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Sensitivity Analysis for Pedestrian Lower Leg Impact

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Micro Abstract
Pedestrian safety has gathered a lot of attention in recent years among academic and industrial researchers, promoted by the quick evolution of regulation and consumer test requirements. The current work presents the challenges involved in pedestrian lower leg impact test and attempts to deal with them in the field of structural optimization. A sensitivity analysis of the FlexPLI injury criteria is carried out, as motivation for the development of a parametric simplified vehicle front-end model.

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1 Introduction

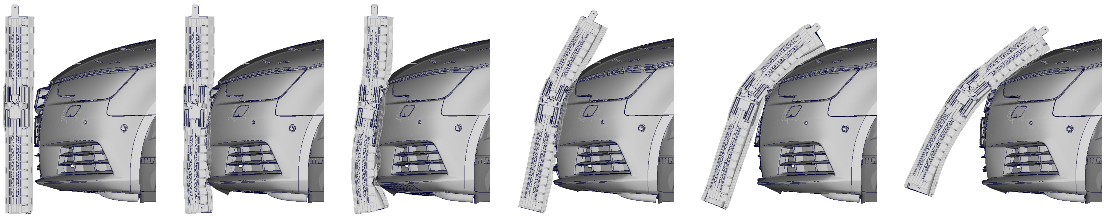
In 2013, 1.25 million fatalities worldwide were related to road traffic and the 49% of them were among people with the least protection: motorcyclists (23%), pedestrians (22%) and cyclists (4%) [10]. In the same year, over 5500 pedestrians were killed on European Union roads, representing the 21% of total road traffic deaths in this region. Taking into account the time span 2002-2012, the reduction in fatalities of vulnerable road users (-39%) has not followed the same pace of that in car occupants deaths (-53%), pointing out the need to further improve safety precautions and vehicle design for those outside of the vehicle [1].

The first regulation regarding pedestrian protection was enacted in 2003 by the European Commission with the directive 2003/102/EC. The pedestrian lower leg impact test was based on the work of the European Experimental Vehicles Committee Working Group 17, which proposed in 1998 a subsystem test procedure using the legform impactor developed by the Transport Research Laboratory (TRL) [2]. The lack of biofidelity of this impactor induced, since 2002, researchers of the Japan Automobile Research Institute to develop a completely new impactor, the so-called Flexible Pedestrian Legform Impactor (FlexPLI), which presents human-like flexible femur and tibia shafts [9]. This impactor was adopted in 2014 by the EuroNCAP consumer test and in 2015 by the UN Regulation 127, valid in Europe.

1.1 Lower Leg Impact Test

In Figure 1, the simulation of the lower leg impact test at the vehicle mid-plane on a large family car is shown. The impactor is presented in cross-section view. According to regulation, the FlexPLI is shot against the vehicle front-end at a speed of 40 km/h with a height of 75 mm from the ground level. The force-time curves at the three main load levels are displayed in Figure 2. The lower load level covers the area of the lower stiffener, the middle that of the bumper foam and the upper encloses the bonnet leading edge. The lower load level is the first to be triggered and exerts the maximum force at about 5 ms, inducing a large bending moment on the lower part of the tibia (Figure 1b). The bumper foam is fully compressed at about 10 ms, followed shortly after by the impact on the bonnet leading edge (Figure 1c). At about 30 ms (Figure 1e), the femur completes the rotation over the bonnet; the misalignment between femur and tibia generates a significant elongation in the Medial Collateral Ligament (MCL).

Two impact positions are considered in the current work: the vehicle center-plane, i.e. y=0 mm, and one towards the side of the vehicle, at y=450 mm, where the bumper starts to incline for styling purposes. This characteristics sets up a force component in the y-direction, which induces a rotation of the leg around the vertical axis, as shown in Figure 3.



(a) t=0 ms **(b)** t=5 ms **(c)** t=10 ms **(d)** t=20 ms **(e)** t=30 ms **(f)** t=40 ms

