TOWARDS A WORLD-WIDE HARMONIZED PEDESTRIAN LEGFORM TO VEHICLE BUMPER TEST PROCEDURE

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ABSTRACT

A biofidelic flexible pedestrian legform impactor (FlexPLI) has been developed from the year 2000 onwards and evaluated by a technical evaluation group (Flex-TEG) of UN-ECE GRSP. A recently established UN-ECE GRSP Informal Group on GTR9 Phase 2 is aiming at introducing the FlexPLI within world-wide regulations on pedestrian safety (Phase 2 of GTR No. 9 as well as the new UN regulation 127 on pedestrian safety) as a test tool for the assessment of lower extremity injuries in lateral vehicle-to-pedestrian accidents. Besides, the FlexPLI has already been introduced within JNCAP and is on the Euro NCAP roadmap for 2014.

Despite of the biofidelic properties in the knee and tibia sections, several open issues related to the FlexPLI, like the estimation of the cost benefit, the feasibility of vehicle compliance with the threshold values, the robustness of the impactor and of the test results, the comparability between prototype and production level and the finalization of certification corridors still needed to be solved. Furthermore, discussions with stakeholders about a harmonized lower legform to bumper test area are still going on.

This paper describes several studies carried out by the Federal Highway Research Institute (BASt) regarding the benefit due to the introduction of the FlexPLI within legislation for type approval, the robustness of test results, the establishment of new assembly certification corridors and a proposal for a harmonized legform to bumper test area. Furthermore, a report on vehicle tests that previously had been carried out with three prototype legforms and were now being repeated using legforms with serial production status, is given.

Finally, the paper gives a status report on the ongoing simulation and testing activities with respect to the development and evaluation of an improved test procedure with upper body mass for assessing pedestrian femur injuries.

INTRODUCTION

A biofidelic flexible pedestrian legform impactor (FlexPLI) is foreseen for being implemented within world-wide regulations on pedestrian safety as well as consumer test programmes as a test tool for the assessment of knee and tibia injuries caused within lateral vehicle-to-pedestrian accidents.
After the evaluation by a technical evaluation group (Flex-TEG) of GRSP in 2010, the FlexPLI was rated as not yet being ready for legislation. Thus, a new Informal Group on GTR9 Phase 2 was established under the umbrella of GRSP, dealing with the remaining open issues related to the introduction of the FlexPLI. The current timeline foresees the submission of a final draft of phase 2 of GTR9 to the December 2013 meeting of GRSP and an adoption of the draft by WP.29 in June 2014. The application of the FlexPLI for type approval testing could then be expected as from 2016 on.

The tasks that IG GTR9-PH2 was mandated by GRSP to cover were related to the Flex-TEG activities, the FlexPLI biofidelity, the benefit and the costs, the technical specifications (drawings) and PADI, the durability, the test procedure itself, the certification tests, a review and exchange of test results, the reproducibility and repeatability, the injury criteria and threshold values, the vehicle countermeasures, and to the development of a draft proposal to amend UN GTR No. 9 as well as a complementary draft proposal to amend the UN Regulation on pedestrian safety.

In this paper, several studies of the Federal Highway Research Institute (BASt) as contributions to the work to be covered by the IG GTR9-PH2 are described. A benefit study aims at an estimation of the cost reduction due to the introduction of the FlexPLI within legislation. A robustness study gives an overview of the long term performance of test results with the FlexPLI.

New assembly certification corridors for both the inverse and the pendulum certification test were drafted and proposed by BASt to the Informal Group. Furthermore, a proposal for a modification of the lower legform to bumper test area to address the development of vehicle front shapes with extraordinary small test areas was submitted to the Task Force Bumper Test Area (TF-BTA) chaired by the European Commission. Finally, BASt investigated the change in overall performance between the first prototype legs of the build level GTR and the first serial production legs, based on vehicle tests, and thus concluded modified impactor threshold values.

Besides the IG activities, the paper reports about the latest status of the evaluation of an upper body mass (UBM) to be applied to the FlexPLI for the assessment of femur injuries as a possible replacement of the current upper legform to bonnet leading edge test.

ESTIMATION OF COST REDUCTION

Accident data from the German In Depth Accident Study (GIDAS) was processed and transferred to data from the German national accident statistics to estimate a reduction of costs in Germany due to the introduction of vehicles with a pedestrian friendly bumper design. From the national dataset, accidents occurring during the years 2009 until 2011 with two road users, namely one passenger car and one pedestrian involved, were considered. In total, 65.843 accidents resulted in annually averaged 323 fatally injured, 5.774 seriously injured and 15.785 slightly injured road users in Germany, see figure 1.

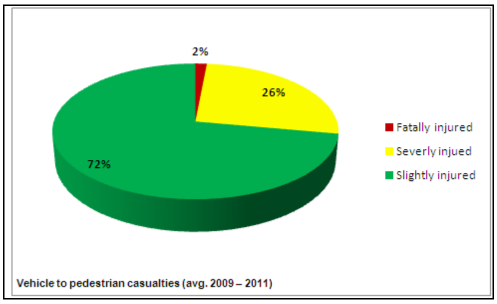

Figure 1. Vehicle to pedestrian casualties in Germany 2009 – 2011.

From the GIDAS dataset (1999 - 2011), only accidents with one pedestrian and one passenger car involved were taken into account. From the 1.925 recorded accidents 1.760 were found as being complete in terms of relevant information as e.g. type of injury, impact location and injury causing vehicle parts and could thus be used for the calculation of a change in MAIS injury distribution due to the introduction of a pedestrian friendly bumper design. Furthermore, only laterally impacted pedestrians with the impact location at 8-10 o' clock and 2-4 o' clock with the injury causing parts on the vehicle front (without bonnet leading edge) were analyzed. To estimate the cost reduction due to the introduction of the FlexPLI the assumption was made that the severity of the detected AIS 1-3 injuries could be shifted downwards by AIS-1 in case of the vehicle being equipped with a pedestrian friendly bumper. Thus, by downwards shifting of AIS-1 an open tibia fracture would e.g. result in a closed tibia fracture, and a closed tibia fracture would result in bruises. When considering all injury types of tibia, fibula, knee, ligaments and subtalar joint, in total 498 vehicle-to-pedestrian accidents in the GIDAS database were affected by the AIS-1 downwards shift. The MAIS injury distribution of all complete pedestrian casualties in the original and the shifted dataset is shown in figure 2:

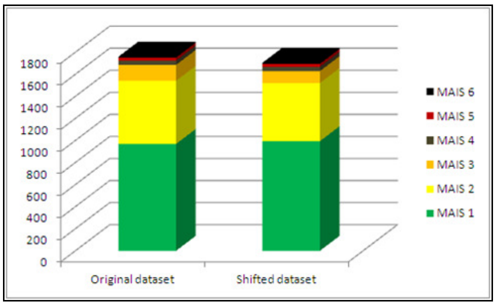

Figure 2. MAIS injury distribution of pedestrian casualties before and after AIS-1 shifting.

Thus, pedestrian casualties with an MAIS 3 were reduced by 25 percent, pedestrian casualties with an MAIS 2 were reduced by approx. 8 percent and consequently MAIS 1 casualties had a slight increase of 2,6 percent. MAIS 4-6 casualties were not affected by the downwards shift of AIS 1-3 lower extremity injuries because afterwards they still remained at their previous MAIS level.

Figure 3 provides the MAIS injury distribution of the fatally, severely and slightly injured pedestrians reported within GIDAS:

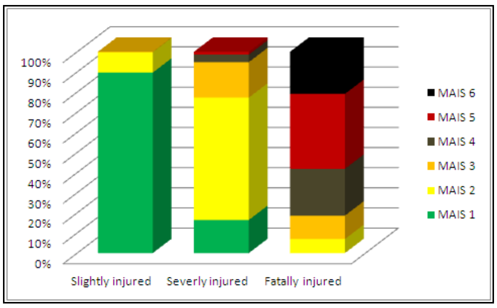

Figure 3. MAIS injury distribution of fatally, severely and slightly injured pedestrians before AIS-1 shifting.

