Optimization of a motorcyclist protection system made of recycled rubber – impact simulation and test uncertainties

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ABSTRACT

This paper describes the design and optimization of a safety barrier to protect motorcyclists in case of an accident, using, as a basis, rubber from used tires. The proposed motorcycle protection system (MPS) attempts increase motorcyclist protection in roads. But, at the same time, it offers a new alterna-tive for the reuse of rubber from used tires, thus contributing to solving the environmental problem created by this type of waste. A first pre-design was proposed and tested according to UNE-135900 standard to evaluate the protection level against motorcyclist impact. Then, a finite element model of the new MPS and the dummy was used to reproduce the experimental impact tests. The model was validated and adjusted using data from material characterization tests and from a full-scale crash test carried out on a first prototype. The main design parameters influencing the deformation shape and the effort peaks obtained during impact were analyzed. Several modifications over the original barrier were made in order to meet the requirements of the standard. The new design of the barrier was tested, showing a lower severity than the initial prototype. In view of the results, the use of rubber appears to be technically feasible for the manufacture of these motorcyclist protection systems. However, some discordances were found between the injuries measured in the tests and the expected results obtained by simulation. High sensitivities to small variations in installation height and/or slight movements of the dummy's head during the launch phase are pointed out as possible causes.

KEYWORDS

Motorcyclist protection system; guardrail; motorcycle safety; impact simulation; impact test uncertainties

1. Introduction

1.1. Road safety and motorcycles

During the last decade, European public administrations have made great efforts aiming to increase road safety by investing in road infrastructure and in awareness campaigns for road users. Road safety statistics show that, between 2007 and 2016, the number of road fatalities decreased by 40% [1]. Car manufacturers have also contributed to the increase of road safety by fitting their vehicles with advanced safety systems that enhance the protection of vehicle occupants and other road users. Despite the above-mentioned efforts, European roads are still far from safe. In 2016, 25651 people died in traffic accidents and over a million were injured [1].

A deeper analysis of statistics, discriminating by transport type, reveals that the decrease in the number of fatalities has been different for the different transport modes. In 2016, more than 3,600 riders (drivers and passengers) of motorcycles died in the EU in road accidents, more than 14% of the total number of deaths [2]. Between 2007 and 2016, this count decreased by about 40%, compared to a 44% decrease in passenger car fatalities [1]. Motorcycling is indeed the mode of transport for which the number of fatalities decreased least in this period, along with cyclists and pedestrians (Figure 1).

If fatality data are weighted according to vehicle fleet distribution, the vulnerability of motorcycle riders and passengers is even more evident. For example, in 2014, motorcycles accounted for just 7.5% of the European fleet while passenger cars accounted for 80% of the fleet [3,4]. But 19% of the fatalities in this year were motorcyclists, 167 deaths per million motorcycles, compared to 47 deaths per million passenger cars.

Compared with passenger cars, motorcycles and mopeds are less stable, less visible and offer less protection to their occupants, making them the group with the greatest risk of a serious accident. One of the main actions to improve motorcyclist safety has been the implementation of motorcyclist protection systems (MPS). MPS prevent the motorcyclist from going off the road and colliding with dangerous objects such as ditches or walls. Moreover, MPS minimize injuries caused by impact with the guardrail, which have sometimes been designed for the containment of vehicles without taking into account two-wheeled vehicles users. It is estimated that in 4.7% of accidents involving injured motorcyclists, these injuries are caused by the impact with the guardrail. However, the damage caused by these accidents is so severe that it represents 15% of motorcyclist fatalities [5].

This article talks about the optimization of a new MPS, which aims to offer a good level of protection for motorcyclists and, on the other hand, to be environmentally sustainable by using recycled materials in its manufacture.

2. Background. Analysis of the state of the art

2.1. Evolution of motorcyclist protection systems in recent decades

The first breakthroughs reducing the severity of motorcyclist accidents appeared with the replacement of support guardrail posts. The old H-shape posts made of steel were very harmful for motorcyclists who impacted against them, often resulting in amputations or severed limbs. These posts were gradually replaced by less aggressive ones (C-shape, Sigma-shape, or round poles) but they still represent a danger to a fallen motorcyclist [6].

There are some discontinuous protection devices that are responsible for attenuating the impact against the guardrail post and preventing contact with sharp edges. These discontinuous protection systems can be seen in Figure 2.

The next step was the installation of continuous beams, similar to those that form the guardrail, at the bottom of the post. This system has proved to be a very effective method in reducing the severity of motorcyclist injuries, because it helps to distribute the impact energy over a larger surface area and prevents the victim from going under the guardrail and colliding with more damaging elements.

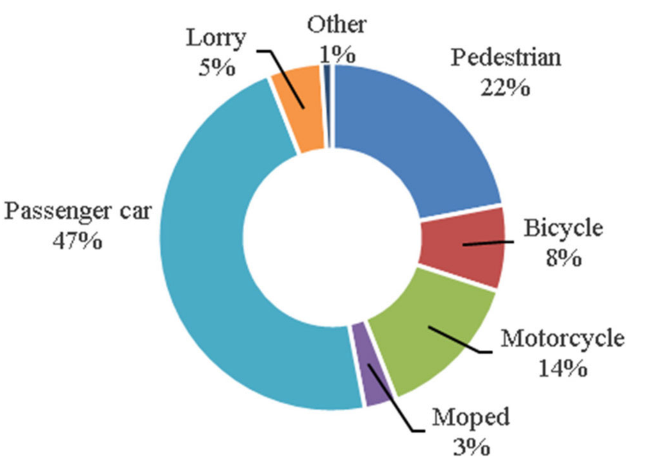

Figure 1. Distribution of fatalities by mode of transport in the EU, 2018 (Adapted from [1]).

The most common designs of continuous MPS consist of a steel plate fixed under the guardrail. In recent years, multiple manufacturers have developed and obtained approval for these types of systems, which are usually very similar to each other. So, it is easy to find them, mainly on some dangerous sections of European roads. The continuous MPS based on steel plates offer an acceptable performance, according to the applicable standards. However, some weaknesses have been pointed out by different authors [8,9], for example, the high sensitivity to small differences in cotes and angles of installation, which is difficult to ensure accurately in actual road assembly.

Other designs based on alternative materials were proposed such as, for example, those shown in Figure 3. In this figure, an MPS that uses an elastic fabric (Figure 3(a)) is shown. There are MPS based on vertical rollers like the MPS shown in Figure 3(b) with a PE cover and urethane core and that shown in Figure 3(c) with recycled rubber rollers. Motor protection systems have also been developed consisting of polyethylene flexible tubes placed longitudinally (Figure 3(d)).

Despite the good test performance obtained, its actual application has been very limited, probably due to complexity or cost.

On the other hand, as a necessary support to the development of these systems, different standards have been developed in Europe over recent decades to set minimum requirements and standardize the performance they offer. This aspect is analyzed in the following chapter.

Finally, it should be mentioned that other projects and actions have been promoted at a European level, aiming to improve motorcyclist protection on the road from different approaches. Some projects address, for example, the collection of information on accidents involving two-wheeled vehicles, essential for undertaking any other action. In this field, it is worth mentioning the MAIDS project [13], carried out by the European Association of Motorcycle Manufacturers. Other projects supported by the European Commission focus on studying the effectiveness of the protective equipment worn by motorcyclists (MOSAFIM [14] and COST 327 [15] projects), and on defining good practices, awareness campaigns and training (eSUM project [16]).

