Pedestrian Passive Safety During the SUV Impact: Regulations vs. Reality

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Abstract This paper investigates the influence of the vehicle front-end geometry on the legform of a pedestrian. The attention is turned towards the legform test, since it was noticed that the disproportion of legform behaviour for the subsystem test and full scale dummy is considerable. The verification of kinematics was conducted by means of appropriate numerical software and validated dummies based on Finite Element Method, multibody as well as Coupling – i.e. multibody interfaced with FEM. The acquired and presented data suggest that for SUV-type vehicles the dummy test is more effective. Based on the research, the authors propose that high-bumper vehicles should be granted the type-approval with regard to the protection of pedestrians, provided they ensure adequate kinematics to a pedestrian – i.e. do not drag a pedestrian underneath the chassis. Secondly, the vehicles must meet the biomechanical criteria encompassed by the current standards which ensure the desired crash energy absorption.

Keywords legform injury, numerical simulations, pedestrian safety, Sport Utility Vehicle

I. INTRODUCTION

In Europe, one of the first groups which examined the fronts of vehicles in terms of pedestrian protection was Working Group (WG) 7 of the European Experimental Vehicle Committee (EEVC). Later, WG 10 was formed in 1988 and membership included representatives of research institutions as well as the automobile industry [1]. The main goal of WG 10 was to expand test methods and regulations which related to vehicle front structure design. In other words, the core of the mandate of the Group was to “determine test methods and acceptance levels for assessing the protection afforded to pedestrians by the fronts of cars in an accident …”[1].

In 1997 the former WG 10 was transformed into a new EEVC Working Group 17 which continues the work on the enhancement of pedestrian protection. The tests and test devices have been refined since then and the latest report was released in 1998 with a 2002 update. In February 2009 a new European Commission Regulation (EC) 78/2009 on pedestrian protection was published. It replaces the EC directives concerning pedestrian protection (2003/102/EEC) and also frontal protection systems (2005/66/EC). It applies to passenger cars, multipurpose passenger vehicles and goods vehicles with a laden vehicle weight less than 2,500 kg. However, after a certain transitional period the regulation will also be applied to vehicles exceeding this mass limit due to an increasing number of heavy vehicles being used on roads.

The current EC 78/2009 regulation encompasses the tests which relate to pedestrians struck by the side of a vehicle front-end [2]. This is because about 80% of accidents involving these vulnerable road users are side-struck scenarios when the pedestrian is crossing in front of the vehicle travel line [3]. These conditions result in injuries unique to the pedestrian-car collision. Figure I depicts the Regulation (EC) 78/2009 subsystem test.

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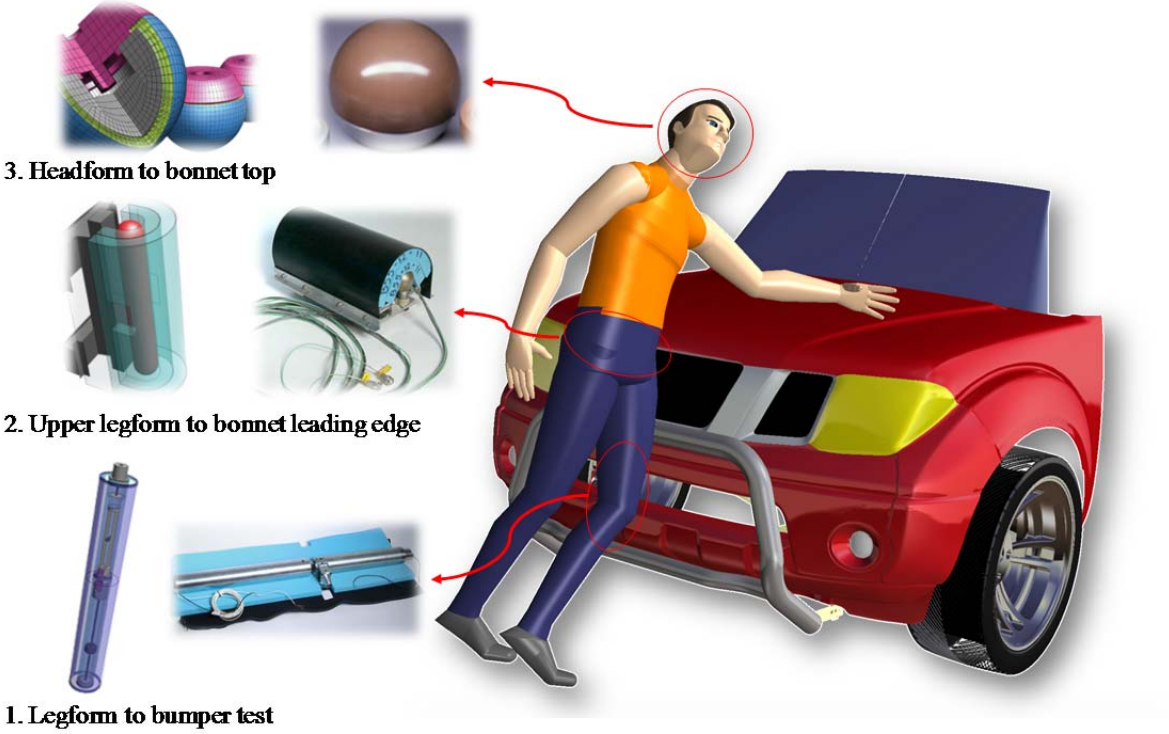


Fig. 1. Pedestrian subsystem tests visualization

The tests comprise:

1. Legform test to prevent leg fractures and knee joint injuries;
2. Upper legform to prevent femur and hip fractures and injuries;
3. Child/adult headform test to prevent life-threatening head injuries.

