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A numerical framework to support the certification of barrier testing

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Abstract

This report describes the numerical framework to study the impact of vehicles on barriers, as part of the vehicle ramming protection strategy development. The numerical framework covers the set-up of the desired parameters of the model and also the computational efficiency of the analysis. Numerical results of passengers and heavy weight vehicle impact against bollards are presented. Finally, we discuss how the numerical simulations can assist in obtaining a better certification of the Hostile Vehicle Mitigation (HVM) systems via guidelines and enhancement of the existing specifications. It is expressed the clear need to develop European models for different vehicle types to support the development of barriers and to foster the European market of barriers.

1 Introduction

In the last years there has been an increasing occurrence of terrorist attacks employing vehicle ramming as modus operandi against public spaces. The so-called vehicle-as-a-weapon attacks are using a vehicle (car or truck) that is moving with a relatively high velocity in a pedestrian area targeting to maximize human casualties and disperse fear to the population. In Europe, several recent events such as the ones in Nice and Berlin in 2016 or Barcelona and London in 2017, have had a very high number of victims. Moreover, it verifies the tendency to attack unprotected public spaces (a.k.a. soft targets) that are a potential target for vehicle-ramming attacks. Therefore, enhancing the effectiveness of measures to protect public spaces has become a priority for the European Commission that has recently issued an Action plan [1] to support the Member States in the protection of public spaces. Part of this plan aims at providing technical solutions to enhance the security of public spaces without disturbing their open nature, pointing at the so-called “security by design” concept.

Within the security of public spaces landscape, vehicle barriers have gained a lot of attention as an effective mitigation measure against vehicle-ramming attacks. The barriers serve as an obstacle to prevent the unauthorized entry of a vehicles into pedestrian zones and they can have various forms, like bollards, wedge barriers, beam barriers, concrete Jersey barriers or even concrete sitting benches, flower planters etc. Recently drafted documents provide an extensive review of the existing barrier protection guidance [2] and a collection of best practices on selecting appropriate security solutions. The performance of barriers against vehicle impact is certified through several publically available documents, the most important of which are IWA 14-1 [17], PAS 68 [16], CWA 16221 [20] and ASTM F2656 [19].

According to these standards, the performance of barriers against vehicle impact is assessed through physical tests using real vehicles, which guarantees that all the complex phenomena under real life conditions are taken into account. On the other hand, the cost of such experiments is very high and therefore a limited number of impact scenarios is usually assessed. The proposed testing protocol used in the majority of the available security barriers certifications is based on only one experimental test under a certain vehicle speed and weight. This means that the experimental results are not verified by repeating the test, which can be problematic since this type of fast loading that embeds many material and geometric complexities. Moreover, the type of vehicle used in the experiment might have a strong impact on the test results even if its weight remains constant.

State of the art numerical techniques have been vastly used from the automotive industry to improve the crashworthiness of their products under different impact scenarios. Thus, the cost of the experimental campaigns has been significantly reduced without sacrificing the desired performance detailed information regarding the response of the product under various impact loading scenarios. Similar numerical techniques may be employed to study the behaviour of security barriers under vehicle impact. Due to the number of parameters present in such an analysis, the numerical simulation needs to be first verified against experimental data, before being able to expand the developed numerical framework to a greater number of impact scenarios and consequently obtain a better, cost-efficient insight on the resistance of a barrier.

This report is a first attempt to set up a numerical framework that can be used for the impact of vehicles against barriers. EUROPLEXUS (EPX) [3] is a computer code jointly developed by CEA DMT Saclay and by the European Commissions' Joint Research Centre Ispra. The code applications domain is the numerical simulation of fast transient phenomena such as explosions, crashes and impacts in complex three-dimensional fluid-structure systems. Therefore, EPX has been selected as a suitable tool for the vehicle impact on security barriers. The second chapter of the current report provides a detailed description related to the set-up of the numerical model and presents an overview of the freely available numerical models and their translation into EPX input files. Special attention has been paid to the broad variety of connections between the several parts of the vehicle model. The material laws and the used contact model are discussed. An investigation on the relation between efficiency and computational cost has also been performed. As a result, MPI (parallel) calculations have been examined along with several proposed developments that can facilitate much more efficient calculations.