Figure 2. Examples of discontinuous motorcyclist protection system installed on European roads [7].

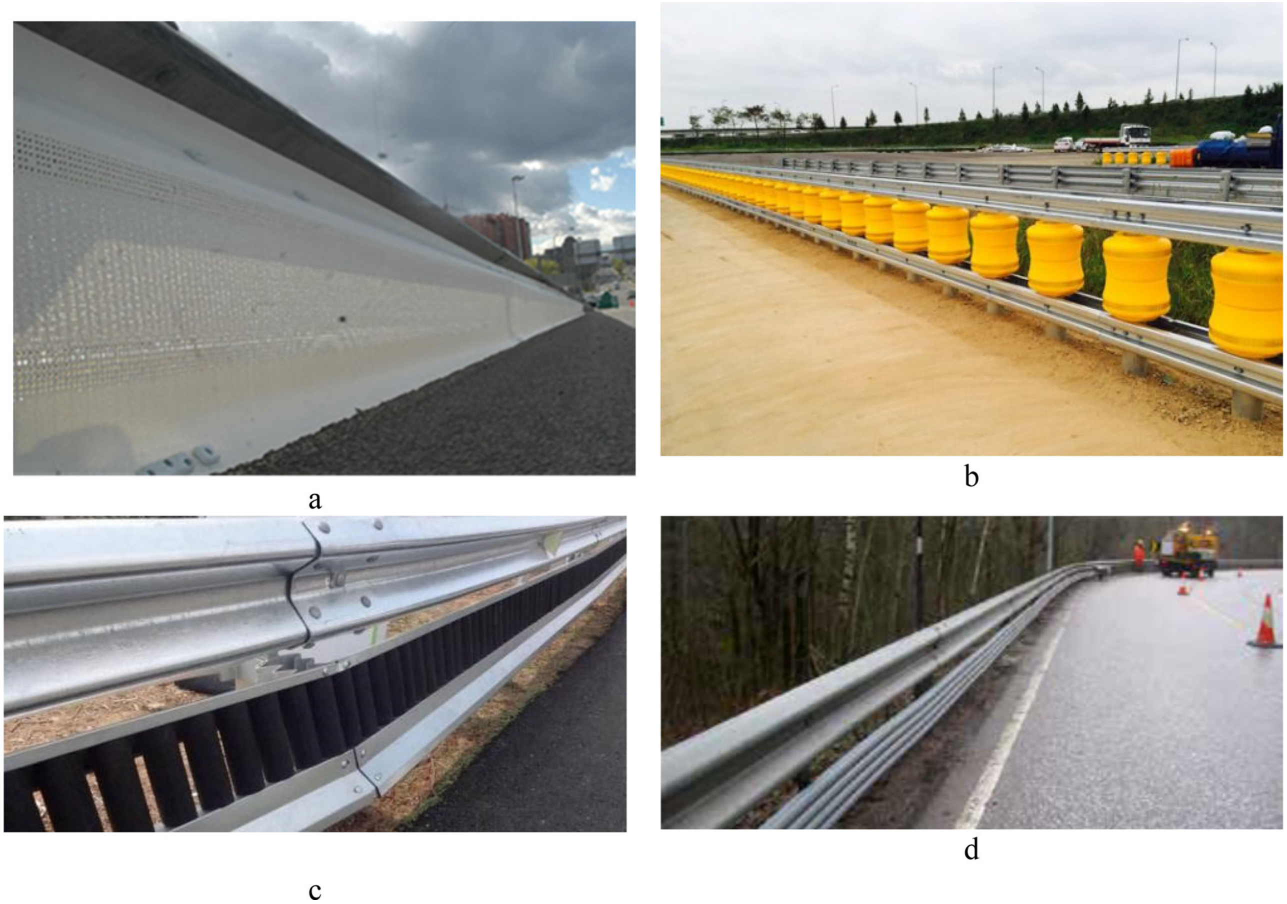

Figure 3. Continuous MPS made from materials other than steel: a) Basyc fabric [7], Shindo Safety polyethylene roller [10]; c) Segurvital recycled rubber [11], Swedish polyethylene tubular subrail [12].

2.2. Regulatory framework

Currently, in Europe there are several protocols for testing MPS in similar situations to those produced in real accidents. These protocols can be classified into three large groups [12]: those based on Spanish, French and German standards.

In the German standard, which was developed by the BASt (the Federal Highway Research Institute of Germany), a motorcyclist riding a motorcycle is launched against the guardrail at 60 km/h. In this standard, a specially designed dummy is used, the Motorcyclist Anthropometric Dummy Test Device (MATD-Dummy). Acceleration and force data measured in the dummy during the impact are compared with the admissible biomechanical limits to approve the MPS [17]. The MPS needs to be tested in two different configurations: one with the motorcycle in an upright position and another one with the motorcycle lying on the floor and sliding until it collides with the barrier.

The French standard, that was also adopted by Portugal, was defined by L.I.E.R. (a French testing laboratory). The dummy selected to perform this test is an assembly of elements coming from other standardized dummies (Hybrid II chest, limbs and shoulders; Hybrid III head and instrumented neck) as well as a special pelvis to allow the upright position. This dummy is thrown against the barrier at a speed of 60 km/h with an impact angle of 30°. There are two different test configurations: one with the dummy lying on the floor aligned with the trajectory and with the head in front, so this is the first part that impacts against the barrier and, another configuration in which the dummy is aligned with the guardrail, so that the shoulder and the arm receive the first impact [18].

In Spain, standard UNE-135900 [19], which has also been adopted by Italy and Norway, was published in 2005. The test protocol defined in this standard also reproduces a scenario where a motorcyclist has fallen down and slides along the floor in a supine position until it collides with the MPS. The standard makes a distinction between continuous and punctual protection systems. In spite of being more expensive, continuous MPS are more effective than punctual MPS since they protect the motorcyclist from impacting against the barrier posts and they prevent running off the roadway and impacting with nearby objects.

The Spanish standard defines two different test configurations for the evaluation of continuous MPS (Figure 2). In the first one, the dummy trajectory forms a 30° angle with the security barrier, and it is launched against the projection on the floor of the center of the mass of the barrier post. In the second configuration, the theoretical point of impact coincides with the middle of the segment that connects two consecutive posts (Figure 4).

