

THE FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR AND ITS IMPACT ON VEHICLE DESIGN



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ABSTRACT

In Japan, a new legform impactor for pedestrian protection testing has been developed during the past 10 years. This legform is called “Flexible Pedestrian Legform Impactor” (FlexPLI). Compared to the existing legform currently used in Europe, the FlexPLI is intended by its developers to better reflect the behavior of a human leg during an impact with a vehicle. In addition to a more humanlike knee section, the new impactor provides for the possibility to also assess injuries of the pedestrian's tibia.

In the first development phase, the legform was considered to be very biofidelic but testing robustness was limited. In its further development, the impactor was modified to better address the needs of a certification tool: The latest version of the legform is more robust than pre-versions, the handling is acceptable, the repeatability of test results seems to be acceptable and the legform fits into the current sub-system test scenario of the global technical regulation (gtr) No 9 on pedestrian safety.

Common vehicle designs use a forward-moved lower structure of the bumper as a load path to reduce the knee bending. However, these structures may cause higher strains in the tibia area of the FlexPLI (and consequently may indicate a risk for tibia injuries in real-world accidents). Therefore, for many vehicles the bumper systems designed to meet the requirements for the lower legform currently used in Europe will need to be redesigned to fulfill the FlexPLI targets.

Nevertheless, the FlexPLI has already been proposed to be used as certification tool in gtr No 9. The study presented below provides first results of tests in a manufacturer's lab with different vehicles of different categories and identifies general concepts for optimization towards FlexPLI requirements' fulfillment. The intention of this paper is to summarize the experiences gained for use as information for future vehicle developments.

DEVELOPMENT OF THE FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR

About 10 years ago, experts of the Japan Automobile Research Institute (JARI) and of the Japan Automobile Manufacturers' Association (JAMA) presented a new legform impactor for pedestrian safety testing. The new legform is called “Flexible Pedestrian Legform Impactor” (FlexPLI).

The European legform impactor was never widely accepted in Japan. During the development of the first impactor and the respective test procedures, the experts of the European Experimental Vehicle Committee (EEVC; later renamed to European Enhanced Vehicle-Safety Committee) decided to prioritize knee ligament injuries while possible bone fractures were to be evaluated via the acceleration of the legform. However, a detailed assessment of fractures of the long bones was not intended [1].

Several pedestrian safety experts, especially the experts of Japan, pointed out that the design of the EEVC legform impactor with its rigid upper and lower part cannot simulate the human lower extremities' motion properly. Also, according to the Japanese experts the EEVC impactor may mislead the protection for the pedestrians' lower extremities since an injury assessment of the lower part of the leg is not possible [2]. Approximately 3 to 4 years ago, Japanese experts presented additional analyses of the Japanese accident statistics showing that around 87 % of all leg injuries were tibia fractures [3]. The missing ability of the EEVC Lower Legform Impactor (EEVC LFI) to assess fractures of the pedestrians' lower extremities in detail was the main reason for Japan to develop their new legform impactor.

During the past 10 years, the FlexPLI had been presented in different build levels: version 2000, version 2002/2003, version 2004, version G, version GT and version GTR. For the later versions, which were thought to be close to a final design, additional prototypes were presented. They were referred to as version xx alpha (or xx α). To improve robustness and reliability of the tool itself, repeatability of test results,

handling of the impactor etc., the impactor was modified significantly during the development process. The latest build level, FlexPLI version GTR (or Flex-GTR), has been available in its production version since early 2010. However, the manufacturer of the legforms still applies additional modifications during the current production to achieve further improvements and especially to be able to meet the agreed corridors for the impactors' certification [4].