The third chapter presents the numerical results of selected cases studies. First, a heavy flatbed truck impacts one barrier, and subsequently a passenger car (Yaris) is tested against two barriers. In all cases the barriers are considered to be rigidly mounted on the ground and the main output results are the vehicle velocity time history, the impact force, the reaction force time history on the barrier and the permanent deformation of the barrier.

The fourth chapter presents the way numerical simulations can contribute to the improvement of the existing standards by filling potential gaps. Special attention is paid on possible simplifications of the vehicle FE model to facilitate the numerical calculations and allow a more detailed representation of the performance of the barrier, which is one of the main objectives of the analysis. The report concludes with a proposal on substituting the vehicle numerical model with a pre-defined impulsive load that may be directly applied on the barrier numerical model.

2 Numerical model

The following section describes the development of the numerical model that can be used to assess the resistance of a certain barrier against a specific vehicle. The numerical model consists of two discrete parts, the vehicle and the barrier. The objective of the numerical simulations is to determine the resistance of the barrier, so its model should be very detailed, accurately including all relevant parameters, like detailed geometrical representation, material modelling, connection/contact specifications among the several sub-components and boundary conditions (such as the foundation). At the same time, the behaviour of the vehicle model should be simulated precisely enough in order to deliver the correct impact load on the target barrier. The focus of the study is not on the passenger protection, unlike in the case of automotive safety crash tests. Therefore, any simplification of the vehicle model should be well justified in order to avoid changing its behaviour under the impact loading conditions. Future research may focus on the simplification of the vehicle numerical model without sacrificing the accuracy on its impact performance. Such simplifications on the vehicle model would decrease the computational cost of the simulation and consequently permit the development of a barrier model with greater details, which is the main target of the study.

As a first step this report focuses on the detailed representation of the vehicle numerical model which obviously is geometrically more complex. During this stage the numerous parts of the vehicle model should not be omitted. Therefore, this chapter focuses on the definition of the elements, the material parameters and the connections between the several parts of vehicle model. The barrier can be modelled as a simple hollow cylinder that is fixed on the ground. Even though this is a rough simplification, it will allow to identify the challenges that are faced during the representation of the very complex vehicle model and to observe the reaction forces on the barrier.

2.1 Existing vehicle models

There are several vehicle Finite Element (FE) models freely available that can be used for the numerical simulation of crash tests. These models have been developed mainly in the USA in different institutes related to safety analysis, highway traffic administration and transportation research. The vehicle models have been prepared in LS-DYNA [18] format and have been validated against real crash tests.

2.1.1 Centre of Collision Safety Analysis

The Centre for Collision Safety and Analysis (CCSA) [4] at George Mason University (US) focuses on using advanced technology to understand collisions involving transport vehicles and to develop appropriate means to avoid or mitigate their consequences and enhance safety and security.

Several passenger vehicle models are freely available on their webpage, such as the Toyota Camry/Yaris and the Chevrolet Silverado, but also generic models of Automated Driving System vehicles, see Figure 1. Each vehicle model can be downloaded in two different mesh sizes: coarse (about 300,000 elements) or detailed (about 1,500,000 elements) model.