A shifting of AIS-1 then leads to the reduction of fatally injured pedestrians by 3,5 percent, the reduction of severely injured pedestrians by 8,8 percent and the increase of slightly injured pedestrians by 1,5 percent. Figure 4 shows the casualties in absolute numbers:

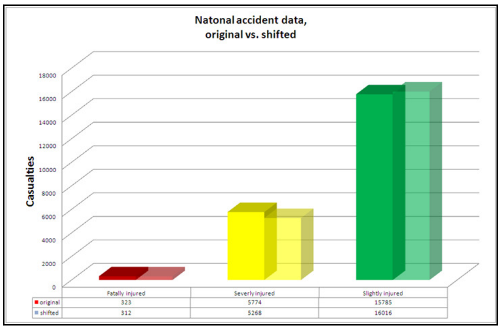

Figure 4. Shifting of fatally, severely and slightly injured pedestrians in national accident database due to AIS-1 shifting.

Under consideration of the corresponding costs per case the maximum annual cost reduction in Germany due to vehicles designed with pedestrian friendly bumper (AIS-1 shifting) is estimated at 63.725.349,- €, as shown in Table 1:

Table 1.
Estimated maximum annual cost reduction.

	original	shifted	Diff. [abs]	costs per case [€]	Reduction [€]
Fatally injured	323	312	11	1018065	11.364.027
Severly injured	5774	5268	506	105477	53.355.492
Slightly injured	15785	16016	-231	4305	-994.170
Σ					63.725.349

When taking into account the injury risk coverage rate of 70% realized due to the introduction of the FlexPLI, the annual cost reduction in Germany is estimated at 44.607.744,- €.

ROBUSTNESS OF TEST RESULTS

At the first meeting of the Informal Group GTR9 Phase 2, OICA (2011) reported about the long term durability of a FlexPLI prototype impactor. In total, more than 300 tests had been carried out with FlexPLI SN02, whose physical damages apparently had no significant effect on the vehicle test results. However, BASt further investigated the robustness of the FlexPLI test results. Basis of the comparative study were the inverse certification test results obtained with two different prototype impactors, one of them containing the formerly used polyester bone core material (SN02), while the other one was equipped with the currently used vinylester bone cores (SN04).

Long term performance of SN02

Inverse certification tests with FlexPLI prototype SN02 were performed at BASt during a time period of approximately three years. During this time period, except the replacement of the string potentiometers in January 2010 and the replacement of the short by long rubber material (as decided during the 8th meeting of the FlexPLI Technical Evaluation Group in May 2009), neither major exchange of parts nor calibration of particular sensors was undertaken. In total, 20 inverse certification tests using three different honeycomb materials according to the draft GTR9 specifications were carried out between January 2009 and November 2011, tests #1-12 using the FlexPLI with short rubber material and tests #13-20 with long rubber material and after the replacement of the string potentiometers. The last test was performed after a complete disassembly and reassembly of the impactor. An overview of the tibia test results is given in figure 5:

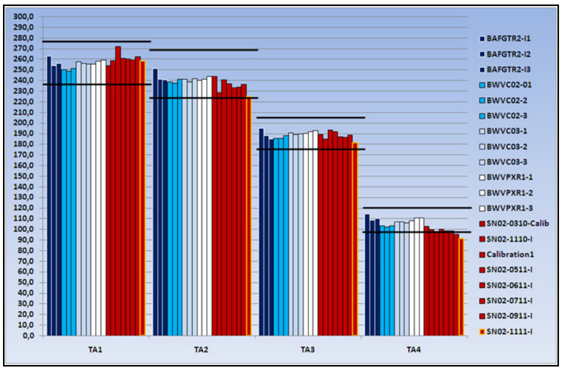

Figure 5. Tibia bending moment test results of inverse certification tests with SN02.

Almost all tibia results fulfilled the first draft inverse certification corridors. Only segment tibia 4 did not meet the draft corridor during the last two tests. Here, the exchange of the string potentiometers and the extension of the rubber material led to a noticeable decrease of the peak bending moments. A further significant decrease was also noted after the disassembly and reassembly of the impactor.

Figure 6 shows the knee ligament test results:

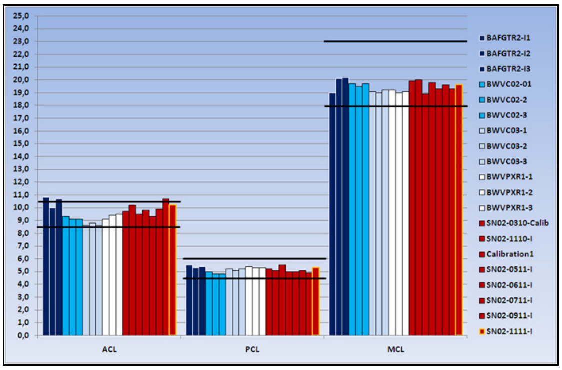

Figure 6. Knee ligament elongation test results of inverse certification tests with SN02.

All elongation results of the medial collateral and the posterior cruciate ligament met the draft inverse certification corridors. Only with the anterior cruciate ligament a few issues were detected in the course of the test series when the corridor was not met during three tests. An influence of the string potentiometer replacement, the rubber extension and the impactor disassembly and reassembly at BASt on test results was not noticed.

Table 2 demonstrates the comparatively low scatter of tests results with SN02 regardless the exchange of string potentiometers, extension of the rubber sheets and the disassembly and reassembly during the test series. While tibia segments 1-3 as well as MCL had a good repeatability with coefficients of variation below 3%, the repeatability of the remaining segments was still acceptable (CVs at or below 7%)

Table 2.
Repeatability of SN02 test results.

	T1	T2	T3	T4	ACL	PCL	MCL
MV	257,53	238,70	188,78	103,90	9,62	5,17	19,46
SD	5,10	5,69	3,40	5,99	0,67	0,21	0,40
CV [%]	1,98	2,38	1,80	5,77	6,96	4,06	2,08
Max	271,80	251,30	194,90	114,50	10,80	5,50	20,20
Dev. from MV [%]	5,54	5,28	3,24	10,20	12,32	6,40	3,80
Min	248,50	224,90	181,10	91,00	8,60	4,80	18,90
Dev. From MV [%]	3,51	5,78	4,07	12,42	10,56	7,14	2,88
Max. dev. From MV	14,27	13,80	7,68	12,90	1,19	0,37	0,74
Max. dev. From MV [%]	5,54	5,78	4,07	12,42	12,32	7,14	3,80
Range	23,30	26,40	13,80	23,50	2,20	0,70	1,30

For a more detailed analysis of the test results, the time history curves of four of the inverse tests were investigated. Test #2 was performed with the FlexPLI in baseline condition, test #13 approximately one year later and after the replacement of the string potentiometers and extension of the rubber material, test #15 another year later and test #20 after the complete disassembly and reassembly of SN02. Figure 7 illustrates the time history curves for the tibia 2 results of the four tests:

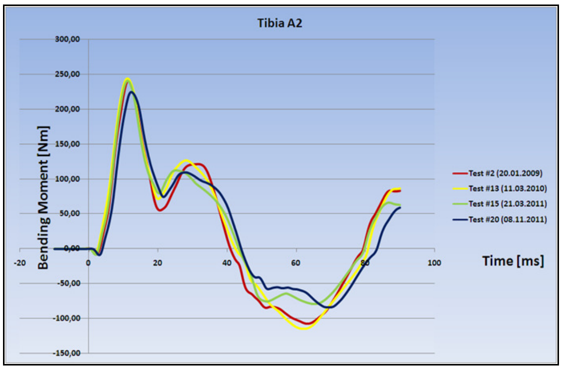

Figure 7. Tibia 2 time history curves of four inverse tests with SN02 at different build levels.

As observed for all SN02 segments, the repeatability during the primary impact phase was quite good. On the other hand, test #2 always showed the highest decay after the first peak. The test performed after the disassembly and reassembly procedure showed for most of the segments a slightly different behavior especially after reaching the maximum value.

The time history curves of the remaining segments can be found in the appendix.