COMPARISON OF THE EEVC LOWER LEGFORM IMPACTOR AND THE FLEXIBLE PEDESTRIAN LEGFORM IMPACTOR

The EEVC LFI is often referred to as “WG17 impactor” according to the EEVC working group responsible for the development of the impactor or as “TRL impactor” according to the company that had finalized the design and is merchandising the impactor now. It mainly consists of two stiff metal tubes, two deformable knee elements made of steel and a shear-spring system with a hydraulic damper (see figure 1). The two stiff metal tubes represent the femur and the tibia of a human leg. The deformable knee elements represent the human knee, specifically the ligaments, with the ability to withstand a certain bending. The metal “ligaments” are used to assess possible knee injuries. The shear-spring system simulates lateral shear displacement between femur and tibia at the knee level; the damper is necessary to limit vibrations caused by the mass of the shear-spring system. An accelerometer is used to indirectly measure the contact force applied to the tibia, representing a provisional assessment of the risk of bone fractures. For testing, the legform is covered with a 25 mm thick foam layer and a 6 mm neoprene skin, together representing the human's flesh and skin (see figure 2) [5].

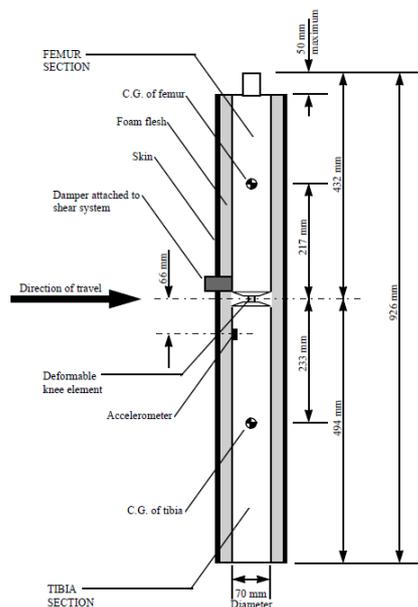
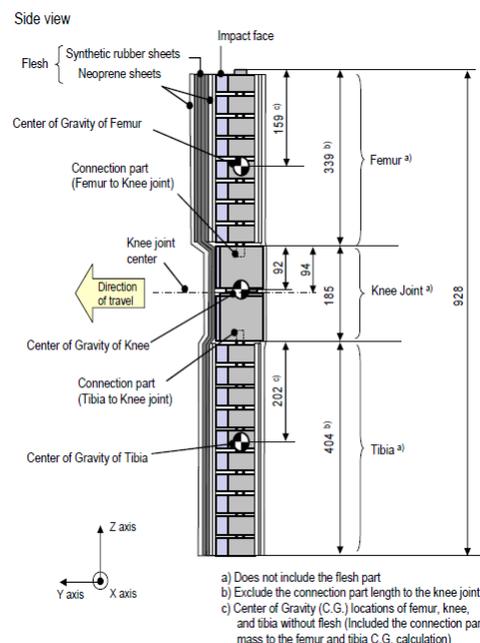


Figure 1. Design of the EEVC Lower Legform Impactor [6]



Figure 2. Photograph of the EEVC LFI without and with flesh and skin simulation [7]

The FlexPLI consists of a femur and a tibia, which are composed of bone cores made of fiber glass, and several nylon segments attached to them. The overall design of femur and tibia represents the human bones and their ability to be bent. Strain gauges, glued to the fiber glass core, are used to measure the bending moments at the different segments and thereby assess the risk of bone fractures. The knee element consists of two complex blocks, where string potentiometers assess the risk of ligament injuries (see figure 3).



- a) Does not include the flesh part
- b) Exclude the connection part length to the knee joint
- c) Center of Gravity (C.G.) locations of femur, knee, and tibia without flesh (Included the connection part mass to the femur and tibia C.G. calculation)

Figure 3. Design of the FlexPLI version GTR [8]

Human skin and flesh are formed by several layers of rubber and neoprene sheets. To closer follow the geometry of a human leg, the number of layers is different for femur, knee and tibia [8].

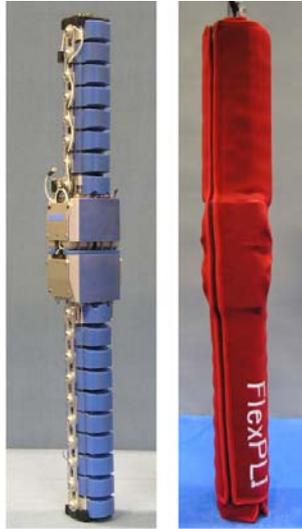


Figure 4. Photograph of the FlexPLI version GTR without and with flesh and skin simulation [9]

The EEVC LFI is a simplified design, approximately representing the human leg with the intention to measure specific loads at limited locations. In contrast, the FlexPLI especially in its earlier versions had been designed simulate the biomechanical behavior of a human leg when being impacted by a vehicle (see figure 5).