Based on biomechanical and injury tolerance criteria, the above tests must meet limits to ensure that the risk of severe injuries during a real on-road accident is minimized. The fundamental assessment criteria, which are applied for pedestrian impact tests, are summarized in [2]. The impactors are fired into a stationary car at a speed up to 11.1 m/s, which is a judged limit at which pedestrian protection could be feasibly provided at the current level of technology.

A number of limitations have been identified in the legform impactor, where the rigid structure of both the tibia and femur tubes are the most frequently questioned issues [4]. Essentially, the only compliance criteria of the leg bones are a 25 mm thick layer of the "flesh" foam and 6 mm Neoprene "skin" layer. Hence, the Flex legform is being developed as a next step in increasing the biofidelity of the legform impactor and should result in better representation of bending of the human's lower extremity bones [5].

Although the current regulations require vehicle manufacturers to test vehicle fronts with the impactors, such testing might not mirror the actual kinematics of an impacted pedestrian. Consequently, for vehicles with high bumpers and high bonnet leading edges, the test procedure proposed in current regulations may not fully assess the risk to the vulnerable road user.

Thus, the authors carried out multibody simulations using MADYMO (MAthematical DYnamic MOdeling) coupled with the explicit code of LS-DYNA. The simulations reported in this paper focused on the legform test, since it has been noticed that there are considerable anomalies in legform behaviour for the subsystem test and full scale dummy [6].

II. METHODS

Computer simulations have been developing coincident with the rapid growth of advanced computers. Currently, their contribution to the car designing process is crucial. Additionally, when the Finite Element Method (FEM) was implemented and started to be used by appropriate software, the complexities of modelling, including safety issues, could be addressed. What is more, Euro NCAP pedestrian protection ratings released in 1997 were also a trigger for a fruitful start of virtual tests. Nowadays, numerical simulations constitute the basis for the Computer-Aided Engineering (CAE) [7]. The great development of computation power and the expansion of FEM enabled researchers to widen the possibilities and applications to include pedestrian-to-car front-end collisions. FEM is also utilized in order to reduce the costs and time needed to carry out a pedestrian-to-car front test using certified impactors. Thus, the authors were able to conduct their simulation research based mainly on the models of the 50th percentile male dummy from the MADYMO library, the ARUP-certified legform and validated vehicle models.

The research involved the application of two different FE models of vehicles. The first model, representing a typical small family car, based on the FE Dodge Neon from FHWA/NHTSA National Crash Analysis Center (NCAC) at the George Washington University [8]. Since the authors do not have any information about the legform response of the physical Dodge Neon, the vehicle used was a standard, low-bumper vehicle. Figure 2 depicts the front-end of a Dodge Neon featuring a relatively low bumper height.

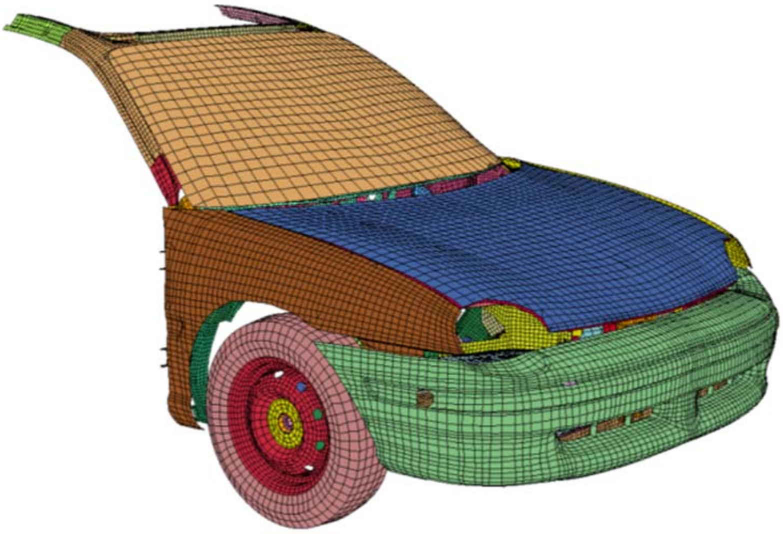


Fig. 2. The FE front-end of Dodge Neon obtained from NCAC

To contrast the legform impactor response as well as the dummy kinematics after vehicle strike, an FE model of a Nissan Navara was further developed. Based on the actual vehicle, the point cloud was obtained through 3D scanning. Afterwards, a set of vertices in a three-dimensional coordinate system was converted into a usable 3D CAD model. Subsequently, the authors generated the finite elements onto the CAD model. Attention was particularly turned towards the quality of the model and boundary conditions since the input determines the level of the output. Figure 3 shows the real Nissan Navara, whereas Figure 4 presents the obtained point cloud of the scanned Nissan Navara front-end.

Fig.3. Nissan Navara SUV prior to 3D scanning

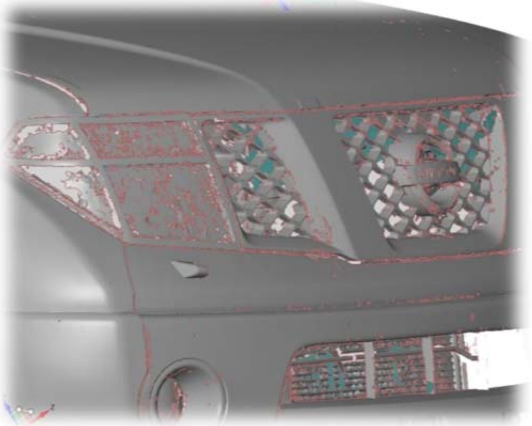


Fig. 4. Point cloud of Nissan Navara front-end

Once the cloud of points was converted into a usable 3D CAD model, finite elements could be generated. Due to the fact that the validation of the Nissan Navara legform test was carried out with the bull bar fitted on the vehicle, the additional FE model of the bull bar had to be included in the simulation. The properties of materials used for the Nissan Navara front-end were similar to those used in the Dodge Neon [8]. Nevertheless, the strain-rate effects were also added to steel components, based on the Simplified Johnson-Cook model of material.