The dummy used is the Hybrid III 50th Percentile Male [20] with some modifications: the pelvis and lumbar spine must be replaced by other models that allow the upright position of the dummy, and the clavicle of the impact side

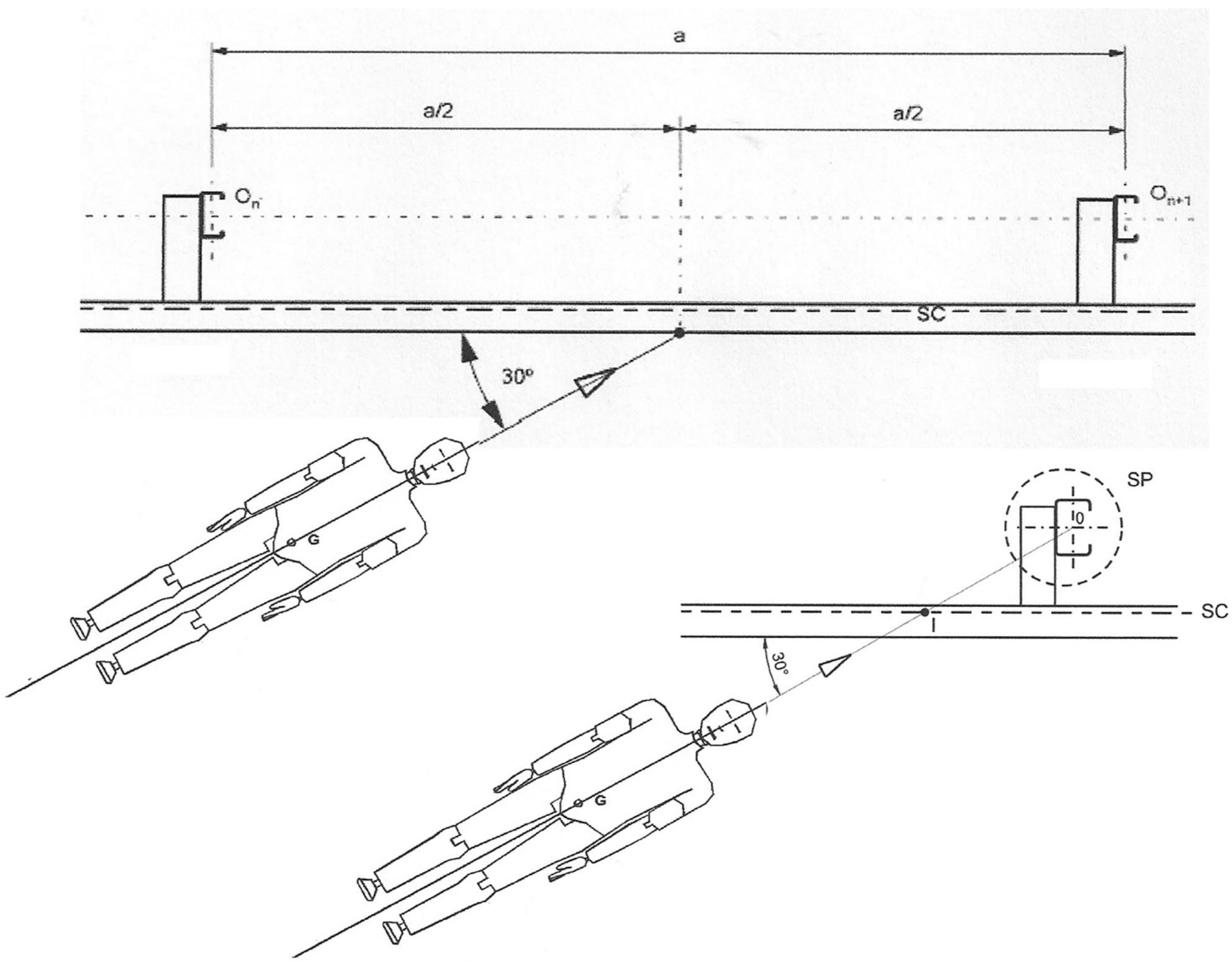

Figure 4. Test configurations: impact in center of the span (above) and impact against the post (below).

must be replaced by a fuse part that simulates the breakage of the motorcyclist's clavicle at a certain force. The dummy is equipped with an integral helmet with a smooth polycarbonate shell, a leather body suit, long-sleeved cotton shirt, leather gloves and boots. The total weight of the instrumented and equipped dummy must be 87.5 ± 2.5 kg.

The regulation specifies two different impact speeds, to achieve two different levels of protection for which barriers for 60 km/h for 'Protection Level 60' and 70 km/h for 'Protection Level 70' can be approved. The biomechanical values that have to be evaluated are the HIC36 (standardized head injury criteria, obtained from the triaxial accelerations measured in the head), forces, and moments in the neck. Depending on the results obtained for these indices, a Severity Level I or II is assigned. In this way, an MPS may be approved for a Protection Level 60 or 70 depending on the test speed, and with a Severity Level I or II according to the test results. The acceptance limits for the different indices are included in Table 1.

The main differences between the aforementioned standards are impact speeds, dummy orientation, impact point on the barrier and admissible biomechanical values [12,17]. In addition, only in the German standard is the dummy riding a motorcycle. These differences between regulations mean that an MPS may be approved in a country without fulfilling the requirements for another European country.

In recent years, the European Committee for Standardization (CEN) worked on a European standard to harmonize MPS acceptance criteria and to increase the international market for these safety barriers. That standard was initially included as part 8 of standard EN-1317 on road restraint systems, but a revision has recently been published as a new Technical Specification, CEN/TS-17342:2019 [21]. Most of the contents and specifications of that European standard project coincide with standard UNE-135900, used in this article.

2.3. Proposal for a barrier made of recycled rubber

Most MPS currently approved by UNE-135900, which is mandatory for installation in Spain, are made of steel plate. Their operation is based on redirecting the trajectory of the motorcyclist to avoid a collision against the post or objects adjacent to the road.

This article deals with the optimization of a new concept of MPS, manufactured using rubber from used tires as a base material. The recovery and recycling of used tires is a requirement derived from the 2008/98/CE Directive on waste [22]. The directive established a 'waste hierarchy' or priority order for waste management policy: prevention, reuse, recycling, energy recovery, and finally disposal (forbidden for tires). Almost 4 million tons of used tires are

Table 1. Significant peak values obtained in tests and simulation. Comparison with standard requirement.

	HIC36	Fx (N)	Fz (N) Traction	Fz (N) Compress	Mcox (Nm)	Mcoy (Nm) Extension	Mcoy (Nm) Flexion
Level I requirement	650	1900	2700	3200	134	42	190
Level II requirement	1000	3100	3300	4000	134	57	190
Original MPS (TEST)	279	525	1910	3530	58	29	16
Redesigned MPS (SIMULATION)	619	750	1235	2599	53	44	58
Redesigned MPS (TEST)	192	598	2186	3340	47	34	28

produced in Europe every year, of which less than 30% are reused or retreaded according to the first option provided by the waste hierarchy [23]. Indeed, almost 40% goes to energy recovery, the least favorable of the options allowed. Although, over recent years, several uses for the material recycling of tires have been developed, the problem is not yet fully resolved and it is necessary to study new uses and ways of recycling the rubber from used tires. Its use in the manufacture of new safety barriers will open up a new way to recycle this material, thus helping to solve the environmental problem caused by this type of waste. However, it is first necessary to evaluate their technical feasibility and possible contribution to reducing the severity of motorcyclist injuries.

A priori, the use of this material could help to reduce the peak values of head acceleration and neck forces during impact due to its deformability and energy absorption capacity. But it is necessary to ensure that local deformation and friction with the barrier do not prevent the motorcyclist from being redirected and continue sliding to achieve progressive deceleration.

The development started from a first barrier previously designed by the company MCE Mezclas Caucho S.A.U. This MPS consisted of a 4 m long rubber barrier, including an inner core of steel plate for reinforcement. This reinforcement was perforated to ensure a correct adhesion with rubber. This barrier, whose geometry can be seen in Figure 5, is installed under the guardrail, hanging thereof by using steel supports.

In the first tests done on the prototype, the requirements established in the standard for traction-compression force in the neck were just fulfilled, being very close to the admissible limits. In addition, in the test against the center of the span between posts, the barrier was lifted, the arm went under it, and was caught by the barrier. Although the norm allows the existence of entrapment provided that the release of the dummy does not require tools, this is not a desirable behavior. In a real accident it would lead to serious injury in extremities and make it more difficult to assist the injured person.