Analysis

During a time period of approximately three years 20 inverse certification tests with SN02 were carried out at BASt. Four (out of seven) segments showed a good repeatability at least during the main impact phase. The repeatability of the ACL/PCL results was naturally lower than for most of the other segments. After the replacement of the string potentiometers and the rubber extension a decrease of the tibia 4 results was observed.
After the disassembly and reassembly of the impactor a decrease of the tibia results and slight change of the time history curves was noticed. From test #13 on the tibia 4 results constantly decreased. Altogether, no major influence of the physical damages reported by OICA on the test results was detected.

Long term performance of SN04

Inverse certification tests with FlexPLI prototype SN04 were performed at BASt during a time period of approximately 2,5 years. Before the start of the test series, the optional sensors including the aluminium brackets were removed. No further major exchange of parts nor calibration of particular sensors was observed. During the entire test period, SN04 was equipped with vinylester bone core material. All inverse certification tests at BASt were performed with long rubber material. Altogether, 14 inverse certification tests with SN04 were carried out between July 2009 and February 2012. Figure 8 presents the test results of the tibia segments:

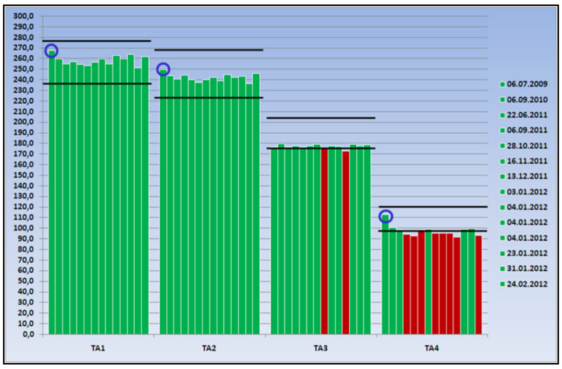

Figure 8. Tibia bending moment test results of inverse certification tests with SN04.

Nearly all tibia 1-3 test results met the first draft inverse certification corridors. On the other hand, the broad majority of the maximum loadings of tibia 3 and 4 was at the lower end or outside the draft corridors. Furthermore, test #1 provided the maximum results for three of the segments.

In terms of the ligament elongation results, all MCL and the majority of PCL results met the draft corridors while most of the ACL results were at the upper end or outside the corridor, as demonstrated in figure 9. Again, test #1 provided the maximum results for two of the elongations.

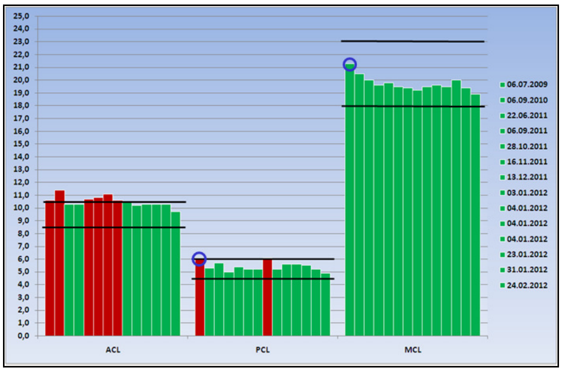

Figure 9. Knee ligament elongation test results of inverse certification tests with SN04.

Regarding the repeatability of test results, the observations made for SN02 were confirmed with SN04. Table 3 shows a good repeatability of the test results of tibia segments 1-3 and MCL. For the remaining segments, the coefficients of variation were still acceptable (CVs ≤ 7%).

Table 3.
Repeatability of SN04 test results.

	T1	T2	T3	T4	ACL	PCL	MCL
MV	258,45	242,08	177,16	97,44	10,51	5,43	19,73
SD	4,65	3,50	1,82	5,28	0,42	0,36	0,59
CV [%]	1,80	1,45	1,03	5,42	3,96	6,72	3,01
Max	267,90	249,40	179,70	112,90	11,40	6,10	21,30
Dev. from MV [%]	3,66	3,02	1,43	15,86	8,50	12,37	7,97
Min	251,50	236,20	172,60	91,40	9,70	4,90	18,90
Dev. From MV [%]	2,69	2,43	2,58	6,20	7,68	9,74	4,20
Max. dev. From MV	9,45	7,32	4,56	15,46	0,89	0,67	1,57
Max. dev. From MV [%]	3,66	3,02	2,58	15,86	8,50	12,37	7,97
Range	16,40	13,20	7,10	21,50	1,70	1,20	2,40

For a further investigation of the robustness of test results, again the time history curves of four different tests were analyzed in detail and compared to those of SN02. Here, test #1 was chosen as it provided outliers for five segments. Tests #2 and #4 were carried out one year later each. Test #13 was the fourth test chosen.

Figure 10 shows the time history curves for the PCL elongation of SN04 during the four tests and gives a comparison to those of SN02.

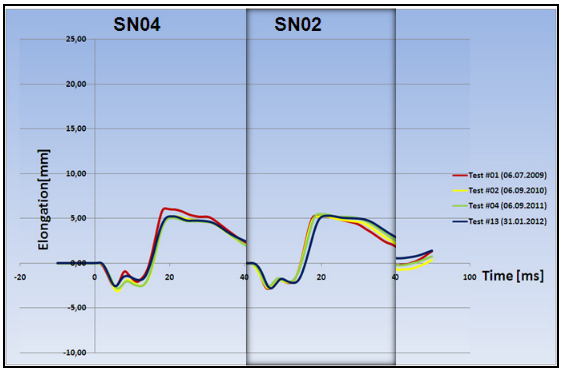

Figure 10. PCL time history curves of four inverse tests with SN04 and comparison to SN02.

As for most of the other segments, the SN04 curve characteristics showed a repeatable behavior and were quite alike to those of SN02 during the impact phase. However, test #1 contributed with the maximum result in many cases to an increase of scatter.

As for SN02, all other time history curves of SN04 are listed in the appendix.

Analysis

14 inverse certification tests with SN04 were carried out at BASt during approx. 2,5 years. As with SN02, the same four (out of seven) segments showed a good repeatability. The repeatability of ACL/PCL results was naturally lower than with most of the other segments.

Test #1, providing the maximum result for five (out of seven) segments and signing responsible for a significant repeatability decrease of Tibia A4, PCL and MCL, could be considered to some extent as being an outlier. This is of further importance because test #1 described the SN04 impactor condition before vehicle tests with different legforms carried out by OICA in August 2009 and reported within OICA (2012), showing lower curve levels and peak values of SN04 than of other impactors.

Altogether, all SN04 curve characteristics were comparable to those of SN02 during the primary impact phase.

REFINEMENT OF FULL ASSEMBLY CERTIFICATION CORRIDORS

Draft inverse and pendulum certification corridors had been proposed by the Japanese Automobile Research Institute (Konosu, 2009) and BASt (Zander, 2009-2) to and agreed by the Technical Evaluation Group (Flex-TEG) of GRSP using prototype legform impactors of the final build level GTR. After the issue of the first serial production legforms it has been found that the test performance of the impactors partly differed between the prototype and serial production build level, latter ones in various cases not fulfilling the draft certification corridors anymore. Thus, a subgroup of the IG GTR9-PH2 was tasked with the review and a possible update of the dynamic assembly certification corridors. Based on test results with three master legforms representing the latest serial production build level and tested in three experienced test houses, BASt undertook a recalculation of the first draft inverse and pendulum certification corridors.

Methodology

As impactors for the tests, two completely overhauled legforms (SN01 and SN03) as well as a new engineering leg (E-Leg) were chosen. The results of the tests in three different test houses were validated against the first draft corridors, which were, if necessary, re-calculated afterwards. The method used for updating the corridors was the procedure proposed by BASt to and agreed by Flex-TEG (Zander, 2009-2). First, based on the actual test results, reproducibility corridors were defined by picking the segments of all impactors having coefficients of variation (CVs) below 5%. From those, the pooled means for all segments were calculated and the reproducibility corridors were defined, considering a scatter of +/- 10% to the particular pooled means. Subsequently, the maxima and minima of all test results of each segment meeting the reproducibility corridors were determined. Finally, the limits of the certification corridors were defined under consideration of scatter by adding 5% to the particular maxima and subtracting 5% from the corresponding minima.