Having completed the FE discrete model of both the small family car (Dodge Neon) and SUV (Nissan Navara), the authors verified the parameters encompassed in the Regulation (EC) 78/2009. The explicit LS-DYNA code was used to check the vehicle performance against the biomechanical limits. Figure 5 depicts the visualization of the collision between the SUV, with the bull bar fitted, and the pedestrian's virtual leg. The numerical legform impactor, which imitates the performance of the lower extremity, can be seen in the figure. In Figure 6, a high speed camera shot from a validation test using a physical legform impactor is presented.

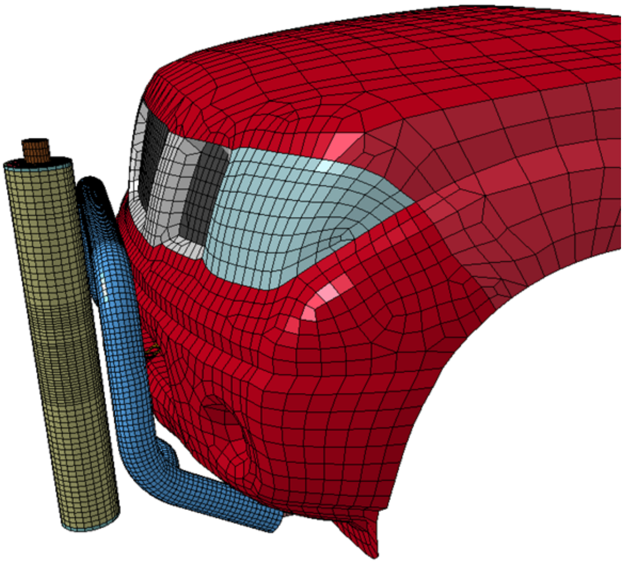


Fig. 5. FE model of Nissan Navara and legform impactor

Fig. 6. Physical object - Nissan Navara and legform impactor during validation test

The physical experiment results showed good agreement with the outcomes from numerical simulations. Figure 7 depicts two acceleration runs recorded from both the physical and the numerical legform. The detailed validation results of the Nissan Navara are described in [9].

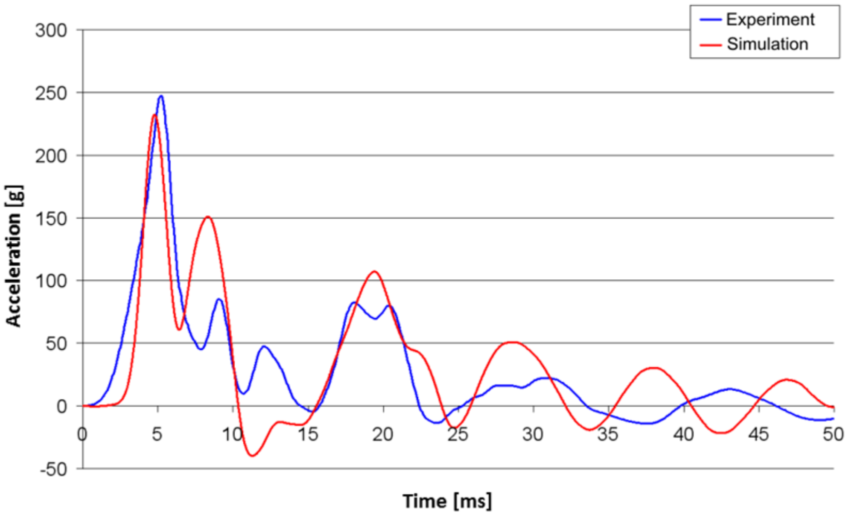


Fig. 7. Comparison of legform acceleration runs for the experimental test and numerical simulation for Nissan Navara fitted with bull bar

The second type of the numerical analysis is not as computationally efficient as the subsystem test. However, it provides the detailed data of pedestrian kinematics and may more fully assess injury risk. The Coupling method is characterized by a unique capability that allows the MADYMO dummy to be used in a co-simulation with an external, explicit LS-DYNA solver. Figure 8 depicts an example of a MADYMO pedestrian dummy coupled with the FE model of a vehicle front-end.

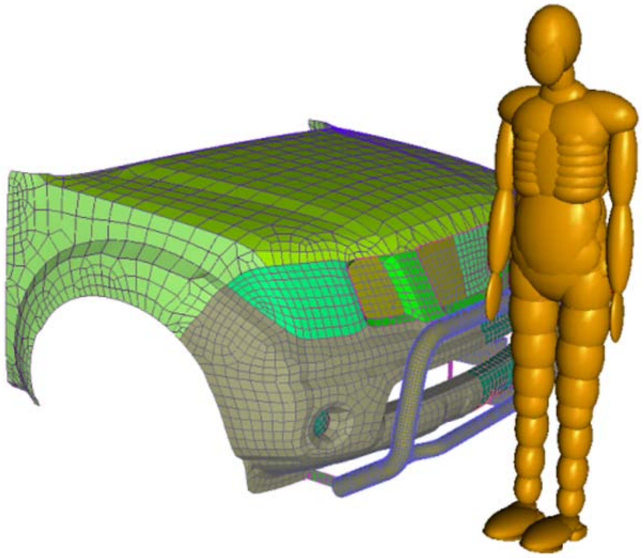


Fig. 8. MADYMO multibody 50th percentile male dummy coupled with FE model of Nissan Navara

All of the simulation runs mirror the situation, where a vehicle strikes the side of the dummy model or the impactor at 11.1 m/s (40 km/h). It should be noted that in the subsystem test the impactor strikes the vehicle, in contrast to the dummy test where the vehicle hits the pedestrian dummy. From the physical point of view, there should not be any difference. However, this issue will be discussed and clarified further in the paper.