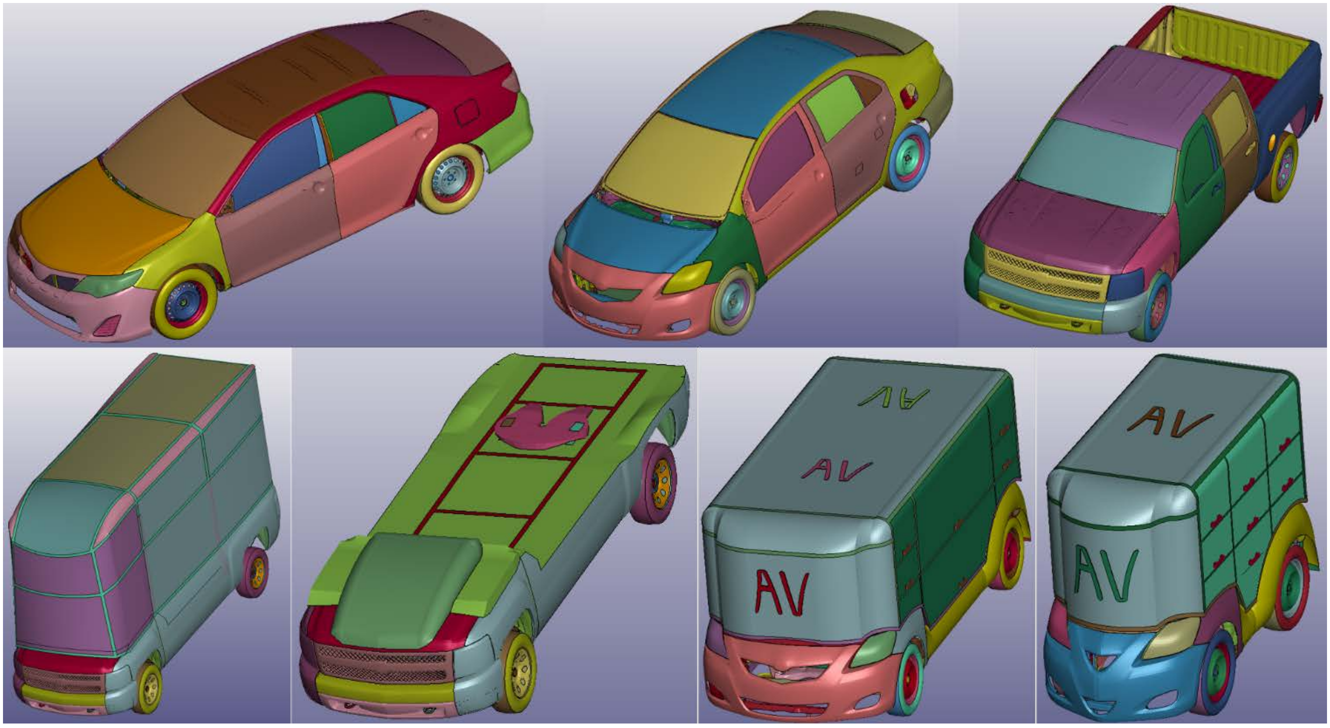


Figure 1: Vehicle numerical models from CCSA [4]

2.1.2 National Highway Traffic Safety Administration

The mission of the National Highway Traffic Administration (NHTSA, US) is to prevent injuries and reduce the economic cost due to road traffic crashes, through education, research, safety standards and enforcement activity. Part of their research is related to the development of full vehicle finite element models (FEM) including vehicle interiors and occupant restraint systems. Their FE models have been calibrated and correlate well with the performance exhibited in full vehicle crash tests. On their webpage a big variety of vehicle models in LS-Dyna format are freely available. The FE models contain many details from the actual vehicles, while their mesh size can vary from medium density (about 500,000 elements) to very fine (about 5,000,000 elements) discretization. The vehicle library includes both passenger cars and heavy-duty vehicles, as depicted in Figure 2 and Figure 3.