Inverse certification test

Three completely overhauled or brand new serial production impactors were tested three times each in three experienced test labs. Altogether, 15 out of 189 segment results did not pass their corresponding first draft inverse certification corridor, most of them in section tibia 3, with borderline results at the lower end of the corridor for tibia 4 as well. On the other hand, the results for tibia 1-2 as well as the ligament elongations still looked promising, meeting those corridors in most of the cases (figures 11 and 12).

Table 4 illustrates that most of the segments delivered repeatable results with CVs below 5%. Only five out of 27 segments could not be used for the calculation of reproducibility corridors.

Table 4.
Repeatability of inverse test results with master legforms.

Segment	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
Setup 1							
Setup 2							
Setup 3							
Setup 4							
Setup 5							
Setup 6							
Setup 7							
Setup 8							
Setup 9							

After deleting the segments with insufficient repeatability, the remaining results were used for the definition of the reproducibility corridors, applying +/-10% to the pooled means of the particular segments:

Table 5.
Definition of reproducibility corridors for inverse certification test.

Segment	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
Setups for Reproducibility Corridor [CV < 5%]	1-9	1-9	1-9	1-9	1234678	123789	1-9
Pooled Mean with CV < 5%	248,98	230,47	177,61	100,74	8,95	4,91	19,09
Upper Limit	273,88	253,52	195,37	110,81	9,84	5,41	21,00
Lower Limit	224,08	207,42	159,85	90,67	8,05	4,42	17,18

All setups and segments with reproducible test results were then used for the definition of the inverse certification corridors by determination of their individual maxima and minima and consideration of scatter, adding 5% to their maxima and subtracting 5% from their minima:

Table 6.
Definition of certification corridors for inverse certification test.

Test #	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
Setup 1							
Setup 2							
Setup 3							
Setup 4							
Setup 5							
Setup 6							
Setup 7							
Setup 8							
Setup 9							
Maximum	259,98	240,13	183,73	103,27	9,60	5,40	20,20
Minimum	241,68	220,47	173,90	97,00	8,40	4,45	18,20
Max * 1,05 (Consideration of scatter)	272,98	252,14	192,92	108,44	10,08	5,67	21,21
Min * 0,95 (Consideration of scatter)	229,60	209,45	165,21	92,15	7,98	4,23	17,29
Certification Corridor Upper Limit	272	252	192	108	10	6	21
Certification Corridor Lower Limit	230	210	166	93	8	4	17

Figures 11 and 12 show the inverse test results with the three master legforms and their fitment within the first draft corridors (black) and the new corridors (green).

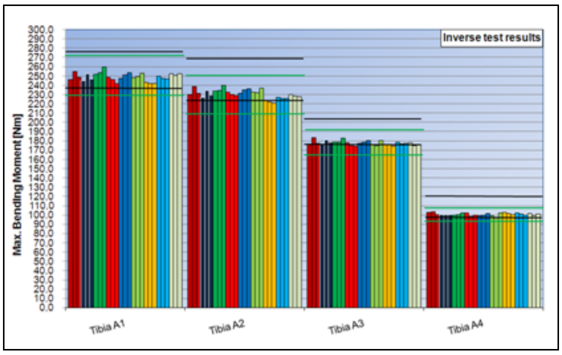

Figure 11. Tibia results of inverse certification tests with master legforms.

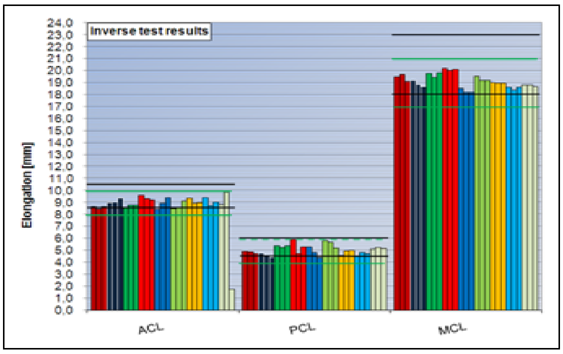

Figure 12. Ligament results of inverse certification tests with master legforms.

All regular certification test results passed well the new inverse corridors. Only one test failed due to an ACL potentiometer failure.

Pendulum certification test

As with the inverse test, three completely overhauled or brand new serial production impactors were pendulum tested three times each in three experienced test labs. In total, 35 out of the 189 segment results, most of them MCL elongations and some ACL/PCL elongations did not pass their corresponding first draft pendulum certification corridor. While most tibia results were located well in the middle or the upper half of the corridors, most ligament results were borderline at the lower end or out of the corresponding corridor (figures 13 and 14).

As it can be seen in table 7, all segments performed well in terms of repeatability with CVs below 5% and could thus be used for the definition of the pendulum reproducibility corridors:

Table 7.
Repeatability of pendulum test results with master legforms.

Segment	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
Setup 1							
Setup 2							
Setup 3							
Setup 4							
Setup 5							
Setup 6							
Setup 7							
Setup 8							
Setup 9							

The reproducibility corridors, that were again calculated by drafting a 10% variance around the pooled means, are given in table 8:

Table 8.
Definition of reproducibility corridors for pendulum certification test.

Segment	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
Setups for Reproducibility Corridor [CV < 5%]	1-9	1-9	1-9	1-9	1-9	1-9	1-9
Pooled Mean with CV < 5%	253,34	203,09	153,32	102,63	9,38	4,20	22,40
Upper Limit	278,67	223,40	168,65	112,89	10,32	4,62	24,64
Lower Limit	228,00	182,78	137,99	92,36	8,44	3,78	20,16

Those setups and segments with reproducible test results were then again taken into account for the definition of the pendulum certification corridors, determining their individual maxima and minima and considering a scatter of 5%, added to their maxima and subtracted from their minima:

Table 9.
Definition of certification corridors for pendulum certification test.

Test #	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
Setup 1							
Setup 2							
Setup 3							
Setup 4							
Setup 5							
Setup 6							
Setup 7							
Setup 8							
Setup 9							
Maximum	259,94	208,81	158,31	106,39	9,90	4,61	23,10
Minimum	247,30	195,80	146,10	94,70	8,75	3,80	21,68
Max * 1,05 (Consideration of scatter)	272,94	219,25	166,22	111,71	10,40	4,84	24,26
Min * 0,95 (Consideration of scatter)	234,94	186,01	138,80	89,97	8,31	3,61	20,60
Certification Corridor Upper Limit	272	219	166	111	10,5	5	24
Certification Corridor Lower Limit	235	187	139	90	8	3,5	20,5

Figures 13 and 14 show all pendulum test results with the three master legforms and their fitment within the first draft corridors (black) and the new corridors (blue).

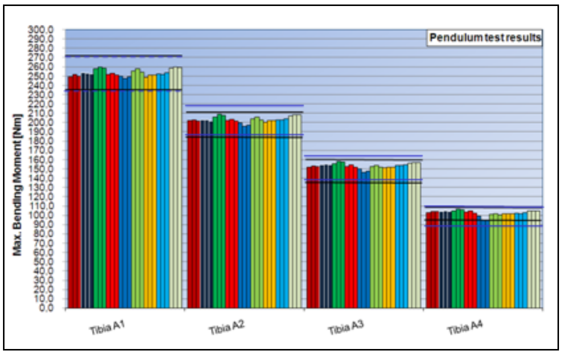

Figure 13. Tibia results of pendulum certification tests with master legforms.

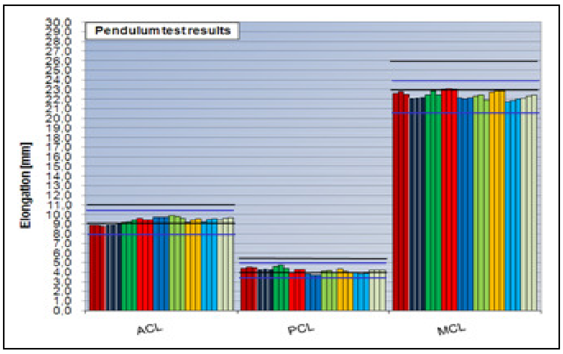

Figure 14. Ligament results of pendulum certification tests with master legforms.