III. RESULTS

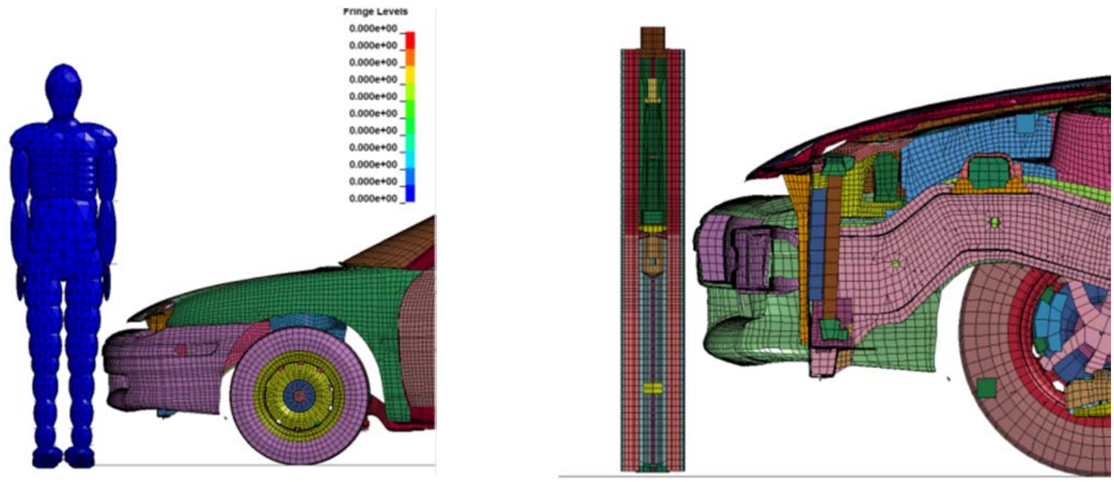
The comparison of the above methods enabled the authors to conclude that the legform subsystem test underestimates the risk of knee injuries during an impact with a high-bumper vehicle such as a Nissan Navara.

Two types of analysis were carried out:

a) Legform impactor test in accordance with EC 78/2009;

b) Coupling – MADYMO linked with the Finite Element LS-DYNA code, where the dummy features the biofidelity of MADYMO and the Nissan Navara is a full FE model with all its advantages.

In Figure 9, the combined results of the calculations performed in MADYMO and LS-DYNA explicit code can be seen. The left side of the figure depicts the kinematics of the dummy during an impact with the Dodge Neon. The longitudinal displacement [mm] was plotted to give better understanding about the pedestrian body movement (the fringe level). While the left side of the figure presents an overview of the full pedestrian kinematics, the right side of the figure depicts the response of the legform impactor. In 15 ms after the impact the maximum knee bending for both the impactor and human model is shown. The vehicle performance in accordance with Regulation (EC) 78/2009 may be fully checked and the biomechanical limits can be verified.



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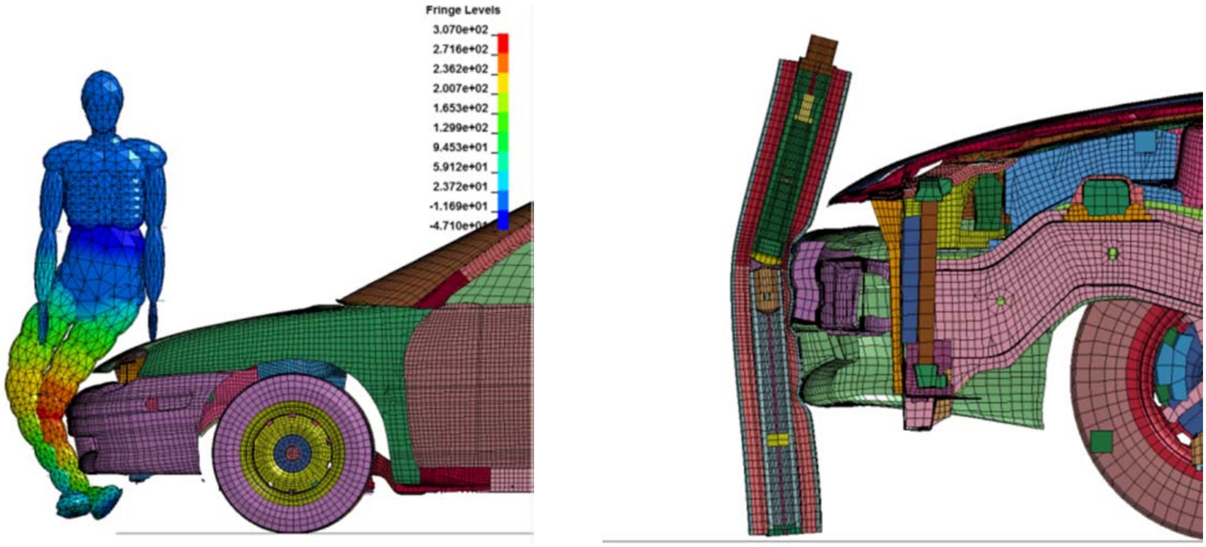