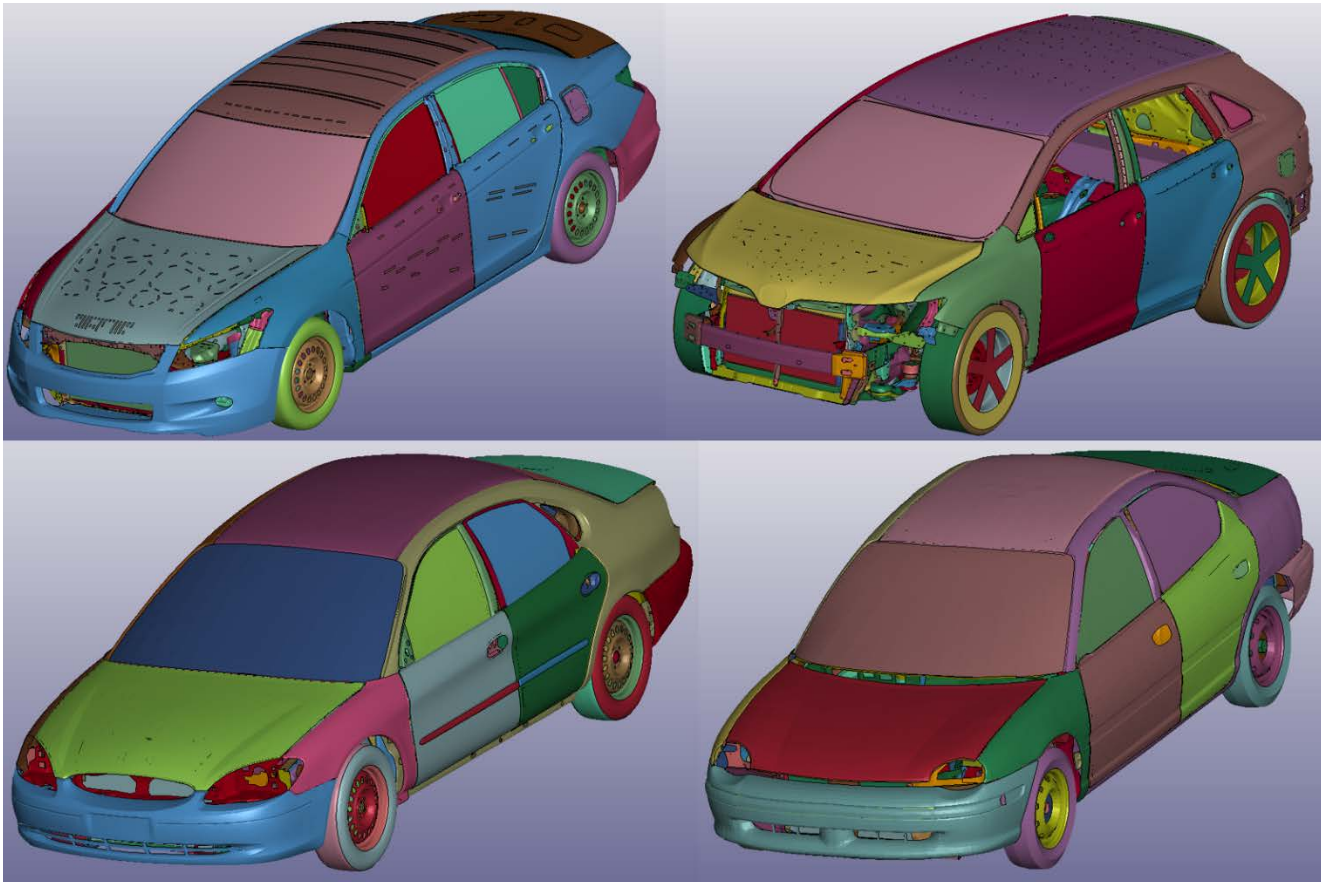


Figure 2: Passenger vehicle numerical model from NHTSA [5]