All certification tests with the master legforms passed the new pendulum corridors.

Analysis

The inverse and pendulum certification corridors have been revised, taking into account the test data from three completely overhauled or brand-new legform impactors (master legforms). As a method of updating the corridors, the established method as agreed by the Flex-TEG was used.

Based on the available test data, the first draft inverse corridors have been further tightened for four segments and slightly widened for two segments for the establishment of the new inverse corridors. One corridor width remained unchanged.

Furthermore, the first draft pendulum corridors have been widened for six segments in order to define the new pendulum corridors. One segment remained unchanged.

The inverse mid corridor for all segments was shifted downwards (between 2,3 and 7,8 percent), while the pendulum mid corridor for all ligaments was shifted downwards (between 7,5 and 9,5 percent), for two tibia segments upwards (2,5 and 3,4 percent), and for two tibia segments it remained almost unchanged. In order to comply with the latest requirements, a detailed check-up and, where necessary, update of all previously built impactors is strongly recommended.

HARMONIZATION OF LOWER LEGFORM TO BUMPER TEST AREA

At the 1st meeting of the Informal Group GTR9-PH2 a request of the European Commission to amend the terms of reference of the IG was discussed. It was requested that this amendment would contain re-assessment of the legform test zone to counteract manufacturer‘s practice of making the bumper test area as narrow as possible by using different vehicle design means. There was consensus within the IG that no amendment of the terms of reference was needed as those already covered the general possibility of modifying the pedestrian test procedures for the legform impact.

BASt detailed a proposal on how possibly modifying the legform test area.

Background

Within the current GTR9 test procedure, the bumper test area is defined as the “frontal surface of the bumper limited by two longitudinal vertical planes intersecting the corners of the bumper and moved 66 mm parallel and inboard of the corners of the bumpers” (UNECE, 2009). Several years ago the manufacturer’s practice to keep the bumper test area narrow using means of design, resulting in possibly hard structures outside the bumper test area being unassessed, was already noted by Euro NCAP.

In order to also enable tests to and assessments of structures outboard of the bumper corners that are likely to be more injurious than in the adjacent inboard area, this problem was addressed by Euro NCAP (2012) by widening the bumper test area to either the ends of the bumper cross beam or the bumper corners, eliminating the 66 mm inboard distance, whatever area is larger, see figure 15:

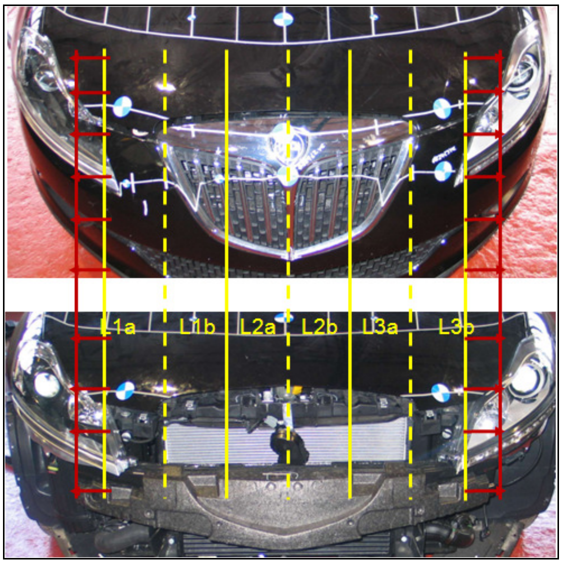

Figure 15. Bumper test area limited by bumper corners according to current GTR9 and former Euro NCAP Protocol (yellow limitations) and according to current Euro NCAP protocol (red limitations).

Though the current practice of Euro NCAP was a step into the right direction, the premature limitation of the bumper test area still needs to be investigated. An early draft of a bumper test procedure (1985) defined the corners of the bumper by the vehicle‘s point of contact with a straight edge which makes an angle of 45° with the vertical longitudinal plane of the vehicle and is tangential to the outer bumper surface. Within a draft proposal for a European Council Directive a change of the angle to 60° was implemented (EC, 1992). In 2002, the British Transport Research Laboratory (TRL) found an actual vehicle with very small bumper test width, just between the inner ends of the headlights, and therefore proposed to Working Group 17 of the European Enhanced Vehicle-safety Committee (EEVC WG 17) to change the angle back to 45°. However, WG 17 (2002) found that further research would be necessary and for the time being decided to keep the 60°.

Proposal for lower legform to bumper test area

A premature limitation of the width of the test area has been found to exclude potentially injurious structures on the vehicle front from being tested and assessed accordingly. Without in depth accident investigations the assumption has to be made that vehicle-to-pedestrian accidents addressed by the EEVC WG 17 procedures are equally distributed over the whole vehicle width; therefore the vehicle should be assessed accordingly. If legislation aimed at the limitation of the legform test zone e.g. by its definition by structural elements like cross beams, longitudinal beams etc., detailed information on impactor validation would be needed.

The aim of appropriately defining the bumper test area should be enabling the test lab to always test the most injurious impact locations. Therefore, as test area the whole width of the vehicle excluding the mirrors is proposed. For European Regulation, the test area is then to be subdivided into three equal parts:

Figure 16. Bumper test area defined by the entire vehicle width (without mirrors).

Analysis of extended test area

During the latest discussions, a concern has been expressed that the legform impactors are unlikely to be appropriate test tools for application outside the bumper corners because high impactor rotation outside the current GTR test area could occur in case of the bumper being impacted at an angle smaller than 60°.

On the other hand, the bumper corners limiting the GTR9 legform test area are described in the EEVC WG 10 report already; here no indications with respect to impactor validation for selected impact angles are given. Up to now there is no proof for testing outside the current GTR test area necessarily providing unacceptable impactor rotation. Tests even outside the bumper corners were proven to sometimes provide higher or at least equal test results, as shown in figure 17:

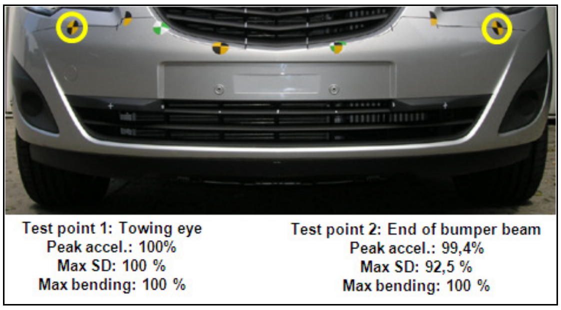

Figure 17. Testing outside bumper corners.

Furthermore, the bumper corners are defined using the outer bumper surface which is not relevant for the feasibility of tests. Altogether, no evidence for the inappropriateness of the extension is given.

As the proposal foresees tests to be performed on potentially injurious test points only, no further problems are expected. On test points with possibly high rotation of the impactor no tests should be conducted. Therefore, as before, the test lab is supposed to always check the structures behind the bumper cover / surface and thus to remove the bumper cover in order to decide whether a test makes sense or not.

COMPARATIVE VEHICLE TESTS

After the issue of the first serial production legforms it has been found that the performance between the prototypes used for the Technical Evaluation Group activities and the serial build level differed to some extent. To get a better understanding of the difference of real world performance within FlexPLI to bumper impacts, tests on vehicles formerly tested with the FlexPLI prototypes (Zander, 2009) have been repeated by BASt with the serial production legforms that were used for the establishment of the certification corridors.

Test overview

An overview of the tests is shown in figure 18:

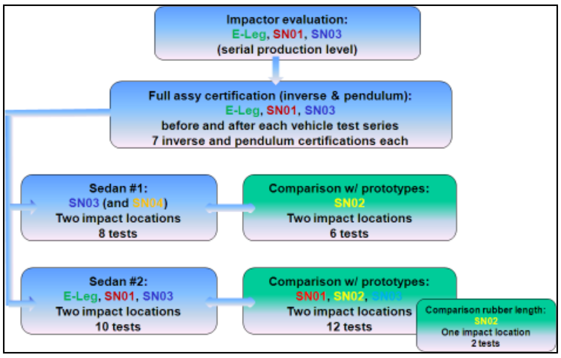

Figure 18. Vehicle tests with master legforms at BASt and comparison to prototype results.