Figure 5. Principle behavior of the EEVC LFI compared to the FlexPLI

However, one compromise regarding biofidelity at the knee of the FlexPLI was necessary: The element is designed almost symmetrically, whereas the human legs have a mirrored position of the ligaments. This

was necessary to allow one single impactor to be used for vehicle testing and to avoid the necessity of using a right hand and a left hand legform impactor separately.

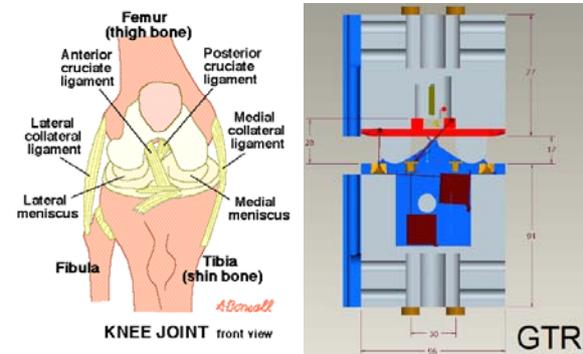


Figure 6. Comparison of a schematic view of the (right leg's) human knee joint [10] and a CAD drawing of the FlexPLI knee element [11]

In addition to the knee section with its improved biofidelity compared to the EEVC LFI (see figure 7), the FlexPLI provides for the possibility to assess injuries to the pedestrian's tibia in detail. For research purposes the FlexPLI may be equipped with up to 32 measurement channels recording e.g. the loads to the femur and the detailed motion of tibia and femur [11].

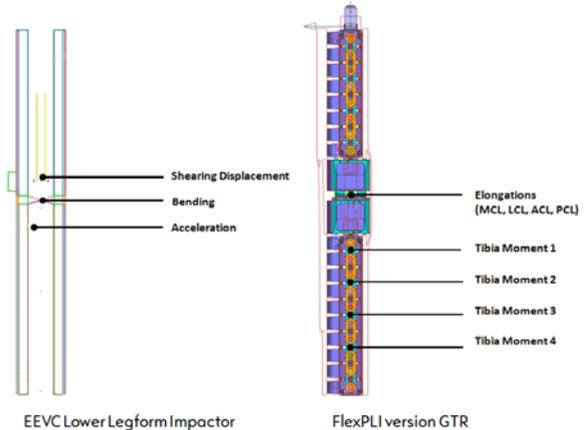


Figure 7. Comparison of the measurement abilities of the EEVC LFI and the FlexPLI as proposed for regulatory purposes

During first development phases, the FlexPLI had restrictions regarding its use as a test tool, e.g. a limited robustness. As mentioned, this improved significantly during the several development steps of the impactor. From the beginning, the legform had been designed to fit into the sub-system test scenario as it is currently standard for pedestrian protection in regulatory and consumer testing. Japan therefore proposed to use the FlexPLI for the pedestrian safety testing according to the grt No 9 [12].

TESTING OF DIFFERENT BUMPER CONCEPTS WITH BOTH LEGFORM IMPACTORS

During the development of the different FlexPLI build levels, the automobile industry had frequently impacted vehicles to assess the legform as a test tool. Tests were conducted by manufacturers in joint projects of the European Automobile Manufacturers' Association (ACEA) with partners or on their own. Usually, existing serial production vehicles were used for these trials. Those vehicles often have protruding lower structures of the bumpers as support to initiate rotation of the legform, which is necessary to meet existing regulatory and consumer testing requirements. Such devices are often referred to as "lower bumper stiffeners" (LBS). An LBS helps reducing the knee bending and therefore limits the knee loads.

However, test results indicated that bumper concepts with protruding LBS's may create high peaks in the tibia bending moment of the FlexPLI at the contact position with the LBS and consequently may lead to the risk for tibia injuries in real-world accidents. Therefore the bumper systems designed to meet the EEVC LFI requirements need to be optimized to fulfill the FlexPLI targets.

