response of the Knee Joint to the Pedestrian Impact Loading Environment; SAE International 2004-01-1608, 2004

[17] J. Kajzer, Y. Matsuia, H. Ishikawa, G. Schroeder, U. Bosch: Shearing and Bending Effects at the Knee Joint at High Speed Lateral Loading; SAE International 973326, 1999

[18] J. Kajzer, Y. Matsui H. Ishikawa, G. Schroeder, U. Bosch: Shearing and Bending Effects at the Knee Joint at Low Speed Lateral Loading; SAE International 1999-01-0712, 1999

[19] A. Soni, A. Chawla, S. Mukherjee, R. Malhotral: Sensitivity Analysis of Muscle Parameters and Identification in Low Speed Lateral; Impact at just below the Knee; SAE International 2009-01-1608, 2009

[20] CONCEPT TECH:
CONCEPT-6yo PDI, User Manual-Specification-Certification;
Concept Technology, Graz

[21] L. van Rooij, M. Meissner, K. Bhalla, J. Crandall, D. Longhitano, Y. Takahashi, Y. Dokku,Y.Kikuchi: The evaluation of the kinematics of the MADYMO human pedestrian model against experimental tests and the influence of a more biofidelic knee joint; University of Virginia, 2003

[22] W. Goldsmith: Impact – The Theory and Physical Behaviour of Colliding Solids, Dover Publications, 1960, 2001

[23] T. Martin (UTAC)
Improvement of Vehicle Crash Compatibility through the Development of Crash Test procedures (VC-COMPAT) (2005)