Before and after each vehicle test series, a full assembly inverse as well as pendulum certification test was performed with each impactor. While the first vehicle (Sedan #1) was tested with the SN03 master leg three times each on two impact locations, the second vehicle (Sedan #2) was tested with all three master legforms three times each on the first impact location and one time with SN03 on a second impact location. The test series was amended by two tests with prototype SN04 against Sedan #1. The test results were then compared to those obtained with the FlexPLI prototypes SN01-SN03. In addition, the influence of long and short rubber sheets was investigated, using SN02 prototype at Sedan #2.

Full assembly certification tests.

All three master legforms used for the comparative study were inverse and pendulum certified before and after each test series. For the inverse certification tests, all impactors met the new corridors. However, it was noted that the results for tibia 4 were partly low to borderline. For the pendulum test, all impactor results for all segments except one tibia 4 and two PCL results were well within the new certification corridors. Altogether, the new corridors were entirely met by all impactors during every test.

Sedan #1 test results

Figures 19 and 20 show the tibia and knee test results on Sedan #1 that was tested on two different impact locations three times each with prototype impactor SN02 as well as with master leg SN03. Besides, one additional test was performed with prototype SN04 on both impact locations.

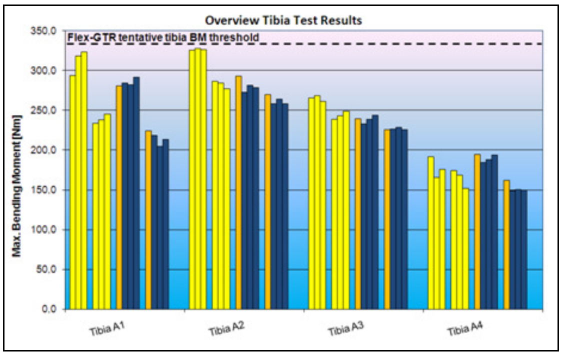

Figure 19. Tibia results of Sedan #1 tests with SN02 prototype (Y), SN03 master leg (B) and SN04 prototype (O) on two impact locations.

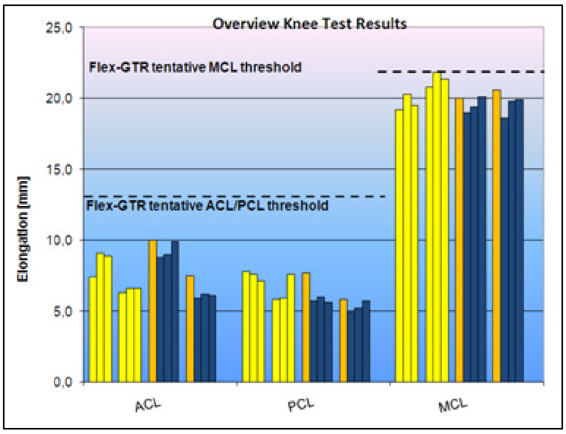

Figure 20. Knee results of Sedan #1 tests with SN02 prototype (Y), SN03 master leg (B) and SN04 prototype (O) on two impact locations.

It can be seen that all FlexPLI threshold values as proposed by the Flex-TEG were met in all tests with Sedan #1. A comparison of the test results on impact location #1 shows that the tibia 1-3 and PCL results were lower while tibia 4 as well as ACL gave higher results with the serial production leg. For MCL, no significant difference between prototype and master leg could be observed, see table 10:

Table 10.
Deviation of mean values of SN03 serial production leg from SN02 prototype – impact location #1.

	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
MV SN02	311,83	326,33	264,87	177,50	8,47	7,50	19,67
MV SN03	285,97	277,47	238,63	188,87	9,23	5,77	19,50
Dev. [%]	-8,30	-14,97	-9,90	6,40	9,06	-23,11	-0,85

Tests on impact location #2 consistently showed lower results of the master legform SN03:

Table 11.
Deviation of mean values of SN03 serial production leg from SN02 prototype – impact location #2.

	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
MV SN02	239,07	282,27	243,50	164,97	6,50	6,43	21,30
MV SN03	212,20	260,00	227,03	149,77	6,07	5,30	19,43
Dev. [%]	-11,24	-7,89	-6,76	-9,21	-6,67	-17,62	-8,76

Furthermore, a slight tendency of SN04 to produce higher results than SN03 could be noted in most cases.

Table 12 demonstrates the repeatability of the SN02 prototype test results being partly marginal (CV > 7%) or unacceptable (CV > 10%):

Table 12.
Coefficients of Variation of SN02 prototype and SN03 master leg on Sedan #1.

Setup	Tibia 1	Tibia 2	Tibia 3	Tibia 4	ACL	PCL	MCL
Sedan #1 P1 SN02 Proto	5,05	0,34	1,43	7,43	10,97	4,81	2,89
Sedan #1 P2 SN02 Proto	2,45	1,75	2,10	7,08	2,66	15,72	2,35
Sedan #1 P1 SN03 Serial	1,76	1,55	2,24	2,51	6,35	3,61	2,86
Sedan #1 P2 SN03 Serial	3,28	1,33	0,69	0,44	2,52	6,80	3,72

The serial production leg SN03 shows an improved repeatability with all coefficients of variation in at least an acceptable range (CV ≤ 7%).

Sedan #2 test results

The results of the Sedan #2 tests are shown in figures 21 and 22:

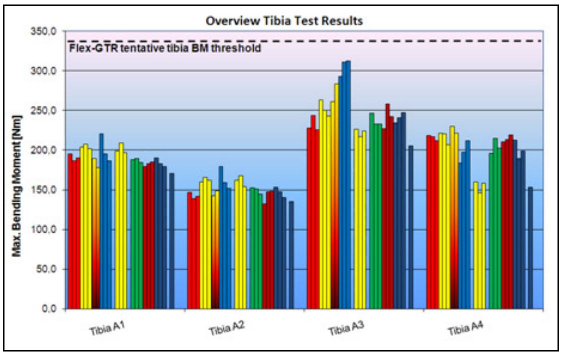

Figure 21. Tibia results of Sedan #2 tests with SN01 prototype + masterleg (R+DR), SN03 prototype + master leg (B+DB), SN02 prototype (Y), E-Leg masterleg (G) and SN02 prototype with long rubber (O) on two impact locations.

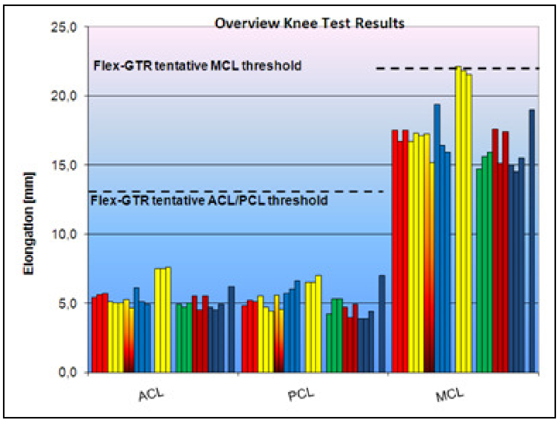

Figure 22. Knee results of Sedan #2 tests with SN01 prototype + masterleg (R+DR), SN03 prototype + master leg (B+DB), SN02 prototype (Y), E-Leg masterleg (G) and SN02 prototype with long rubber (O) on two impact locations.

All but one test passed on Sedan #2 the TEG tentative tibia and knee threshold values. Only the MCL requirement was failed once with the SN02 prototype. On impact location #1 the tests performed with the serial production legforms resulted in generally lower values than those with the prototype impactors, as it can be seen in table 13:

Table 13.
Deviation of mean values of serial production legs from prototypes – impact location #1.