One question that could not be answered satisfactorily during earlier tests was whether such peaks in the bending moment can be controlled and how existing bumper systems can be modified to meet the injury criteria of the new legform. Trying to find an answer to this question, tests were conducted on-site at Adam Opel AG / General Motors Europe Engineering in late 2010. Three different bumper concepts, which are currently in production, were assessed. The concepts differ in their principle characteristics (see also figure 8):

- Concept A has an LBS with a medium (average) elastic displacement ability. This elastic displacement ability refers to the component characteristics and not to the material properties only. In vehicle x-direction, the offset between the LBS contact surface and the bumper main beam in this concept is relatively small. The force reaction surface of the vehicle front is quite homogenous.
- For concept B, the elastic displacement ability of the LBS is lower, the x-offset between the LBS contact surface and the bumper main beam is medium and the force reaction surface is not homogenous.
- The LBS of concept C shows a medium elasticity, the x-offset between LBS contact surface and the bumper main beam is quite large and the force reaction surface is also quite homogenous.

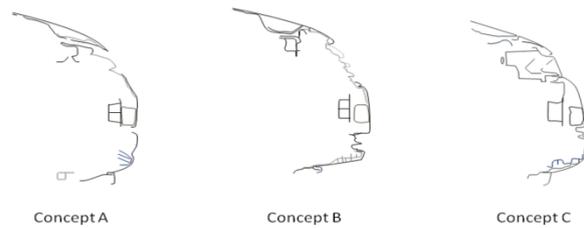


Figure 8. Sketches of different bumper concepts assessed with the FlexPLI in this study

All three concepts were assessed with the FlexPLI version GTR, even though none of the concepts needs to meet any requirements with this new impactor. The impact positions matched earlier tests with the EEVC LFI. Test results from regulatory as well as from consumer metrics tests were available for this impactor, to be evaluated against the new results.

In general, to compare the performances of the different bumper systems, the regulatory limit was considered to be 100%. According to gtr No 9 [12] these limits for the EEVC LFI are:

- 19 degrees for the maximum dynamic knee bending angle;
- 6 mm for the maximum dynamic knee shearing displacement;
- 170 g for the acceleration measured at the upper end of the tibia.

For the FlexPLI, the limits were used as proposed for the amendments to gtr No 9 [8]. These limits are:

- 22 mm for the maximum dynamic elongation of the medial collateral ligament (MCL);
- 13 mm for the maximum dynamic elongation of the anterior cruciate ligament (ACL) and the posterior cruciate ligament (PCL);
- 340 Nm for the dynamic bending moments at the tibia; a possible relaxation zone as proposed for the gtr No 9 amendment was not considered in the initial assessment.

Values above 100% consequently would represent an excess of the respective current or proposed regulatory limits. However, it also needs to be noted that, from a manufacturer's point of view, a margin to the pass/fail criterion is applied.

DISCUSSION OF TEST RESULTS

For bumper concept A with its medium (average) elastic displacement ability, the relatively small offset between the LBS contact surface and the bumper main beam plus the homogenous force reaction surface, the shearing and the bending reached around 50 % of the regulatory limits when being tested with the EEVC LFI (see figure 9). The tibia acceleration was slightly above 75 %.