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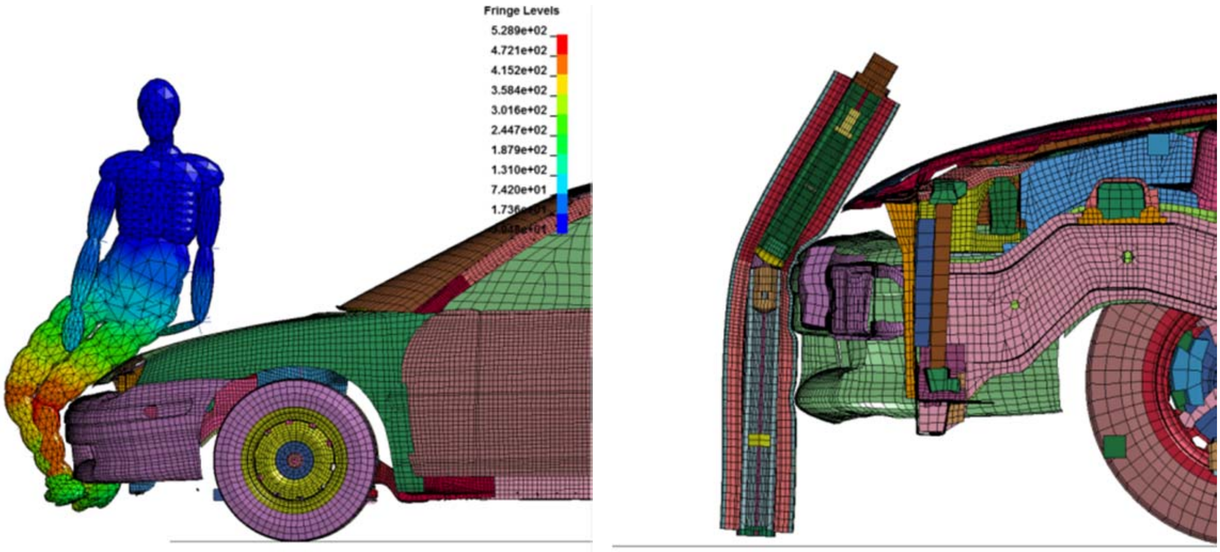

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Fig. 9. Kinematics of MADYMO 50th percentile dummy (left) and subsystem impactor numerical model (right – section view) during impact with Dodge Neon

The first event in the pedestrian crash with the Dodge Neon is the bumper impacting the upper tibia. The lateral bending of the knee, both for the dummy and impactor, takes place within 10 ms after the impact. The inertia of the dummy causes the dummy's upper body to remain still, while the lower limbs pick up the velocity of the vehicle. In the impactor's tubes, imitating the tibia and femur, there is no joint to model fracture. As a result, the femur of the impactor pivots around the point of the initial contact with the vehicle bumper at the height of the impactor knee joint.

The bending of the knee joint both for the dummy and the impactor was recorded. Figure 10 presents two runs of the knee joint bending during the Dodge Neon impact. The maximum knee bending value for the legform impactor was 22˚, whereas the dummy's knee joint recorded 29˚of bending. This gives a suggestion that the legform impactor may overestimate the real knee joint bending in the pedestrian lower limbs for low bumper vehicles, such as small family cars. Nevertheless, the overall kinematics for both models is similar.

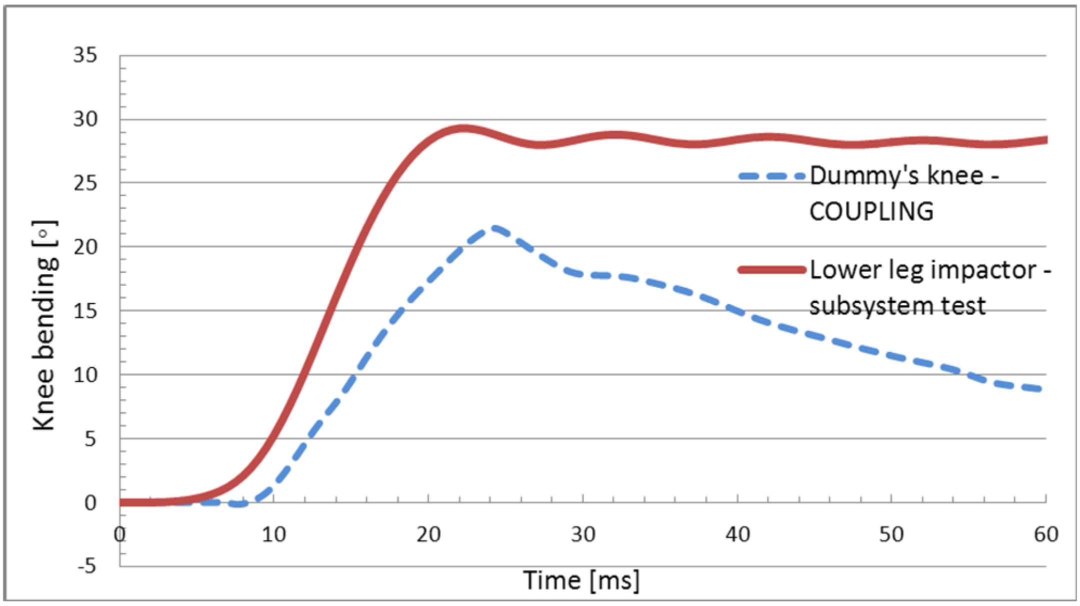
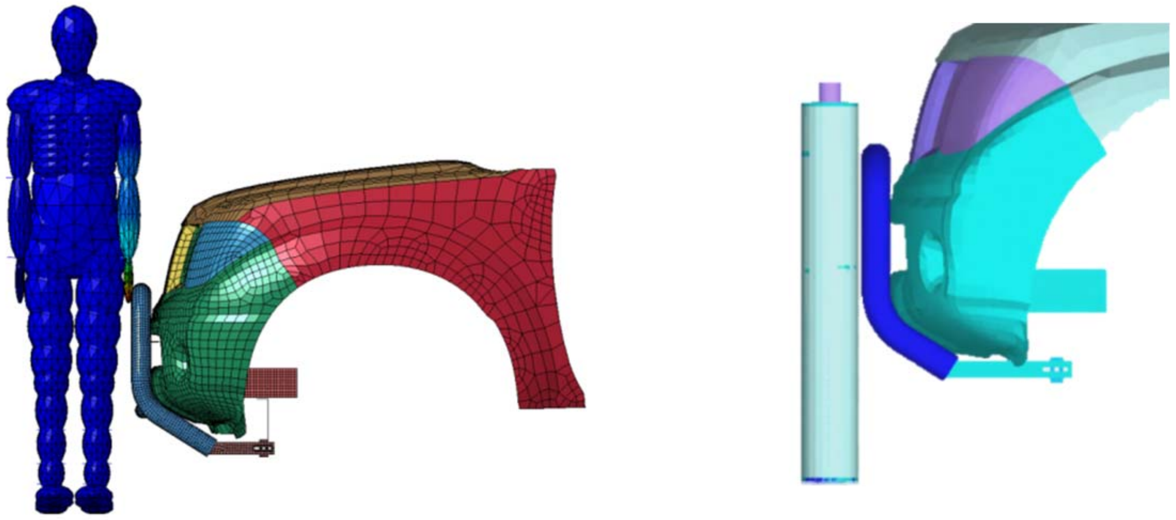