Another undesirable behavior detected in the tests was the excessively flexible joint between adjacent barrier stretches. In the impact against the post area, that flexibility leads to an appreciable gap between stretches and an abrupt discontinuity in the deformed shape of the barrier, which allows the shoulder to be blocked at this point. It causes tensile stress in the neck and can also produce additional collateral injuries.

Therefore, it was decided to undertake design optimization through simulation. This is the origin of the study described below, which led to a new definition of the prototype that was finally tested.

3. FEM modelling and validation

For the development of the MPS, an FEM model of the barrier, the dummy and the contacts between them and the ground, using the explicit finite element software LS-DYNA, was carried out. This model was set and validated from the experimental data available from the initial tests mentioned above [24], and will be used to simulate the behavior of successive MPS versions when undergoing the test for the UNE-135900 standard. The use of this model allowed multiple design modifications of the barrier to be tested, assessing its behavior and optimizing the MPS design to meet the requirements.

3.1. FEM model

The first barrier geometry was generated using CAD from the drawings of the original prototype, meshed using ANSYS, and subsequently exported to LS-PrePost. To simulate the behavior of rubber, the parameters of an hyperelastic Mooney-Rivlin material model were adjusted taking the behavior of rubber samples in a laboratory test [24] as a reference. As different compounds are used in the front surface (where low friction and enough local stiffness are needed) and in the back part (lighter), characteristic curves of both materials were obtained from compression tests performed according to the standard ISO 4664-1. The stiffer compound (front side) shows a fairly linear behavior, with a stiffness around 25 MPa, while the stiffness of the rear compound is about half.

The inner reinforcement was modeled with shell elements with an elastoplastic material model. The material choice for the steel plate was S235 structural steel, which is very common in this type of applications [25,26]. The friction coefficient between barrier and helmet was also measured experimentally, obtaining an average value of 0.8.

The bolted connections between guardrail, poles, separators and other steel elements were modeled using surface-to-surface contacts. Elements were also introduced in the bolted connections of the rubber barrier with the support beam, looking for a more accurate representation of the geometry and the deformation of different materials. The joint between the 4 m long stretches was also modeled in detail, including the steel plates and bolted connections used in the prototype. Although the failure capacity of connections was considered, it is worth mentioning that no breakages of bolted connections in the simulation nor full-scale test were detected.

The ground on which the dummy slides was modeled as a rigid material. Typical concrete properties were assigned for the stiffness of contact calculation.

Figure 5. Front and rear view of the original prototype of MPS.

Regarding the dummy, an LS-DYNA open model of the Hybrid III 50th (the LSTC.H3_50TH_STANDING.100630) was modified to be used. The model allows extended position of the legs, and some additional modifications were made to enable some parameters to be measured according to the UNE-135900 standard. Motorcyclist clothing was not modeled, due to the challenge of simulating the behavior of these elements and their friction with the ground. Nevertheless, clothing only prevents abrasion of dummy parts as a result of friction with the ground and does not significantly alter dummy dynamics.

A helmet FEM model was added to the dummy. All of the biomechanical indices considered for the approval of the MPS (head acceleration, neck forces and moments) are influenced by the properties of the helmet and its energy absorption capacity. So, a detailed modeling of them is essential for the accuracy of the simulation.

The outer layer of the helmet is usually made of a thermoplastic polymer such as polycarbonate or ABS. This layer was modeled using Shell elements with Belytschko-Tsay formulation and using an elastic-plastic material model. The inner polystyrene foam, which is lighter than the helmet shell, is responsible for absorbing the greater part of the impact energy (approximately 85%) [27] and for distributing the force on the motorcyclist's head thereby helping to reduce maximum head acceleration. For the polystyrene foam simulation, solid elements and a specific low-density foam material model were used. The mechanical properties of the helmet materials were obtained from literature [28].

Finally, the contact stiffness and the material damping for the barrier rubber were fine-tuned iteratively, by comparing the full-scale impact results obtained in first simulations with the values from real tests.

3.2. Model validation

The results of the full-scale test of the first prototype were compared with the simulation results in order to ensure proper agreement between them [24]. In the model validation, special attention was paid to neck force due to fact that this is the only parameter that showed adverse values in the tests.

A good correlation between the FEM model results and the experimental data was appreciated. The peak of neck compression force, which usually corresponds with the first contact of the helmet, was well represented. In the impact against a post, as well as against the center of the span. And the rest of the biomechanical indicators considered in the standard (HIC36 and moments in the occipital condyle) were also well approximated, being far from acceptable limits.

On the other hand, the model of the initial prototype of the MPS also satisfactorily reproduced some specific, qualitative problems encountered in the tests. The arm entrapment when this passes under the barrier was well simulated [24], as well as the blocking of the shoulder in the joint between stretches, due to excessive flexibility and discontinuity in the deformation.

4. Redesign proposal using the validated FEM model

4.1. Geometry changes intended to modify deformation mechanisms

In a first stage, the geometry of the MPS has been redesigned, aiming to change the deformation mechanism of the barrier, and to solve the two 'qualitative' problems encountered in the first barrier prototype during the first tests: arm entrapment during the impact against the center, and shoulder blocking due to the excessive gap between stretches in the impact against a post.

An angled design has been proposed for the cross-section (Figure 6), in such a way that the deformation during impact tends to close the gap between the barrier and the ground. And the inner reinforcement was weakened in the bottom fold to allow that desired deformation.

On the other hand, to reduce excessive bending deflection when impacting in the center of the span, a stiffer intermediate support was designed, taking into account that the MPS has to be installed on roads without the need for

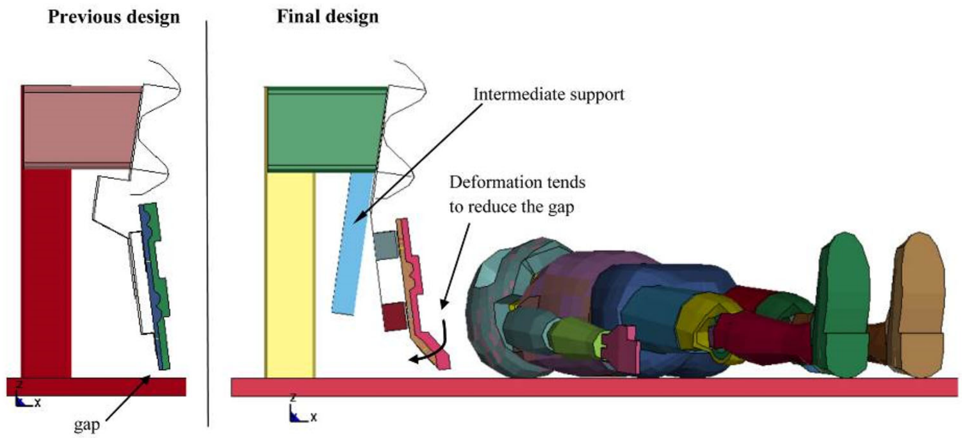

Figure 6. Finite element models of the original and the redesigned rubber barrier.

modifying the existing guardrails. It consists of a C profile hanging from the upper guardrail to limit the barrier deformation. Moreover, the new design introduces the possibility of also installing 2 m-long barriers using the same support parts, which can facilitate assembly in certain situations.