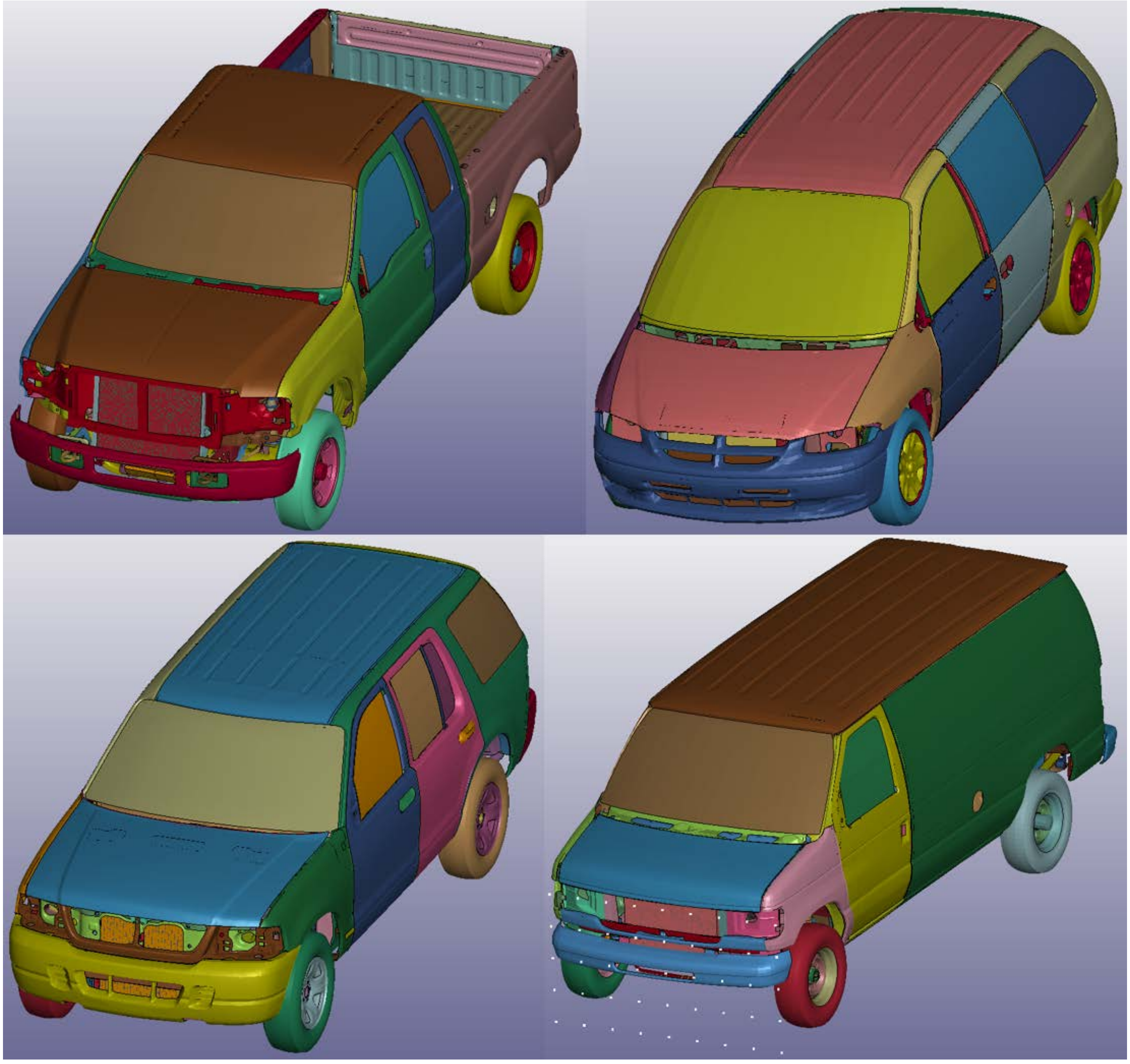


Figure 3: Heavy vehicle numerical model from NHTSA [5]

2.1.3 National Transport Research Centre (NTRCI)

The National Transportation Research Centre (US) webpage [6] contains freely available FE models of tractor and trailer assemblies. The tractor model is available in different versions (day or sleeper cabin) while the trailer model can have a length of 45 or 48 ft (13.7 or 14.6m), see Figure 4. The medium mesh size models allow the user to perform full crash simulations in reasonable computational time.