Fig. 10. Knee bending runs for two types of numerical simulations: Dummy's knee – Coupling and legform impactor subsystem test in accordance with (EC) 78/2009; Dodge Neon

In the impact against the Nissan Navara, the behaviour of knee bending angle obtained for the MADYMO pedestrian dummy is different from the one recorded for the legform impactor. Figure 11 depicts the kinematics of the MADYMO 50th percentile dummy (left) and the subsystem impactor numerical model (right) during the impact with the Nissan Navara.



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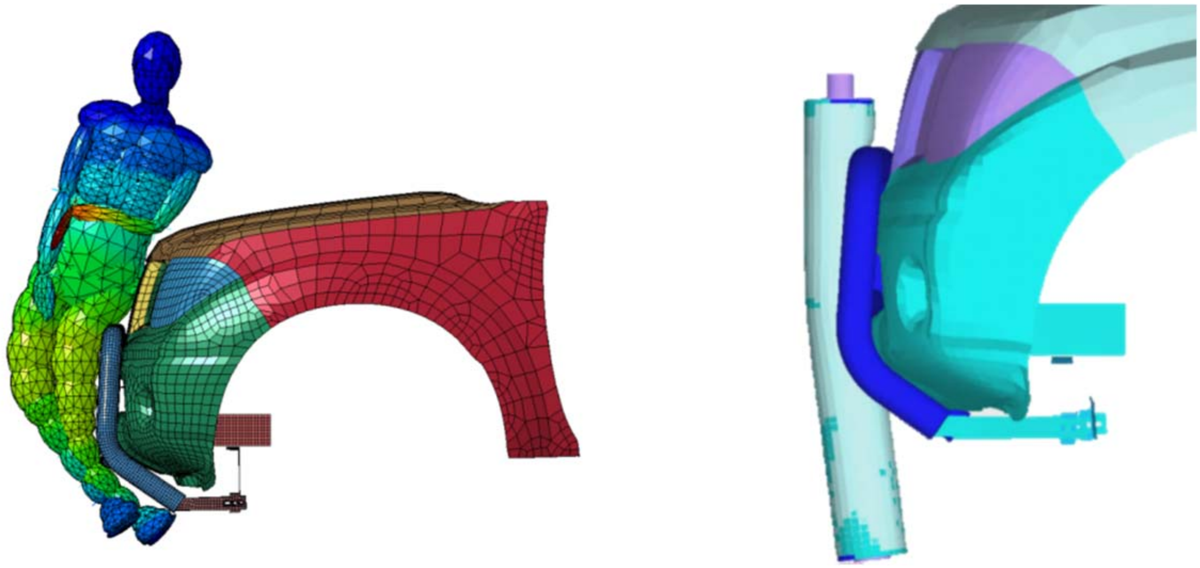

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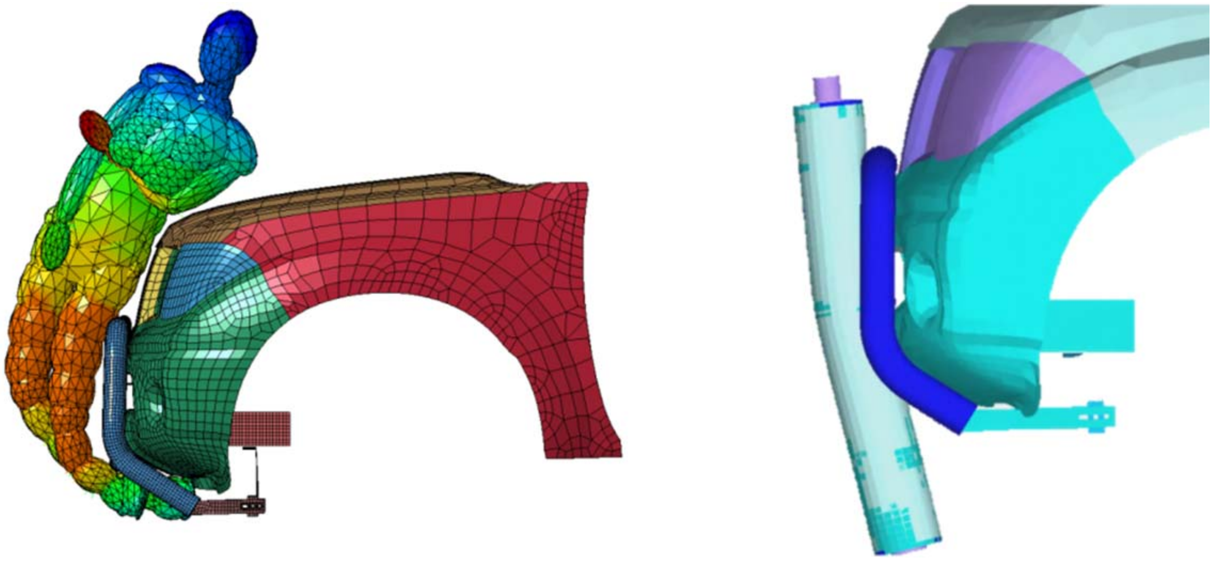

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Fig. 11. Kinematics of MADYMO 50th percentile dummy (left) and subsystem impactor numerical model (right) during impact with Nissan Navara

The response of the subsystem is similar to a rigid body, where bending in the knee joint is only partial. Nonetheless, in pedestrian impacts the resulting bone fractures caused by knee bending have been reported [5]. As it was mentioned above, the femur and tibia factures were replicated in the multibody dummy model. Hence, the bending moments and shear forces triggered the leg fractures as would occur in a human leg. In the legform the influence of the torso and head is disregarded as well as the foot to ground friction. Therefore, the phenomenon of dummy's legs being dragged under the SUV bumper cannot be validated.