	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
MV SN01-SN02-SN03	198,58	156,21	263,31	209,81	5,32	5,33	17,17
MV E-Leg-SN01-SN03	184,66	146,40	240,29	206,29	4,91	4,51	15,70
Dev. [%]	-7,01	-6,28	-8,74	-1,68	-7,72	-15,42	-8,54

On impact location #2, most results (except PCL) were again lower with the serial production impactor SN03 (table 14), however, the statistical significance of this comparison is limited because only one test was performed with SN03.

Table 14.
Deviation of SN03 serial production leg results from mean values of SN02 prototype – impact location #2.

	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
MV SN02	201,40	161,37	222,57	154,87	7,53	6,67	21,80
Single Test SN03	170,30	135,40	205,20	153,20	6,20	7,00	19,00
Dev. [%]	-15,44	-16,09	-7,80	-1,08	-17,70	5,00	-12,84

Table 15 shows the repeatability of the prototype against serial production legform test results. While the scatter of the cruciate ligament elongations sometimes remains unacceptable (CV > 10%), the tibia repeatability is improved, having all CVs in an acceptable range (≤ 7%). The scatter of the knee results has partly increased.

Table 15.
Coefficients of Variation of prototypes and master legs on Sedan #2.

Setup	Tibia 1	Tibia 2	Tibia 3	Tibia 4	ACL	PCL	MCL
Sedan #2 P1 SN01 Proto	2,18	2,78	4,18	1,59	2,74	4,14	2,68
Sedan #2 P1 SN02 Proto	1,40	1,82	4,01	3,69	1,15	11,68	1,79
Sedan #2 P1 SN03 Proto	8,74	8,83	3,57	7,09	11,98	7,51	10,98
Sedan #2 P2 SN02 Proto	3,36	4,23	2,38	4,87	0,77	4,33	1,38
Sedan #2 P1 Eleg Serial	1,28	2,78	3,36	4,64	3,14	12,87	4,06
Sedan #2 P1 SN01 Serial	1,74	6,33	6,45	2,10	11,17	10,42	8,32
Sedan #2 P1 SN03 Serial	2,99	4,47	2,64	5,83	4,26	7,10	3,33

The influence of the rubber length evaluated with SN04 shows inconsistent results, depending on the location of the particular vehicle load paths:

Table 16.
Deviation of results with impactor SN02 with long rubber sheets to those with short rubber sheets – impact location #1.

	Tibia A1	Tibia A2	Tibia A3	Tibia A4	ACL	PCL	MCL
MV SN02 SR	204,47	162,67	252,20	216,10	5,03	4,87	17,03
MV SN02 LR	184,3	146,0	272,8	226,1	5,0	5,1	16,3
Dev. [%]	-9,89	-10,25	8,17	4,60	-0,66	4,79	-4,60

Analysis

18 impactor tests with three different serial production impactors (E-Leg, SN01 and SN03) and SN04 on two different vehicles were carried out at BASt.

The master legforms have been successfully inverse and pendulum certified according to the TF-RUCC corridor proposal before and after each vehicle test series. All test results entirely met the tentative FlexPLI thresholds for tibia bending moments as well as ligament elongations.

A comparison of the serial production impactor test results with prototype results on identical impact locations shows that the serial production impactors are producing in most cases lower output values than the prototypes. This observation is in line with the inverse certification tests presented in this study.

The repeatability of vehicle test results shows an improvement regarding the tibia segments while the scatter in the knee has partly even increased.

The influence of the length of the rubber sheets on the test results is inconsistent and seems to depend on the location of the particularly impacted load paths.

STATUS OF DEVELOPMENT AND EVALUATION OF AN UPPER BODY MASS FOR THE FLEX-PLI

Though the FlexPLI has been proven to have biofidelic properties for an improved assessment of knee and tibia injuries in lateral vehicle-to-pedestrian accidents, the biofidelity of the femur section still needs to be improved, reason why the output of the femur strain gauges is not yet being considered for the assessment of femur injuries.

Thus, an upper body mass (UBM) for the FlexPLI that had been developed in a first step within the FP6 project APROSYS by Bovenkerk et al. (2009), was validated in a second step within tests of different car front shapes and against full scale vehicle to dummy tests with applied FlexPLI by Zander et al. (2009 and 2011). In latter study it was found that the maximum loadings of most of the segments were comparable in component tests with UBM and full scale tests, but that the characteristics of the corresponding time history traces were not always fully alike. While tests against further vehicle frontend shapes should amend the data basis, an optimization of the kinematics and impactor response could be done by vertical and longitudinal UBM alignment, based on additional simulations and component tests. In a third step, an FE model of the UBM was developed on the LS DYNA platform by BASt (Methner, 2012) and applied to the FlexPLI FE model. Simulations with the FlexPLI-UBM against a generic car frontend with adjustable load paths were carried out within the FP 7 project IMVITER by Eggers et al. (2012):

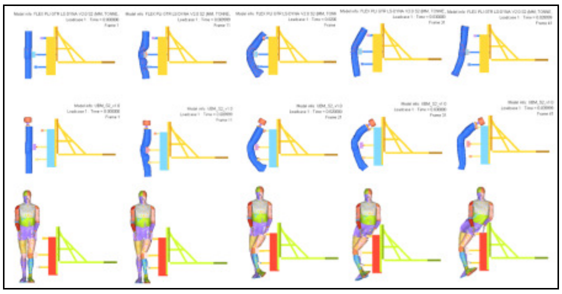

Figure 23. Simulations with baseline FlexPLI, FlexPLI-UBM and THUMS against test rig.

Those simulations were then compared to impactor tests with applied upper body mass against a validation rig:

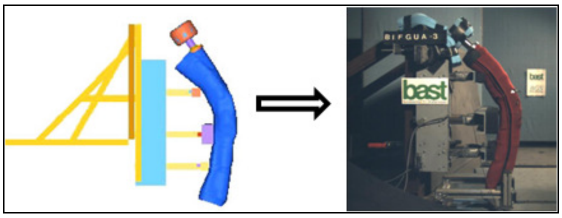

Figure 24. FlexPLI-UBM simulations and impactor tests against test rig.

As already indicated within previous studies, for the sedan and SUV frontend, the FlexPLI with upper body mass showed a much better kinematic correlation with full human body simulation model than the baseline impactor. On the other hand, impactor tests with applied UBM had to be conducted at comparatively low impact speeds. The generic car frontend needs appropriate modifications so that tests at impact speeds around 40 kph will be possible.

In the long run, the bumper test with baseline Flex-GTR and the test of the bonnet leading edge with upper legform impactor which is still carried out within European Legislation as well as the Euro NCAP test programme should be replaced by a unique test with FlexPLI-UBM to appropriately assess tibia, knee as well as femur injuries. Further research in this context is needed and should focus on the correlation between the impactor threshold values and the underlying injuries predicted by human models.

DISCUSSION

The flexible pedestrian legform impactor FlexPLI has been evaluated by a Technical Evaluation Group of GRSP from 2005 to 2010. Aim was the introduction of the FlexPLI within the UN global technical regulation on pedestrian safety (UN-GTR9). However, GRSP found that the FlexPLI was at that stage not ready for legislation and therefore mandated an informal group to address all open issues related to the FlexPLI for being implemented within a second phase of the GTR. This paper presents several studies carried out by the German Federal Highway Research Institute BASt as contribution to the work of the IG. An investigation of the estimated cost reduction in Germany due to the introduction of the FlexPLI results in around 44 Mio € to be annually saved.
A long term study proves the test results with both the FlexPLI at prototype status with polyester bone core material as well as equipped with vinylester bone cores, despite some physical wearing, as being very robust. However, the overall performance between the latest prototype build level and the serial production status have been found to differ to some extent. Therefore, BASt drafted new assembly certification corridors for both the dynamic inverse as well as the pendulum certification test. The FlexPLI serial production legform having a lower output than the prototype was confirmed in a comparative study with tests against vehicles that had been previously tested with FlexPLI prototypes. Thus, a downwards shift of the current draft FlexPLI impactor thresholds (UNECE, 2012) according to the actual performance within the inverse certification tests, as already proposed by BASt to the IG (Zander, 2012-6) , seems reasonable.
A modified definition of the assessment area for lower legform to bumper tests has been proposed by BASt to address manufacturer’s practice to reduce its width by design elements. The proposal that foresees to also test points outside the area limited by the bumper corners is expected to be

feasible for both, the EEVC WG 17 legform impactor described in the current GTR9 as well as the new FlexPLI for GTR9-PH2.