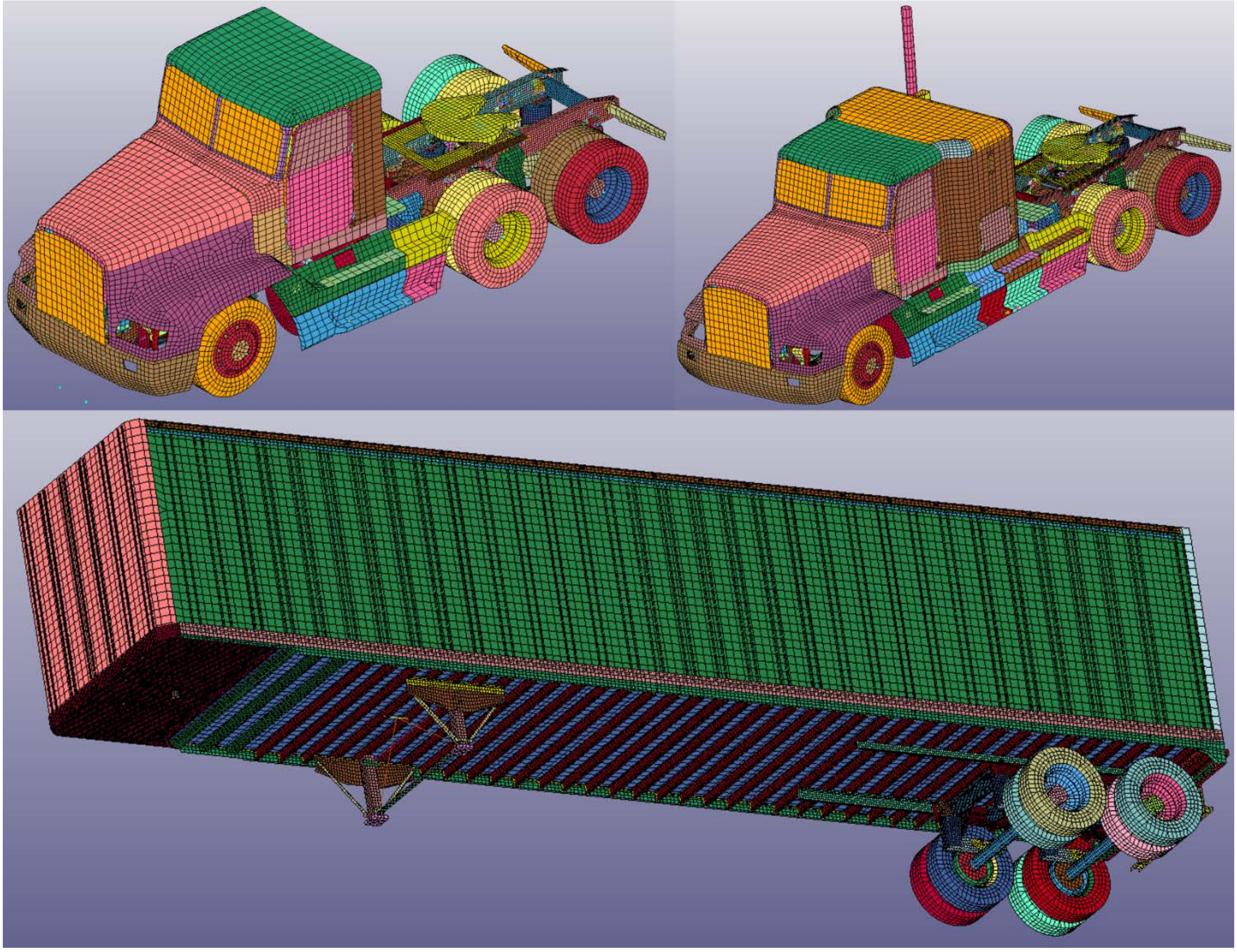


Figure 4: Tractor and trailer numerical models from NTRCI [6]

2.1.4 Barrier models

The EU impact regulation foresees testing of vehicles impacting specific barriers, and several bodies and organizations, such as Euro NCAP, are using these predefined barrier models. The purpose of the barrier models is to provide an experimental framework with sufficient precision to ensure repetitive and correlative results under similar test conditions and to reflect adequately the protective performance of a motor vehicle or item of motor vehicle equipment with respect to human occupants. The moving deformable barrier, that represents another car, consists of two parts: a main honeycomb block and a bumper consisting of three honeycomb elements. The barrier FE models are available in LS-DYNA format and they have been validated against crash test results.

2.2 From LS-DYNA to EPX

LS-DYNA ".k" input file is the most common used format in explicit FE analysis. Therefore, the EPX developers group has made an effort to support, at least partially, this input format, see Figure 5. The LS-DYNA input format includes a huge number of keywords and translating all of them into EPX commands would be a time consuming process. Hence, as a first step, EPX is able to read all the basic inputs that are necessary for initiating a calculation. The most important information from the input file is the geometry, namely the coordinates of the nodes and their connectivity that defines the finite elements. Another important part of the input file is the definition of the groups called SETs in LS-DYNA. Thus, EPX is able to read both nodal and elemental sets that subsequently can be used to define material types, boundary or loading conditions etc.

There are essential keywords in the input file, such as the material laws, that are very difficult to be translated directly into an EPX input. Each material law contains different parameters and doing a mapping between the LS-DYNA material library and the EPX one is a very difficult task. Further developments in EPX are possible to improve the communication between LS-DYNA and EPX. But other data, like for example the thickness of shell elements, are already embedded as their transfer is easier. Some other commands, e.g. several connection types, are partially supported in EPX, as it will be discussed in the next paragraph. As already mentioned, LS-DYNA contains a huge number of keywords that in many cases are not of interest to the EPX so, the next steps in the EPX developments will focus into translating keywords that are meaningful for the desired computations.