Dealing with the undesired discontinuity of the deformation, the joints between barrier sections were redesigned, introducing stiffer and longer joining plates. Moldings were also introduced in the rubber, to allow the bolted joints to connect the steel parts of the sections in a stiffer way, avoiding the effect of rubber flexibility.

On the other hand, the support elements from which the barrier hangs from the guardrail were optimized. In this case, the objective was to obtain a more homogenous deformation of the barrier along its length. A certain deflection of the adjacent supports, not only the one directly impacted, was obtained by simulation. So, a straighter deformed shape was achieved, helping to avoid discontinuities.

4.2. Optimization of first impact performance

Different proposals were checked in order to reduce the maximum compression force in the neck under test conditions. In a first approximation, it might be thought that the new geometry of the barrier described above would contribute to reducing the initial force peak, given that the contact between helmet and MPS seems to be more progressive. Indeed, the new angled geometry redirects the head trajectory during contact, and it could reduce the peak value, as well as contributing to improve the repeatability of the test, reducing sensitivity to the barrier installation height studied by other authors for other types of MPS [21]. And on the other hand, the weakness of the inner reinforcement at the fold could also help to lower the peak.

Unfortunately, after the first simulations, it was concluded that the maximum compression force is reached in the very early contact, long before the redirection of the head or the deformation of the inner reinforcement take place. Thus, the peak value is mainly due to two factors: the local stiffness in the area close to the first impact and the inertial mass of the barrier.

Optimization work was then targeted to obtain a lightweight barrier, by reducing the rubber thickness in the lower part, and making larger holes in the steel reinforcement (an example of that evolution is shown in Figure 7). The stiffness of the first contact area was also studied in detail. But always taking into account the necessary maintenance of longitudinal rigidity, to ensure the resistance of the barrier, and uniform deformation to avoid local discontinuities. For these optimization tasks, the validated FEM model was shown to be a very useful and versatile tool.

As a result of the simulation work, a new detailed design was proposed, where neck compression force was expected to be reduced by 25% compared to the values obtained in the initial tests, while good values are maintained for the rest of the injury indices. In light of those results, the new design would fulfill the regulatory requirements, and its approval as a motorcyclist protection system with a Severity Level of I in Protection Level 60, would be possible. In addition, the new design avoids the undesirable entrapments of arm or shoulder of the motorcyclist, and it would also reduce the bounce that could bring the motorcyclist back on to the road where he could be run over by another vehicle.

A new prototype was then constructed following the new design and tested according to UNE-135900. The results obtained are analyzed in detail and compared with the simulation in the following chapter.

5. Results and discussion

5.1. Final test results

The improvements predicted by simulation in relation to the mechanism of deformation of the new barrier, were confirmed and validated in the tests. On the one hand, entrapment of the arm was effectively avoided. In Figure 11 we can see how the new angled geometry effectively closes the gap between barrier and floor after the first contact (Figure 8).

On the other hand, the tests confirmed the more continuous and straighter deformation of the new barrier. In the test impacting the post area, it has led to the almost elimination of discontinuities and gaps that caused the blocking of the shoulder in the original design (Figure 9).

But the injury parameters measured in the dummy were not as good as expected after FEM optimization. Table 1 shows a comparison of the most significant peak values, and in the following figures, the evolution of the parameters with respect to time is shown, and the degree of compliance with standard limits is analyzed.

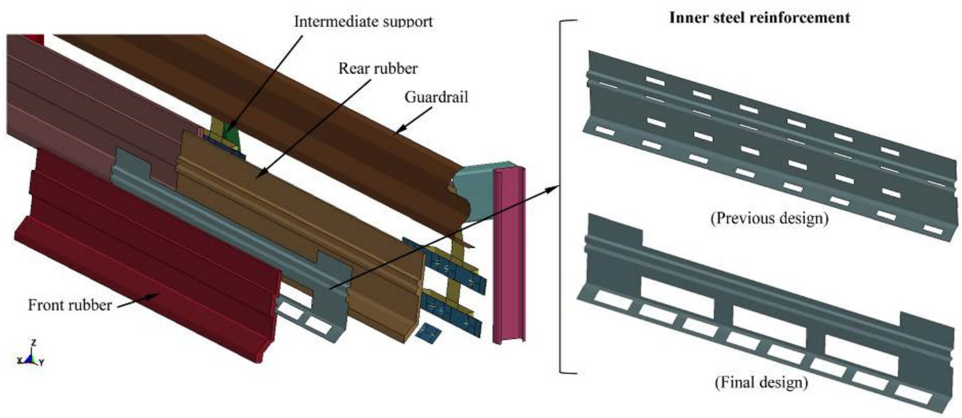

Figure 7. Lightweight evolution of the inner steel reinforcement.

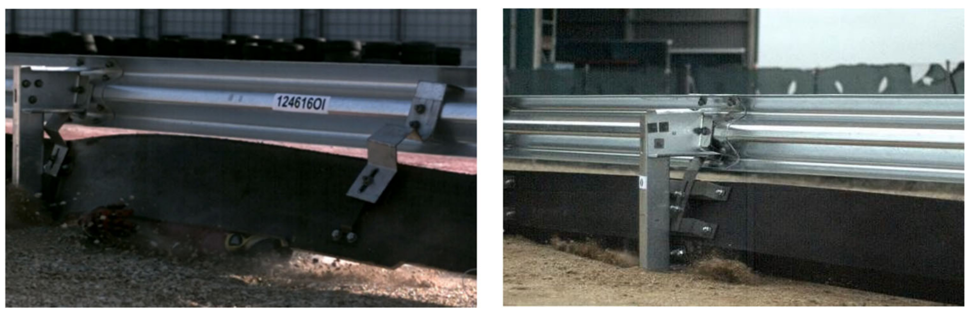

Figure 8. Arm entrapment due to the barrier raising (left), solved by the new proposed design (right).

Figure 9. Discontinuity of the deformed shape at the post area (left), solved by the new proposed design (right).

Regarding neck compression (Z direction), which achieved the most unfavorable result in the first tests, the simulation had predicted an important reduction of the peak force, by 25%, even resulting in the requirements for protection level I being met. The results obtained in the test against the post show only a very light improvement (Figure 10), complying with the requirements for protection level II, but not enough to reach level I.

On the contrary, the results obtained in the new barrier test for the occipital condyle moment Y, were much better than those obtained by simulation. A worsening of these results was expected with respect to the original barrier, due to the initial upward redirection of the head induced by the new angled geometry, almost reaching limits in extension (negative values). But such a worsening was not observed under test conditions (Figure 11).

Looking at head acceleration in the impact against the post area, the simulation predicted a worsening in the HIC36 parameter with the new barrier design, due to a wider acceleration peak during head redirection after the first contact. The first peak now obtained in the new test reaches a maximun value that is slightly higher than the one obtained by simulation (Figure 12). However, it is a very short peak and the HIC36 calculated is much lower than the one predicted, even lower than the one obtained in the test of the original barrier.

In summary, in light of the results obtained in the tests, the new barrier design solves the problems related to the entrapment of the arm and shoulder (as predicted by simulation), and meets the requirements of the standard for protection level II.

However, there are important discordances in the injury parameters measured in the dummy. In particular, the peak value obtained for neck compression force is higher than expected according to the simulation, which does not allow the minimum requirements of the standard for protection level I to be reached.