An improved injury assessment ability of the femur section of the FlexPLI will be addressed with the introduction of an upper body mass representing the pedestrian's torso. Evaluation activities are still ongoing by amending the data basis and developing corresponding correlations between human body models and the FlexPLI with applied upper body mass.

CONCLUSIONS

The FlexPLI prototype build level that has been evaluated and subsequently proposed by the Flex-TEG for the implementation within global technical regulation on pedestrian safety was not ready for legislation at that stage.

The remaining open issues are being addressed by the GRSP Informal Group on GTR9 Phase 2. After the finalization of the work of the informal group, the GTR-PH2 is expected to be adopted by GRSP in December 2013 and subsequently voted by WP.29 in June 2014.

Ideally, a modified bumper test area will be implemented from the start. However, the progress of the Task Force Bumper Test Area won't delay the finalization of the work of the informal group.

The evaluation of the FlexPLI with applied upper body mass requires further research and thus needs to be addressed within a third phase of the global technical regulation on pedestrian safety.

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APPENDIX

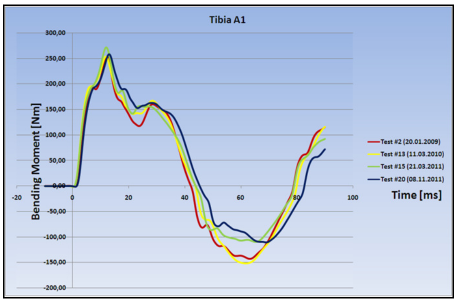

Figure 25. Tibia 1 time history curves of four inverse tests with SN02 at different build levels.

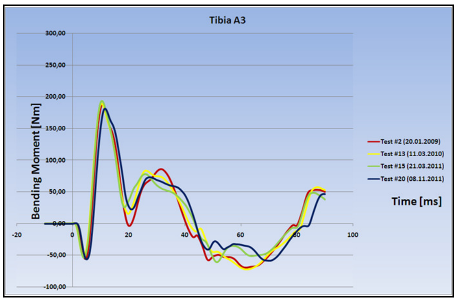

Figure 26. Tibia 3 time history curves of four inverse tests with SN02 at different build levels.

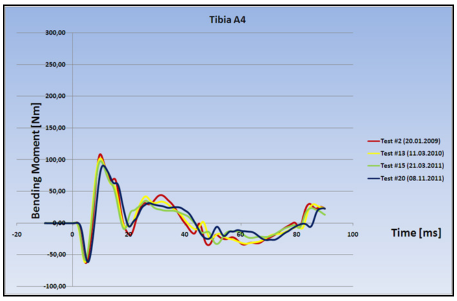

Figure 27. Tibia 4 time history curves of four inverse tests with SN02 at different build levels.

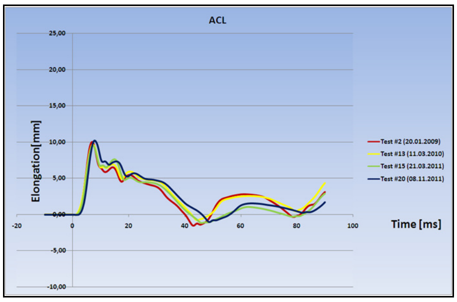

Figure 28. ACL time history curves of four inverse tests with SN02 at different build levels.

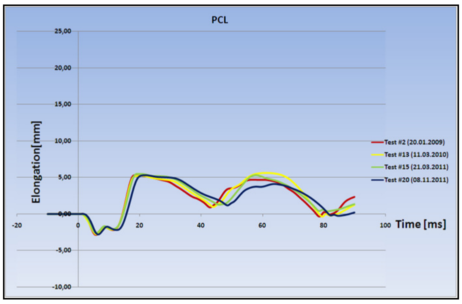

Figure 29. PCL time history curves of four inverse tests with SN02 at different build levels.

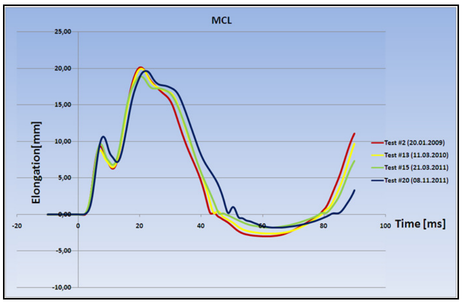

Figure 30. MCL time history curves of four inverse tests with SN02 at different build levels.

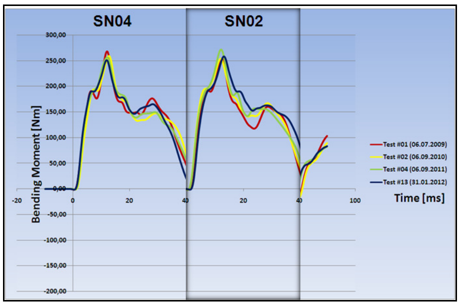

Figure 31. Tibia 1 time history curves of four inverse tests with SN04 and comparison with SN02.

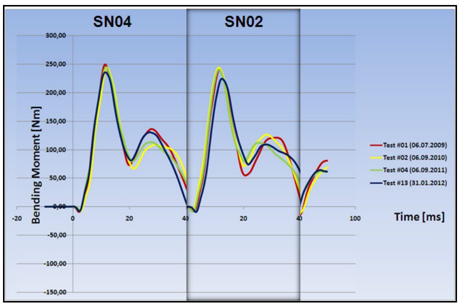

Figure 32. Tibia 2 time history curves of four inverse tests with SN04 and comparison with SN02.

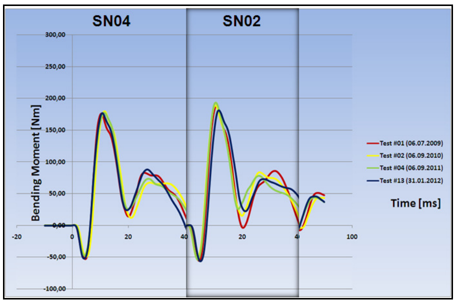

Figure 33. Tibia 3 time history curves of four inverse tests with SN04 and comparison with SN02.

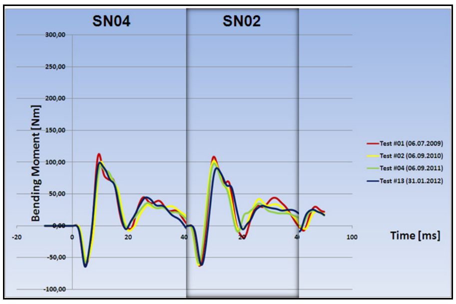

Figure 34. Tibia 4 time history curves of four inverse tests with SN04 and comparison with SN02.

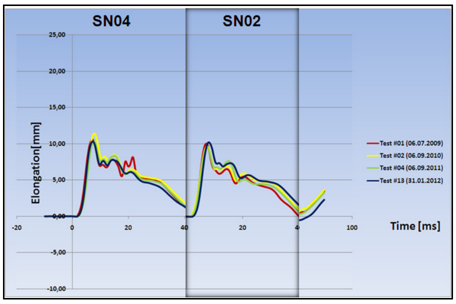

Figure 35. ACL time history curves of four inverse tests with SN04 and comparison with SN02.

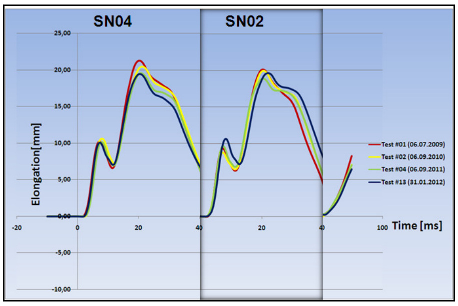

Figure 36. MCL time history curves of four inverse tests with SN04 and comparison with SN02.