Figure 1. Lower Leg Impact Test

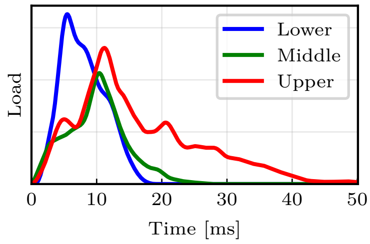


Figure 2. Load Levels Force-Time Curves

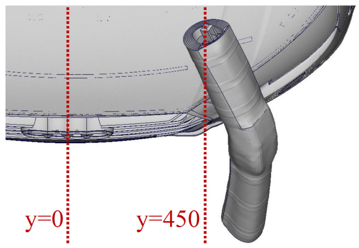


Figure 3. Leg Rotation at y=450 mm

1.2 Literature Review

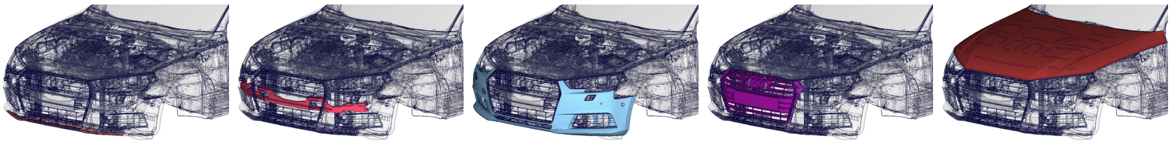
The stringency of regulations and consumer tests has significantly changed the way of designing vehicle front-ends. Furthermore, the introduction of the FlexPLI has raised new challenges to be faced. Several studies investigated methods to improve the front-end design with regard to pedestrian lower leg impact test. Han and Lee, Nanda et al. and Neal et al. assessed the importance of stiffness and geometrical front-end design factors through sensitivity analyses and optimization studies [3, 7, 8]. Lower stiffener, bumper foam and bonnet leading edge were identified as key parameters concerning the legform injury criteria. These works used the TRL impactor, whose requirements were significantly different from the current ones. Furthermore, due to the high computational effort involved with detailed FE models, they most often performed analyses on simplified models, whose validation may not be valid over the entire design space defined in the parametric studies. Lv et al. investigated position and thickness of lower stiffener and bumper energy absorber to reduce both FlexPLI and TRL injury criteria [5]. Lee et al. focused on the positions of lower stiffener, bumper energy absorber and bonnet leading edge for minimum MCL [4]. Mößner et al. developed an advanced simplified front-end model and showed the sensitivity of the lower stiffener position on the FlexPLI injury criteria [6]. These studies concentrated mainly on optimization purposes of geometrical parameters. The aim of the current study, instead, is to enhance the understanding of the most important front-end components from a structural point of view, through a sensitivity analysis applied to a detailed FE vehicle front-end model. Special attention is paid on the relation between load levels and FlexPLI's injury criteria and on the complexity of the legform kinematics towards the side of the vehicle.

2 Sensitivity Analyses

Two sensitivity analyses with different impact positions are performed and compared. Both analyses are accomplished with a Design of Experiments (DoE) of 50 points, sampled according to an optimized Latin Hypercube scheme (LHS). The design variables are five: lower stiffener thickness (h), bumper foam density (ρ), bumper fascia thickness, grille thickness and bonnet thickness, as shown in Figure 4. The range of variation for all the parameters is $\pm 30\,\%$ from the initial design, as approximation of the typical design space considered in the development phase. As the two most critical FlexPLI injury criteria for the case at hand are the mid-lower tibia bending moment and the MCL elongation, only these two measures are presented in the scatter plots.

2.1 First Shooting Position: y=0 mm

The scatter plots of the FlexPLI injury criteria with respect to the design variables for the first shooting position are shown in Figure 5. Superimposed to the plots, the values of the Pearson correlation coefficient r, which measures the linearity of the data set, are expressed. The axes ticks are reported as relative



(a) Lower Stiffener **(b)** Bumper Foam **(c)** Bumper Fascia **(d)** Grille **(e)** Bonnet

Figure 4. Components Defined in the Design Variables

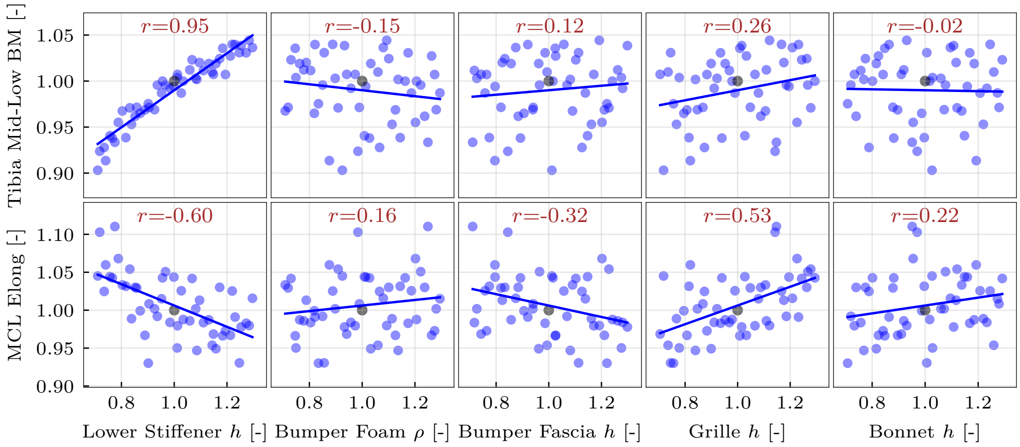


Figure 5. Scatter Plots Design Variables - Injury Criteria at y=0 mm

values to the initial design.