Finally, the results obtained in the test for the force and condyle moment along the X direction are of similar levels

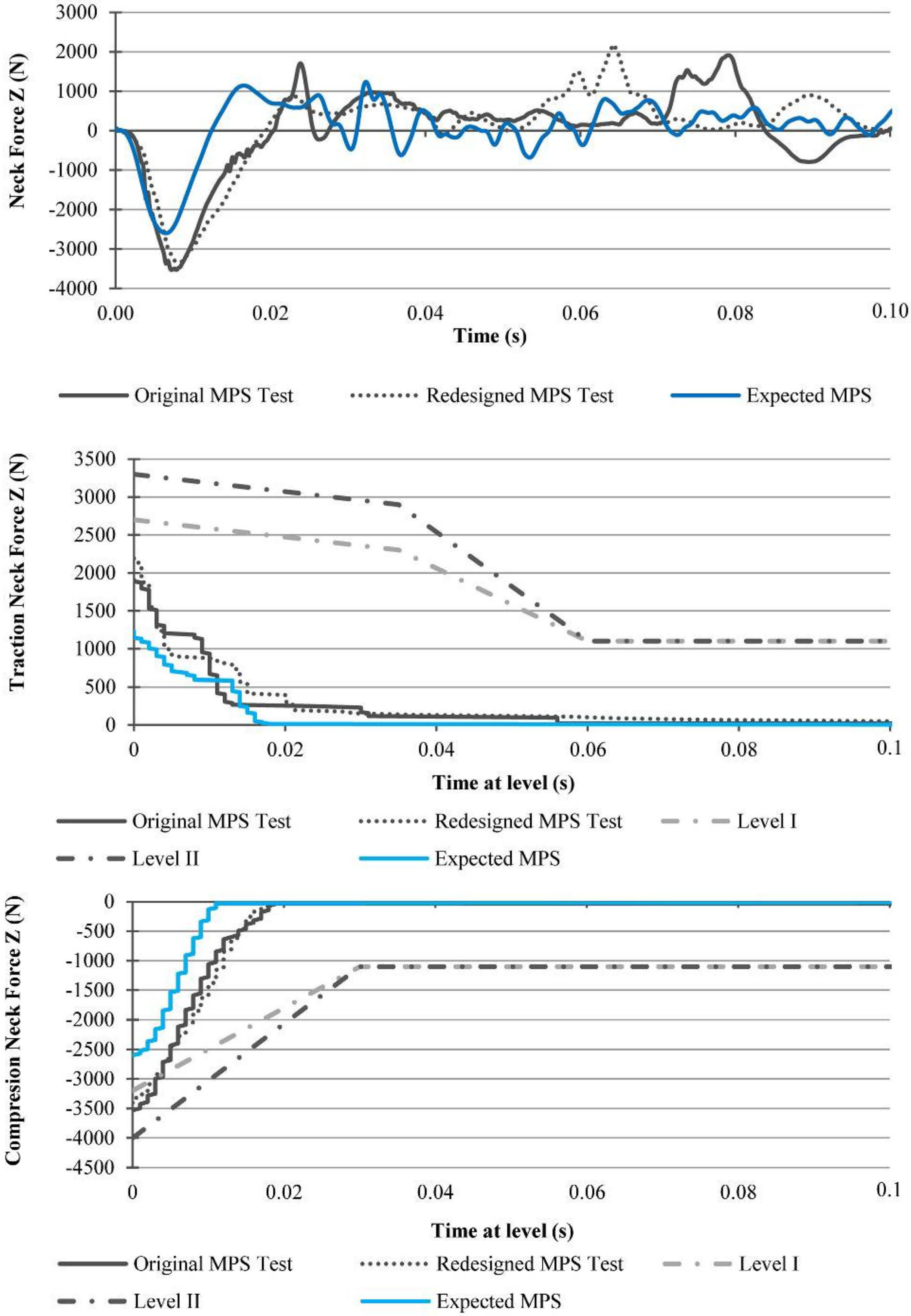

Figure 10. Neck traction-compresion force (Z direction). Comparison between tests and simulation.

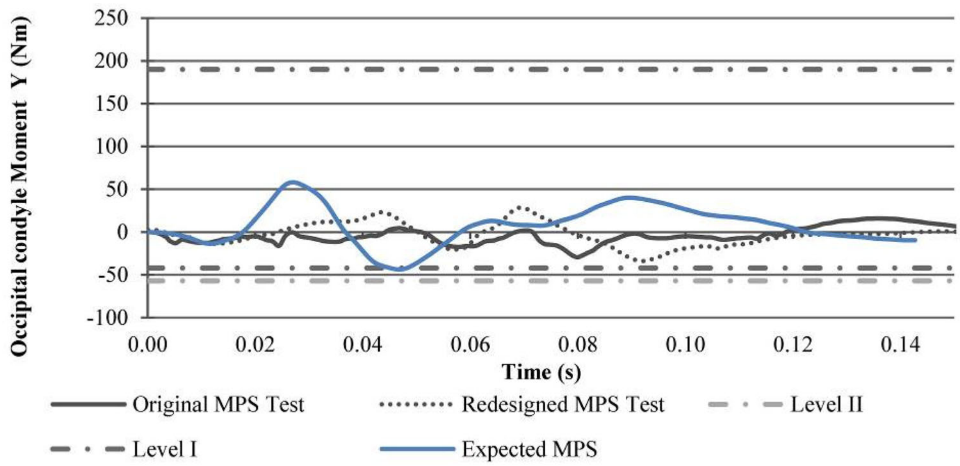

Figure 11. Occipital condyle moment (Y axis) vs time. Comparison between tests and simulation.

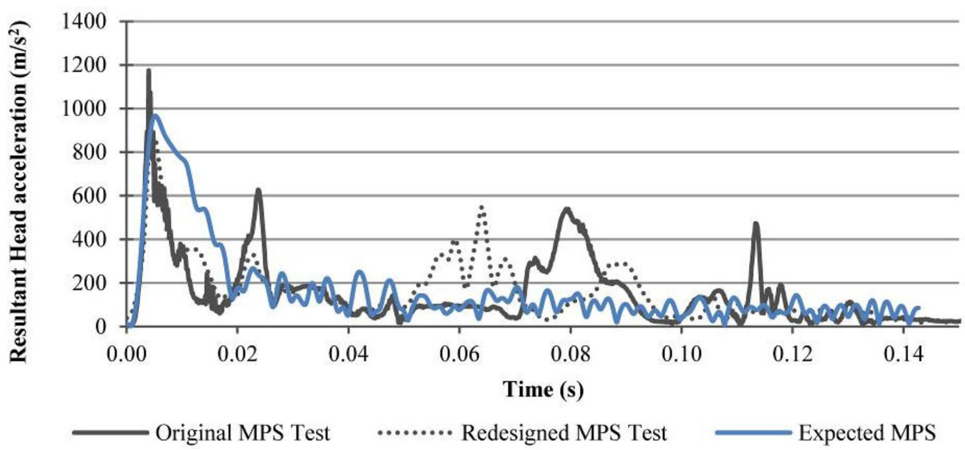

Figure 12. Head acceleration vs. time. Comparison between tests and simulation.