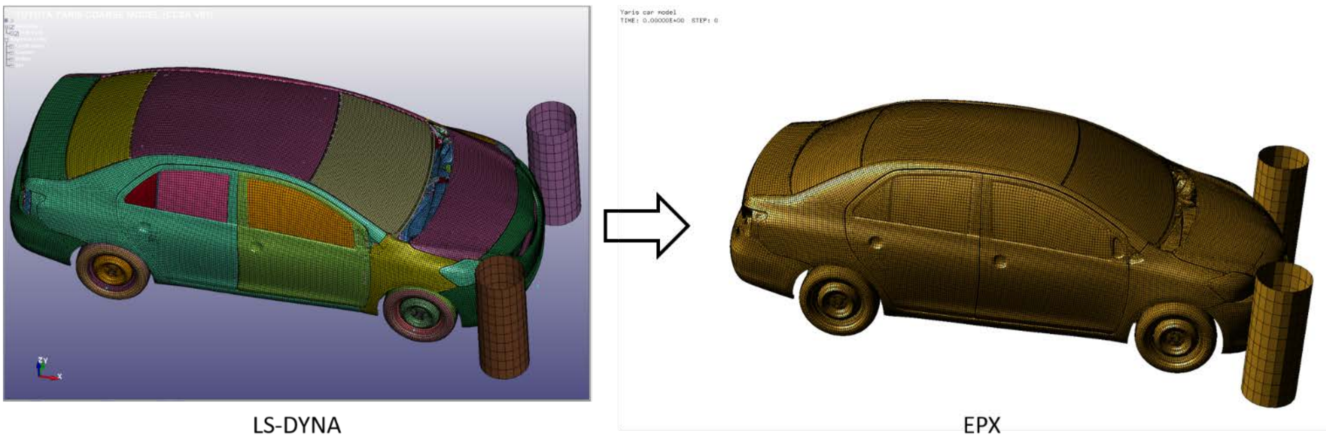


Figure 5: LS-DYNA to EPX translation

2.3 Vehicle model connections

An important aspect, for the impact analysis of the vehicle models with EPX, is the simulation of the connections between the numerous different components of the structure. The existing FE vehicle models consist of numerous parts that are connected to each other with different types of connections, as presented in Figure 6. Table 1 shows some data regarding the connections of the Toyota Yaris vehicle FE model. Typically, there are three types of connections:

1) The simplest type is a **rigid constraint** of the nodes of the components at the connection region. This connection in EPX can be represented with the RIGI keyword that is imposing the same displacements (translation) for all the nodes participating in the interface of the components. Rotations are not allowed with this type of link. Another similar type of connection is also available in EPX through the GLUE keyword that is actually gluing together two incompatible (non-conforming) structural meshes. The nodes of the slave mesh are linked to the faces of the master mesh so that their relative position with respect to the face does not change during motion and deformation. Common rotation is allowed. GLUE links are very handy since the code automatically recognizes the closest regions of the connected parts.

2) The second connection type is the **constrained joint**. The joint can be revolute (like hinge), spherical or cylindrical. The joints are used to represent the rotating parts of the vehicle like for example the wheels. The DIST keyword in EPX can be used to simulate that type of joints by imposing a 3D mechanical relation of constant distance between a point and another point or set of points. For sake of simplicity in the current studies the joints are substituted in EPX with rigid links.

3) The third type of connections are the **spotwelds**. This type of connection is used for welded parts of the vehicle model and are actually used for adding some flexibility to the link. Namely, the spotweld connections are using small beam elements to connect two opposite sides of two components. These beams do not share common nodes with the connected parts, so each extremity is rigidly connected with the closest region of the part.