The Mid-Low tibia bending moment presents a very strong positive linear trend with the lower stiffener thickness (r=0.95), while the other design variables have poor correlation. The MCL elongation correlates well with lower stiffener and grille thicknesses (respectively, r=-0.60 and r=0.53). For the other design variables the scatters are significantly spread around the regression line, therefore the correlation is low.

In Table 1, the percentage of variation of the injury criteria due to a 10 % increase in the design variables, estimated from the slope of the regression line, is presented. The lower stiffener thickness has the highest influence: 2% increase in Tibia Mid-Low and 1.4% decrease in MCL. The grille thickness ensures a 0.5% variation on Tibia Mid-Low and a 1.2% variation on MCL, both positive. The bumper fascia has a good impact on MCL (-0.8%), though the correlation is limited (r=-0.32). Bonnet thickness and bumper foam density seem to have little effect on both injury criteria.

In order to better understand the influence of the design variables on the FlexPLI injury criteria, the three load levels shown in Figure 2 are evaluated, in the form of mean values. In Table 2 the Pearson correlation coefficient between injury criteria and load levels is reported, while in Table 3 the variation percentage of the injury criteria due to a 10 % increase in the load levels is given. The lower load level has a strong correlation with both Tibia Mid-Low (r=0.84) and MCL (r=-0.82). The variation percentages are opposite, yet the magnitude is comparable: 6.2% increase in Tibia Mid-Low and 6.7% decrease in MCL. The middle load level correlates moderately with Tibia Mid-Low (r=-0.46), while the upper load level with the MCL elongation (r=0.44).

2.2 Second Shooting Position: y=450 mm

The scatter plots of the tibia mid-lower bending moment and MCL elongation with respect to the design variables for the second shooting point are shown in Figure 6. In Table 4, the percentage of variation of the injury criteria due to a 10 % increase in the design variables is presented.

Injury Criteria	Lower Stiffener h	Bumper Foam h	Bumper Fascia h	Grille h	Bonnet h
Tibia Mid-Low BM	2.0 %	-0.3 %	0.2 %	0.5 %	-0.1 %
MCL Elong	-1.4 %	0.4 %	-0.8 %	1.2 %	0.5 %

Table 1. Injury Criteria Variation Percentage for 10 % Increase in the Design Variables at y=0 mm

Injury Criteria	F_{Low}	F_{Mid}	F_{Up}
Tibia Mid-Low	0.84	-0.46	0.32
MCL Elong	-0.82	-0.04	0.44

Table 2. Pearson Correlation Coefficient btw. Load Levels and Injury Criteria at y=0 mm

Injury Criteria	F_{Low}	F_{Mid}	F_{Up}
Tibia Mid-Low	6.2 %	-2.7 %	1.3 %
MCL Elong	-6.7 %	-0.2 %	2.0 %

Table 3. Injury Criteria Variation Percentage for 10 % Increase in the Load Levels at y=0 mm

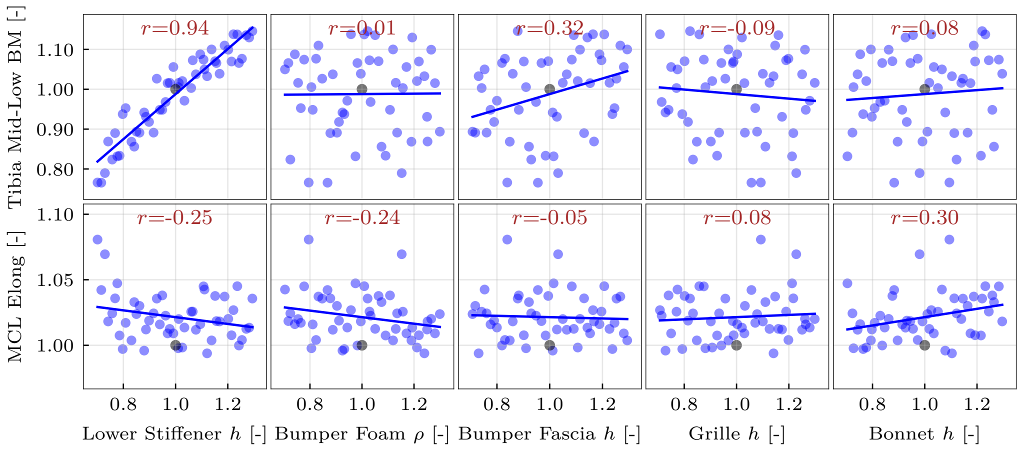


Figure 6. Scatter Plots Design Variables - Injury Criteria at y=450 mm

The most significant correlation is obtained between lower stiffener thickness and Tibia Mid-Low (r=0.94), associated with a large variation percentage (5.7%). The bumper fascia thickness contributes to a relevant variation percentage of Tibia Mid-Low (2%), though the correlation is limited (r=0.32). The MCL does not correlate strongly with any design variables.