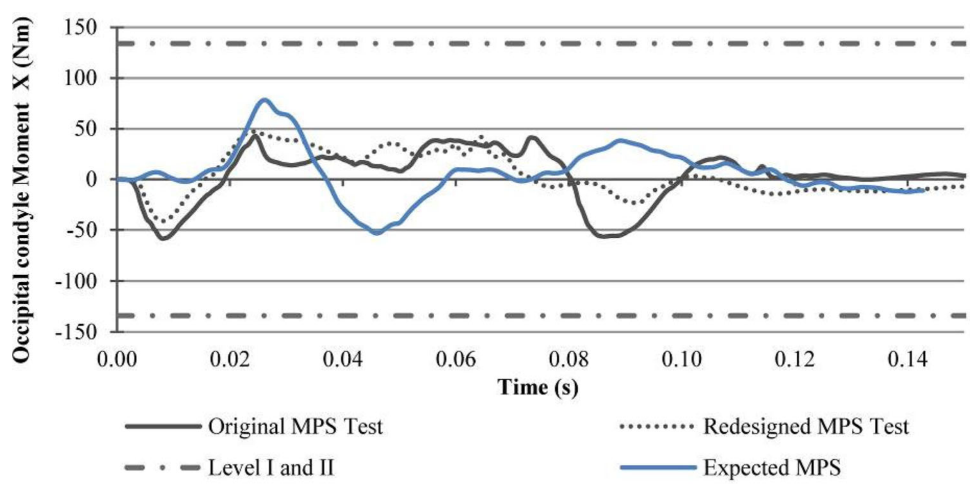

Figure 13. Occipital condyle moment (X axis) vs. time. Comparison between tests and simulation.

as those predicted by simulation, and they are, moreover, far from standard limits (Figures 13 and 14).

5.2. Analysis of possible reasons for discordances with the expected results

An in-depth analysis of the differences found between the tests and the simulation was carried out, yielding interesting results.

Some frames are shown in Figure 15, extracted from high-speed videos of the tests against a post, both for the original and the redesigned barrier. Clear differences can be observed in the position and trajectory of the head just before contact with the barrier. In the first test, the head follows a horizontal trajectory, as is to be expected. But in the second test, the head is in an elevated position (by approx. 50 mm) just 40 m before contact with the barrier, and it is

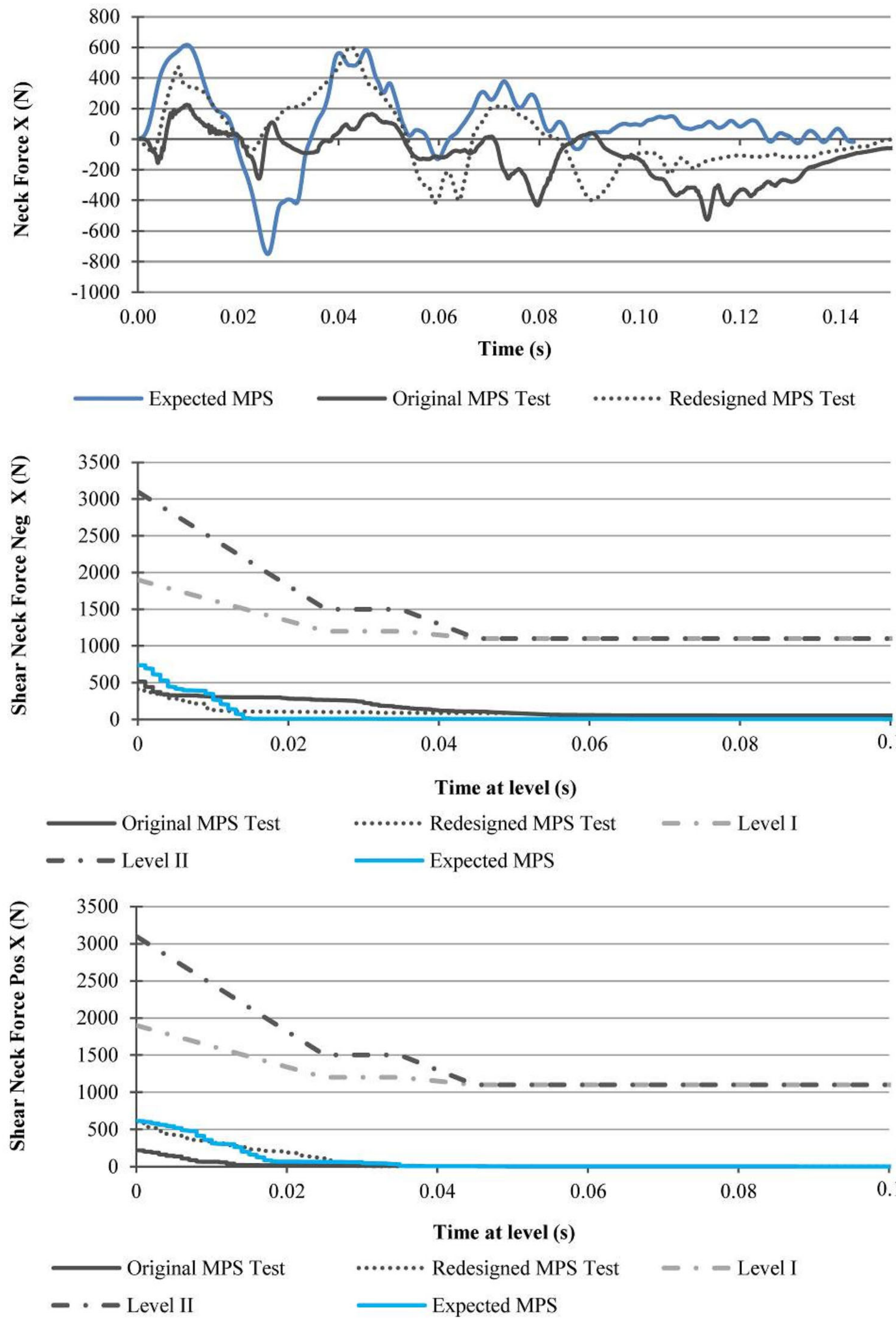

Figure 14. Neck shear force (X direction). Comparison between tests and simulation.

in a descendent trajectory with an appreciable vertical component of speed upon impact.

It must be highlighted first that both tests were carried out in an external laboratory with proven experience and technical capacity, having accredited procedures for those tests, and rigorously respecting the conditions specified by standard UNE-135900. The observed differences could probably be due to uncontrolled impulsive forces in the launch system or in the first contact with the floor. And it is a fact that the standard used does not establish any detailed conditions for acceptability regarding that type of movement of the dummy in the pre-impact phase. These variations could therefore be considered as part of the uncertainty inherent in the test procedure itself.

Whatever the cause, the difference in the position and direction of the contact with the barrier can directly affect the forces during the first moments of the impact. The descendent vertical speed could make the contact direction closer to the norm for the angled part of the redesigned barrier. And it would be consistent with higher than expected peak values for compression neck force and head acceleration, as well as with the lower shear force and occipital condyle moment in the first instants.