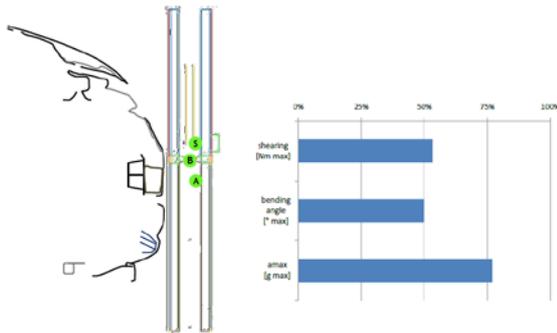


Figure 9. Test results of bumper concept A with the EEVC LFI

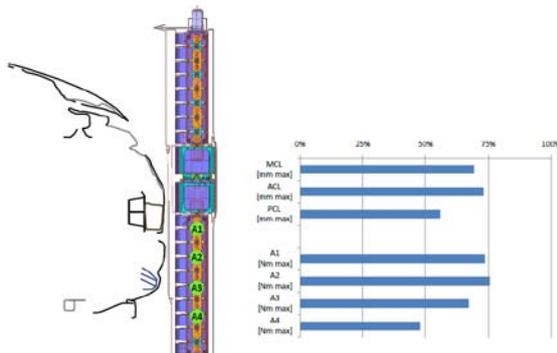


Figure 10. Test results of bumper concept A with the FlexPLI

Testing bumper concept A with the FlexPLI, the knee ligament elongations were close to 75 % for MCL and ACL and around 60 % for the PCL (see figure 10). The tibia bending reached its peak at around 75 % of the proposed regulatory limit at the measurement position 2 where the FlexPLI has the first contact with the bumper surface. The other measurement positions performed with round about 55 % and 75 % respectively of the proposed regulatory limit. In terms of vehicle engineering, concept A would be promising to meet the regulatory limits with both impactors as the characteristics of the respective bumper design seem to be sufficient. However, it needs to be noted that respective loads on the impactor's knee of this bumper concept were significantly lower with the EEVC LFI than with the FlexPLI.

Bumper concept B is characterized by the less elastic displacement ability, the medium offset between the LBS contact surface and the bumper main beam and the in-homogenous force reaction surface. When being tested with the EEVC LFI, this concept produced shearing and bending results well below 50 % but an acceleration of around 80 % of the regulatory limits (see figure 11).

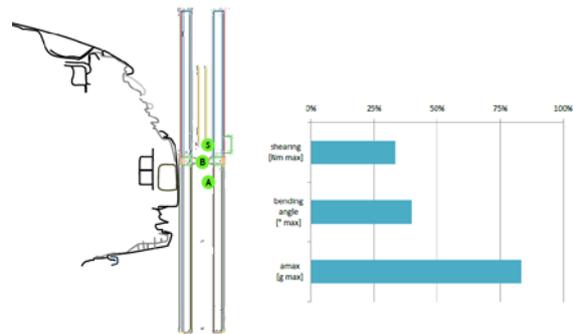


Figure 11. Test results of bumper concept B with the EEVC LFI

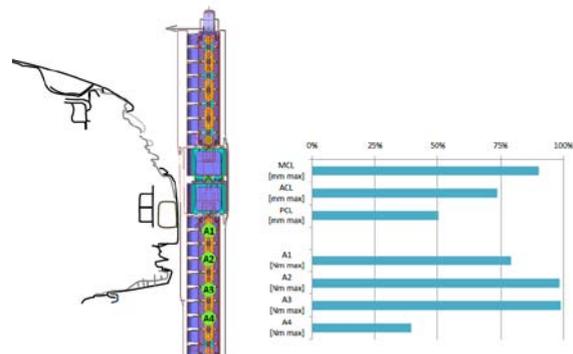


Figure 12. Test results of bumper concept B with the FlexPLI

With bumper concept B, the tibia bending of the FlexPLI was very close to the proposed regulatory limit for two of the four measurement positions. Only the test result at the position without contact to the vehicle surface during impact was well below 50 % of the limit. The elongations of the ligaments were between 50 % and 90 % of the future regulatory limits. From a vehicle engineering perspective, the bumper concept needs an extended review in terms of FlexPLI performance.

Bumper concept C, showing a medium elasticity, a quite large offset between LBS contact surface and the bumper main beam and a quite homogenous force reaction surface, also performed well with the EEVC LFI. The tibia acceleration was around 75 % of the regulatory limit. Shearing and bending were well below 50 % (see figure 13).