Table 5 and Table 6 are analogous to Table 2 and Table 3, though applied to the second impact position. Tibia Mid-Low is well correlated with both lower and upper load levels, together with large variation percentages (respectively, 17.8% and 19%). MCL correlates moderately with the lower load level (r=-0.38).

2.3 Discussion of the Results

The lower stiffener thickness is the most relevant design variable affecting the mid-lower tibia bending moment and the MCL elongation for both impact positions. This is directly related to the relevance of the lower load level. The mid-lower section on the tibia shaft lies nearby the point of impact with the lower stiffener, therefore the stiffer this component, the larger the bending moment. Furthermore, the lower stiffener plays an important role in accelerating the tibia rebound phase, which helps to prevent an excessive MCL elongation. Unfortunately, the influence on the two injury criteria is opposite, therefore a compromise must be found.

Opposite trends with respect to the injury criteria are found for four design variables out of five in both impact positions. The exception is represented, at y=0 mm, by the grille thickness and at y=450 mm, by the bonnet thickness, whose decreases would ensure a reduction in both injury criteria. However, only the influence of the grille thickness on MCL is supported by a good correlation coefficient and can be considered robust. A possible explanation for this influence is that the reduction in the grille thickness softens the area around the bonnet leading edge and, as a consequence, the legform intrudes more, delaying the femur rotation. In support of this interpretation, the upper load level presents a very similar trend with respect to MCL.

The lower stiffener influence on the mid-lower tibia bending moment at the outwards impact position is almost three times that at the central one; the equivalent is obtained when comparing the lower load level. This indicates that towards the side of the vehicle Tibia Mid-Low gets much more sensitive to the

Injury Criteria	Lower Stiffener h	Bumper Foam h	Bumper Fascia h	Grille h	Bonnet h
Tibia Mid-Low BM	5.7 %	0.1 %	2.0 %	-0.6 %	0.5 %
MCL Elong	-0.3 %	-0.2 %	-0.1 %	0.1 %	0.3 %

Table 4. Injury Criteria Variation Percentage for 10 % Increase in the Design Variables at y=450 mm

Injury Criteria	F_{Low}	F_{Mid}	F_{Up}
Tibia Mid-Low	0.96	-0.36	0.50
MCL Elong	-0.38	0.03	0.12

Table 5. Pearson Correlation Coefficient btw. Load Levels and Injury Criteria at y=450 mm

Injury Criteria	F_{Low}	F_{Mid}	F_{Up}
Tibia Mid-Low	17.8 %	-7.7 %	19.0 %
MCL Elong	-1.2 %	0.1 %	0.8 %

Table 6. Injury Criteria Variation Percent for 10 % Increase in the Load Levels at y=450 mm

lower load level. The MCL elongation instead experiences at this impact position a significant reduction in both correlations and variation percentages at all load levels. A possible explanation is that the MCL elongation here is considerably affected by the vehicle front-end geometry and only partly by the structural characteristics of the front-end components.

The design indications coming from the load levels are in agreement between both impact positions: for reducing Tibia Mid-Low, lower and upper load levels should decrease and the middle increase; for reducing the MCL elongation, the lower load level should increase and middle and upper decrease. Nevertheless, the middle load level seems to have tiny correlation and influence on MCL.

3 Conclusions

In the present work, two sensitivity analyses have been performed for the pedestrian lower leg impact test against a large family car at two different impact positions. Five design variables related to the main structural front-end components have been investigated with regard to their contribution to the most critical FlexPLI injury criteria. Good correlations and trends have been identified. The lower stiffener has proved to be the most significant component influencing both mid-lower tibia bending moment and MCL elongation. Concerning the other design variables, the effects are often not concordant between the two impact positions. More robust indications can be obtained by taking into account the load levels. In the outwards impact position, the MCL elongation seems to be little sensitive to the stiffness of the front-end components. This highlights the limitation of the current investigation, where, due to the complexity of the detailed FE vehicle model, geometrical factors of the front-end have not been taken into consideration. The relation between MCL and a combination of geometrical and stiffness parameters at outwards impact positions should be investigated in a subsequent work with the help of a simplified FE model.

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