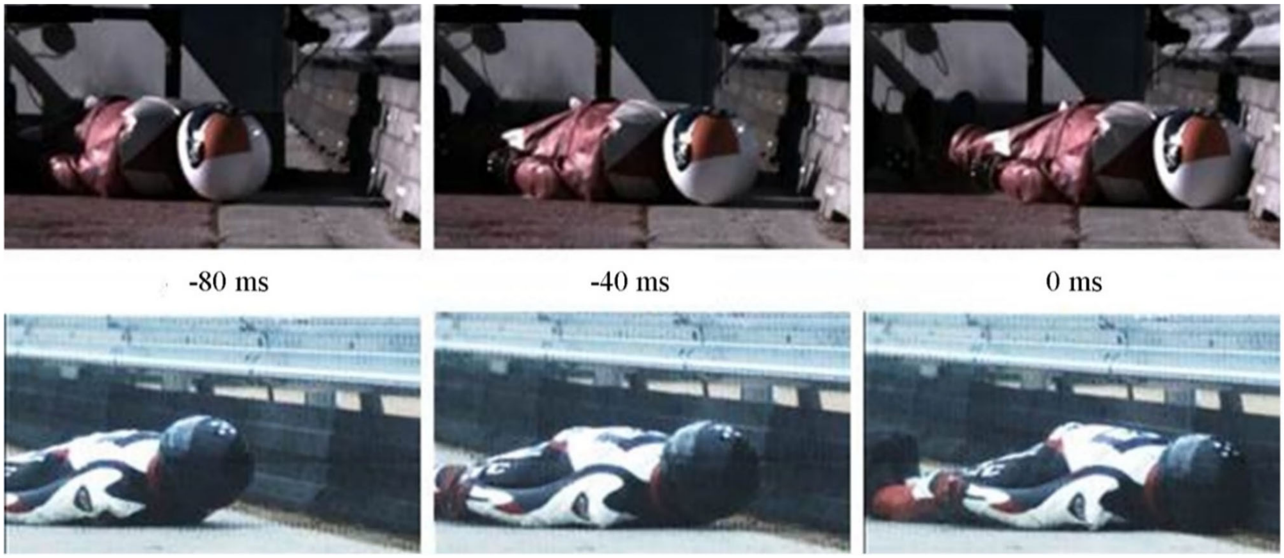

Figure 15. Differences in head trajectory just before contact (original barrier test above, redesigned barrier test below).

Table 2. Sensitivity to barrier installation height (obtained by simulation).

Height	HIC36	Fx (N)	Fz (N)		Mcox (Nm)	Mcoy (Nm)	
			Traction	Compression		Extension	Flexion
−5 mm	271	348	1299	3056	49	5.0	21
0 mm	619	750	1235	2599	53	44	58
+5 mm	269	534	2140	3100	47	24.7	23

Figure 16. Installation out of the paved surface.

From the data available, it is very difficult to know, in a more precise manner, the real position of the dummy in the impact starting point, or to try to reproduce the real conditions of the test by simulation. As a first approach to the problem, a sensitivity analysis has been carried out to estimate the robustness of the design when subjected to working conditions other than nominal, deviating slightly from the standard ones. So, a series of simulations of the impact against the post area were performed, introducing slight variations in the vertical position of the barrier.

The results in Table 2 show a high sensitivity to the height variation. These results are in line with similar conclusions obtained by other authors mentioned above [8,9], in that case for MPS made of steel.

As shown in the Figure 16, as well as the last frames in Figure 15, the barrier tested was installed outside the paved surface. Therefore, a small increase in the effective height of the barrier from the ground in the area of first impact, can be fully compatible with the actual circumstances of the test.

Moreover, a comparative analysis of the data shows a better approximation between the experimental results and those obtained by simulating a height 5 mm above the nominal one (Table 3). The adjustment of these results is particularly good in the traction-compression efforts in the neck, which are the ones that show the most critical values, close to the limits established by the regulations.

6. Conclusions

In spite of advances in road safety over recent decades, it is necessary to continue improving safety on the roads, especially for the most vulnerable users, such as motorcyclists. As a first conclusion of the work that has been shown, a technically feasible motorcyclist protection system has been designed, made of recycled rubber from end-of-life tires. In view of the results obtained, it can be claimed that this kind of recycled material can be used in barriers helping to reduce injuries in the case of motorcyclist accidents. Furthermore, the viability of this MPS may constitute a new alternative for the reuse of the rubber from scrap tires, helping to solve the environmental problem caused by this type of waste.

Starting from the first experimental results, the optimization of the design enabled most of the problems encountered in the first prototype to be resolved. During the optimization process, FEM modeling was shown to be an important aid in developing safety barriers. The model of the MPS (including the rubber barrier properties and the dummy behavior during the test according to UNE-135900, previously validated through the data from first tests), was used to trial successive design variations, until the final design for the new prototypes to be tested was achieved. In addition to the economic benefits of FEM reducing the number of expensive tests, the simulations provide wider information about forces, inertias, strains, stresses and accelerations of the elements involved in the impact, which is

Table 3. Adjustment obtained considering a higher installation height.

	HIC36	Fx (N)	Fz (N)		Mcox (Nm)	Mcoy (Nm)	
			Traction	Compress		Extension	Flexion
Redesigned MPS (TEST)	192	598	2186	3340	47	34	28
Simulation +5 mm height	269	534	2140	3100	47	24.7	23
Difference (%)	40%	11%	2%	7%	0%	27%	18%

essential for understanding the operation and weaknesses of the MPS and optimizing its design.

The redesigned geometry proposed avoids problems of entrapments and discontinuities, resulting in a smother and more uniform deformation, and to a more efficient redirection of the motorcyclist. The results obtained in the test of the new prototype have validated the behavior predicted by simulation in that sense.

But appreciable differences were found between the biomechanical indices measured in the head and neck of the dummy during the first impact in the real test, and those predicted by simulation. An analysis of the possible causes has revealed that some uncertainties due to the test method itself could be largely responsible for these differences. This is the case for small unpredictable movements of the dummy during the launch phase, not controlled or limited by the standard, or small errors in mounting, which can have a decisive effect on the way the first impact with the barrier occurs. The FEM modelling fails to predict the possible effect of most of these variable influences.

However, the proposed barrier offers good performance and protection, it fulfills the requirements for protection level II defined in UNE-135900 and could probably meet the requirements for level I depending on real test conditions. But the design shows a high sensitivity to variables such as installation height, or uncontrolled movements of the dummy during the launch phase mentioned above. Moreover, this variability of results can also affect the effective protection offered to a motorcyclist in a real accident, as it is difficult to control accurately the installation height on roads, and impact conditions can also vary from theoretical ones.

Another aspect to take into account is the possible influence on the performance of the guardrail. The attachment of this MPS may not adversely affect guardrail behavior in the case of a vehicle crash. On the one hand, due to the height and depth of placement, the MPS does not come into direct contact with the vehicle during the main part of the impact. On the other hand, the addition of the MPS does not weaken the original guardrail, but improves the continuity of the barrier and may help to avoid occasional breakage in certain impact situations. Therefore, their inclusion is not expected to affect the results of full-scale crash tests in EN-1317, or could even be beneficial

As a future line of research, it is proposed to obtain a more robust design, which can offer a good level of protection in conditions far from the nominal ones considered by the standard, lowering the sensitivity to those variations.

On the other hand, it should be noted that this sensitivity does not seem to be a deficiency of this particular design, but similar problems have been reported in literature for very different designs. So, a review of the regulation could also be encouraged. New tests could be targeted to evaluate the sensitivity of the protection offered by the MPS, compared to the variation of some conditions or real installation parameters.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study has been funded by the company MCE Mezclas Caucho S. A. The original idea and the initial design taken as a starting point for the analysis presented here belong to the company, as well as industrial property rights.

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