The computed knee bending angles for the Nissan Navara gave a different response. Figure 12 presents two runs of the knee joint bending during the Nissan Navara impact. The maximum knee bending angle for the legform impactor was around 9˚, while the bending angle for the dummy's knee exceeded 14˚, which gives a difference of around 55%.

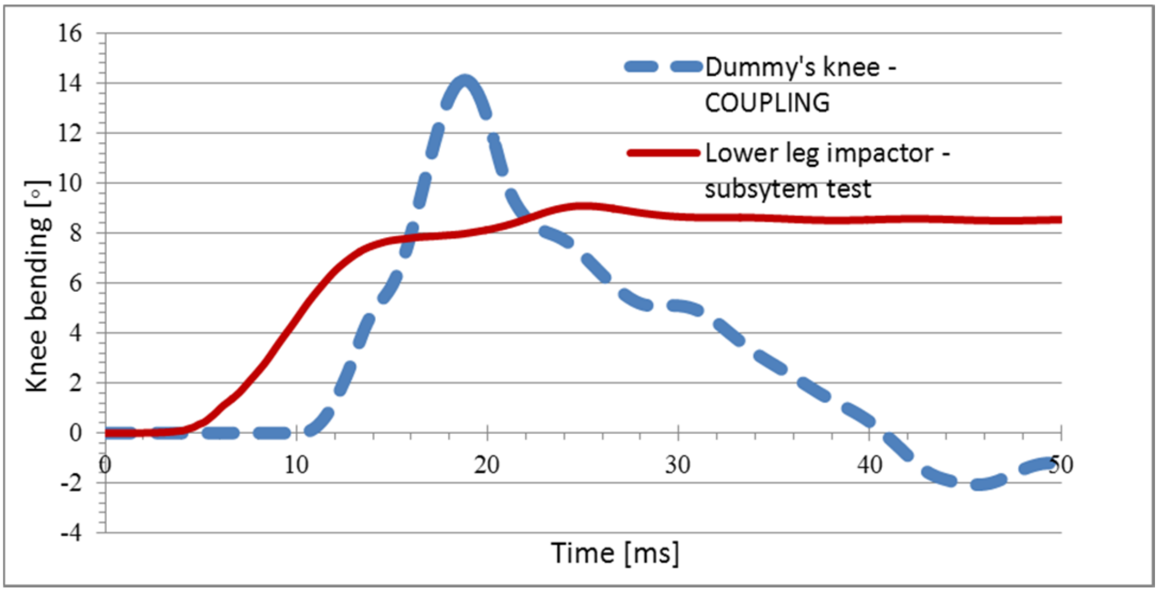

Fig. 12. Knee bending runs for two types of numerical simulations: 50th percentile dummy's knee – Coupling and legform impactor subsystem test in accordance with (EC) 78/2009; Nissan Navara

IV. DISCUSSION

Henary in [10] showed the shift in the passenger vehicle fleet in the USA towards SUVs and pick-ups and vans, claiming that they account for one-half of all new vehicle registrations.

The main problem about the SUV-to-pedestrian accident is that the injury pattern is different from the one for which the regulations were established. The torso of a human body usually experiences no rotation on impact with an SUV, due to the impact being closer to the mass centre. Therefore, it results in the energy impact being several times more intense, causing extensive damage to the head, chest and abdominal region [11]. Thus, the fatality rate for the SUV is almost twice that of passenger cars [12].

The current regulations, as it was stated before, verify the biomechanical criteria using impactors. Nevertheless, due to the change in vehicle front-ends, mainly for SUVs, the impactors may not be appropriate to evaluate the aggressiveness of vehicles with high bumper heights or frontal protection systems fitted. The legform gave a reasonably realistic trajectory when it impacted the bumper of the compact vehicle in contrast to the SUV when it does not rotate sufficiently. The impactors may be sufficient for vehicles with a low edge of the bumper and bonnet. The research showed that for a typical family car with a low bumper reference line the legform impactor overestimates the actual knee bending angle in the dummy's leg. The tested car will eventually not meet the type-approval requirements clarified in [2]. On the other hand, the conducted tests using numerical impactors and a numerical pedestrian dummy confirmed the idea that research based solely on the impactors, for vehicles with a high bumper edge, can lead to some hazardous conclusions. This is because the legform impactor underestimates the risk of knee injuries during an impact with a high-bumper vehicle such as an SUV.

The authors are aware of the limitation of the results presented in this paper. Only one type of SUV with the bull bar fitted was demonstrated here. However, the current research which is being carried out proves the findings. The outcomes will be the basis for future research.

It was proved that the kinematics of the legform differs from an ellipsoid, standing dummy model. Hence, despite meeting the biomechanical criteria obtained from the FE impactor test, the actual post-impact kinematics of a pedestrian cannot be accurately verified. Consequently, for vehicles with high bumpers and high bonnet leading edges, the test procedure proposed in current regulations may not fully address pedestrian safety. The obtained and presented results suggest that for SUV-type vehicles the dummy test would be recommended.

Finally, the authors described their own methodology to validate high bumper vehicles to meet not only type-approval requirements but also to become safer for vulnerable road users.