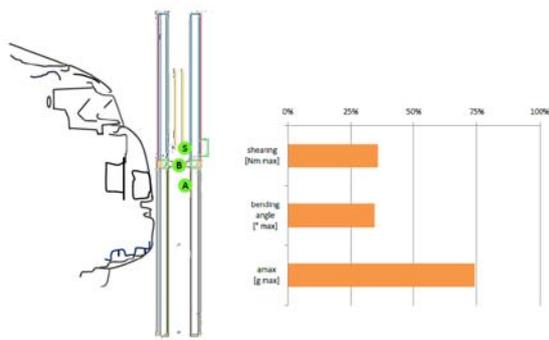


Figure 13. Test results of bumper concept C with the EEVC LFI

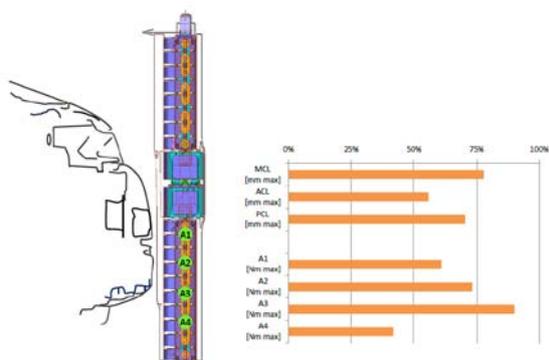


Figure 14. Test results of bumper concept C with the FlexPLI

However, with the FlexPLI this concept was closer to the limits. At the position near the first contact between impactor and bumper fascia, a peak bending moment occurred, reaching almost 90% of the proposed regulatory limit (see figure 14). The lower part of the impactor, without contact with the vehicle surface during the testing, was well below 50 % of the proposed limits. The elongations of the three ligaments were in the range of 55 % and 80 % of the future limits. Generally, the performance of this bumper concept is acceptable for meeting the proposed regulatory limits.

A comparison of the test results above implies that all three bumper concepts already comply with the future regulatory limits as proposed as the gtr No 9 amendments. However additional tuning or even re-design will be necessary to also meet top ratings in expected consumer metrics requirements which usually are more stringent than regulation.

Nevertheless, the bumper systems with a more homogenous reaction surface seem to have conceptual advantages. Also, a certain elasticity of the structure, allowing the FlexPLI to deform the bumper surface, seems to be favorable for meeting the future requirements. The main issues when testing

with the new legform are caused by high levels of stiffness of the LBS's or by large offsets between the LBS contact surface and the bumper main beam in longitudinal vehicle direction. However this was the main intention of the designers of the FlexPLI: to measure the load distribution in the tibia part of the legform in more detail.

Manufacturers may need to find other ways to address this, for example bumper surfaces with multiple force reaction supports. Additionally, design solutions need to control the rotation of the legform in order to avoid increased loads in the knee area and, consequently, to limit the risk of ligament injuries.

The vehicles tested in this study all comply with the current regulatory requirements on pedestrian safety in Europe and in addition have a good performance when being assessed in consumer metrics programs. The results of this study apply to the design characteristics of the three bumper concepts described above but cannot be generalized unconditionally to the variety of concepts existing in the market today.

CONCLUSIONS

Bumper systems that perform well when being tested with the EEVC lower legform impactor do not necessarily have the same performance level with the new Flexible Pedestrian Legform Impactor. However, first test results indicate that today's concepts, engineered to comply with current requirements for the legform tests, may not need to be completely redesigned from sketch or "reinvented" respectively. Generally, measures like a smooth geometry of the vehicle front end with a homogenous reaction surface and a certain elasticity of the bumper structure allowing an elastic displacement of the lower bumper stiffener help to comply with the requirements of the new legform. One focus needs to be on the design of the load paths. Structure and surface elements creating high peaks for the tibia bending moment should be avoided. Structures with multiple load supports are more promising.

However, it needs to be emphasized that the test results discussed above were produced at vehicles that already meet regulatory requirements and furthermore have a good performance in consumer metrics testing. Therefore, those vehicles are well positioned to meet the new requirements.

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FREQUENTLY USED ABBREVIATIONS

ACEA	European Automobile Manufacturers' Association
ACL	anterior cruciate ligament
EEVC	European Experimental Vehicle Committee, later renamed to European Enhanced Vehicle-Safety Committee
FlexPLI	Flexible Pedestrian Legform Impactor
gtr	global technical regulation
LBS	lower bumper stiffener
LFI	(Lower) Legform Impactor
MCL	medial collateral ligament
PCL	posterior cruciate ligament

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