The presented methodology for Sport Utility Vehicles better assesses the vehicle shape aggressiveness and front-end stiffness. It is assumed that the vehicles would meet the requirements for approval only if they:

1. Provide adequate pedestrian protection by wrapping the body over the bonnet, yet not dragging it under the chassis;
2. Meet the biomechanical criteria included in the current (EC) 78/2009 standards through absorbing the injury-generating crash energy.

The dependency matrix encompassing both criteria is shown in Figure 13.

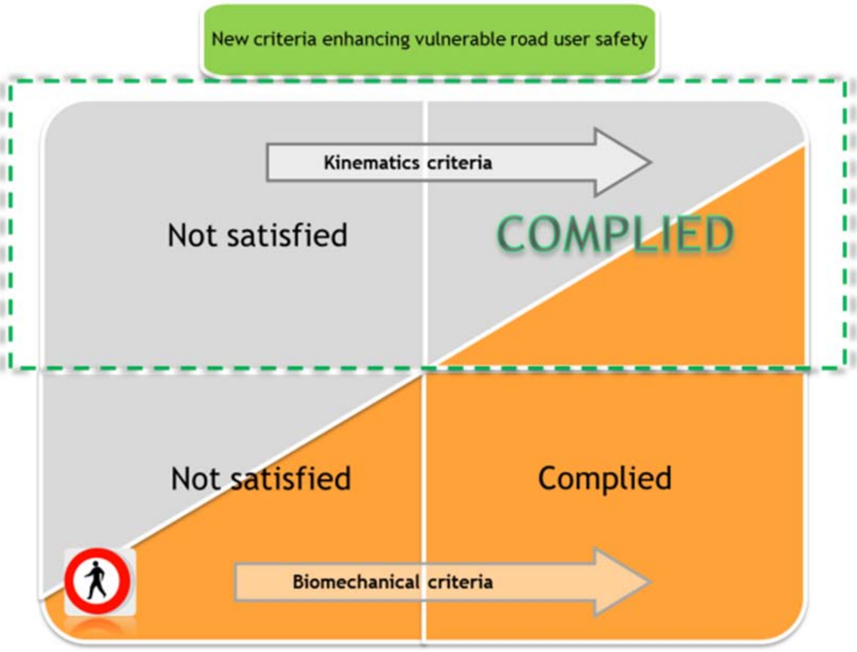

Fig. 13. New safety matrix combining current biomechanical and new kinematic criteria

V. CONCLUSIONS

The increasing number of Sport Utility Vehicles has a serious implication for pedestrian passive safety. The objective of this paper was to evaluate the current European Commission regulations in terms of a high bumper vehicle-to-pedestrian impact. Based on the research it became clear that the current compulsory legform impactor subsystem test has some drawbacks. The source of the discrepancy includes many factors, where the centre of gravity and the no-ground friction for the legform are fundamental.

The FE simulation in the LS-DYNA explicit code, using the legform impactor, provided some crucial data concerning the legform injury risk. It is significant since a bumper of an SUV usually strikes the pedestrian thigh. This leads to complicated ligament injuries and, even worse, the reaction and friction force may cause the pedestrian to be dragged under the vehicle's chassis. Since it was not possible to investigate the kinematics of the pedestrian using only the impactors, the multibody dummy model in MADYMO was also used.

According to the authors, vehicles should be granted the type-approval with regard to the protection of pedestrians and other vulnerable road users, provided the vehicles ensure adequate protection to a pedestrian, i.e. do not drag an unprotected road user underneath the chassis. In addition, vehicles must meet the biomechanical criteria encompassed by the current standards that ensures the necessary crash energy absorption to prevent or mitigate injury.

VI. REFERENCES

[1] A. J. Mclean, “Vehicle design for pedestrian protection,” *Traffic*, no. 5, pp. 1-22, 2005.

[2] European Parliament and Council, “REGULATION (EC) No 78/2009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL,” Brussels, 2009.

[3] C. Simms and D. Wood, *Pedestrian and Cyclist Impact*, vol. 166. Dordrecht: Springer Netherlands, 2009.

[4] A. Konosu, “Information on the Flexible Pedestrian Legform Impactor GT Alpha (Flex-GTa),” *Document TEG-021. Geneva: United Nations Economic Commission for Europe.*, 2006.

[5] G. J. L. Lawrence et al., “A study of possible future developments of methods to protect pedestrians and other vulnerable road users,” *UPR/VE/05/17.01*, 2007.

[6] Y. Matsui, “Evaluation of pedestrian subsystem test method using legform and upper legform impactors for assessment of high-bumper vehicle aggressiveness.,” *Traffic injury prevention*, vol. 5, no. 1, pp. 76-86, Mar. 2004.

[7] E. Rusiński, J. Czmochowski, and T. Smolnicki, *Advanced Finite Element Method for Load-carrying Structures of Machines*. Wrocław: Publishing House of Wrocław University of Technology, 2000.

[8] National Crash Analysis Center, “Finite Element Model of Dodge Neon FE Model of Dodge Neon,” 1996.

[9] M. Ptak, A. Kopczyński, and P. Harnatkiewicz, “The influence of frontal protection system design on pedestrian passive safety,” *Archives of Civil and Mechanical Engineering*, vol. 11, no. 2, pp. 345-364, 2011.

[10] B. Y. Henary, J. Crandall, K. Bhalla, C. N. Mock, and B. S. Roudsari, “Child and adult pedestrian impact: the influence of vehicle type on injury severity.,” *Proceedings of Association for the Advancement of Automotive Medicine, .* Lisbon, Portugal, pp. 105-26, Jan. 2003.

[11] C. Simms and L. O’Neill, “Sport utility vehicles and vulnerable road users,” *Br Med J*, 2005.

[12] D. Lefler and H. Gabler, “The fatality and injury risk of light truck impacts with pedestrians in the United States,” *Accident Analysis & Prevention*, vol. 36, no. 2, pp. 295-304, Mar. 2004.