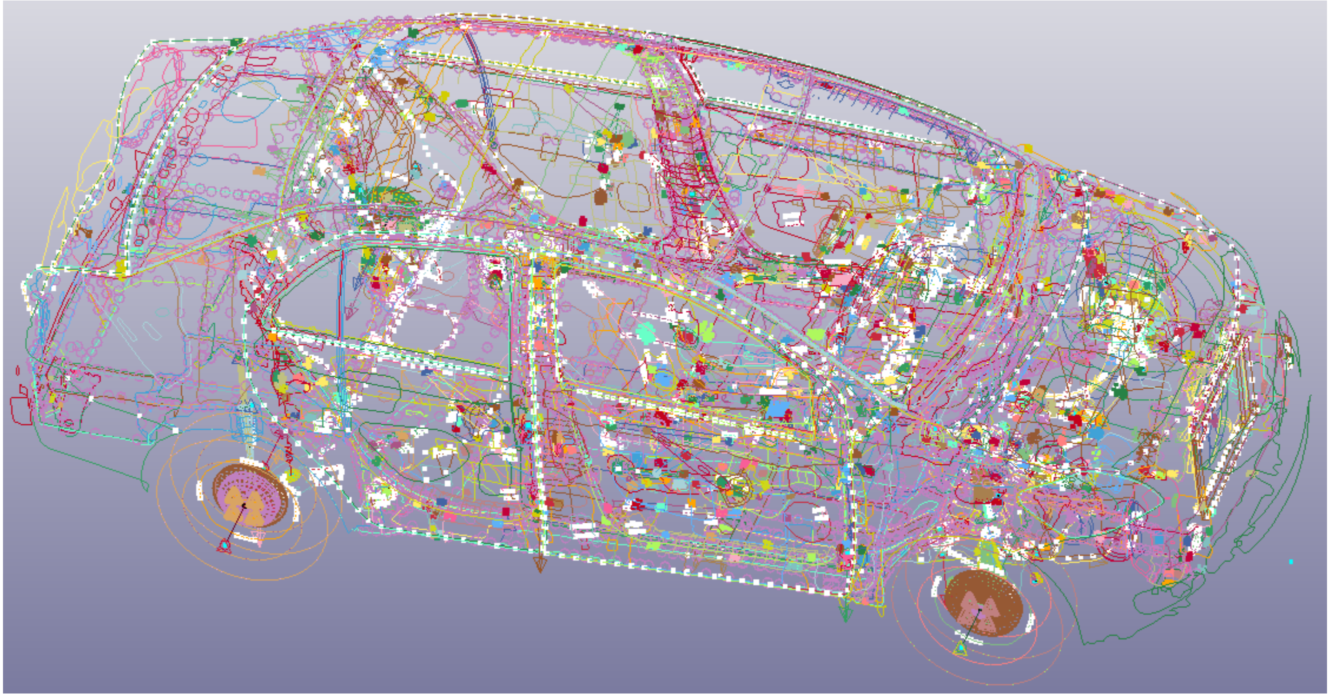


Figure 6: Connections of several components of the FE vehicle model, white spots for the spotwelds and triangular points for the joints [4]

Table 1: Connection types for the Yaris vehicle FE model

Connection type	Number of connections
Rigid	4,802
Joints	44
Spotwelds	3,110

2.4 Materials

An accurate modelling of the various material properties is fundamental for the precise prediction of the behaviour of both the vehicle and the protective structure. In crash analysis it is certain that each structure will undergo significant deformation and the material behaviour will enter into non-linear regime. Aspects such as plasticity, hardening, strain-rate effect and failure should be taken into account. Therefore, suitable material laws need to be selected and it is crucial that the material input data are properly calibrated against experimental tests.

The material of which the vehicle body and the protective barrier is usually made is metal: steel or aluminium alloys. A Von Mises elasto-thermo-visco-plastic material with non-linear isotropic hardening governed by a modified Johnson-Cook ("VPJC", [9]) model has been selected for the representation of the metal parts. The material model is using an explicit elastic predictor with an iterative plastic corrector on the yield surface for taking into account the plasticity. The strain hardening behaviour is described by the Voce saturation type terms, so more parameters are used (in comparison with the standard Johnson-Cook model) for the sake of accuracy. The model is coupled with element erosion through a failure variable. The Cockcroft-Latham failure criterion, based on plastic work per unit volume, is assumed. Material failure takes place at a Gauss point when a damage parameter D reaches the damage threshold set by the user.

The vehicle models contain also other material types, like the glass panels and the tires. For the glass panels, a linear elastic material is used until failure and the strain-rate effect is enabled. The failure criterion is based upon equivalent stress based on a loading time of 60 seconds [12]. After failure of the glass, the stresses are set to zero if the strains are positive (tension), while the material can still react to compression stress (negative strain). For the tires, an elasto-plastic material has been used via radial return algorithm. Isotropic hardening is activated and there is no strain-rate dependency. The material properties for the different types are described in the next tables.

Table 2: Material properties metals modelled with VPJC

Material type	**E [GPa]**	v	**ρ** $[^{kg}/_{m^3}]$	σ_0 **[MPa]**	Q_1 **[MPa]**	C_1	Q_2 **[MPa]**	C_2	**c**	$\dot{p}_0$ $[s^{-1}]$	W_c **[MPa]**
Medium-strength steel	210	0.33	7850	326	235	56	446	4.7	0.001	5E-4	555
Aluminium alloy	70	0.3	2700	160	33	97	65	8.7	0.001	1E-3	125
High-strength steel	210	0.33	7850	605	139	10	709	7.1	0.016	5E-4	1516

Table 3: Material properties for glass and tires

Material type	**E [GPa]**	v	**ρ** $[^{kg}/_{m^3}]$	**Elastic limit [MPa]**	**Stress erosion [MPa]**	**Strain erosion**
Glass	70	0.22	2500	-	160	-
Elastic tires	2.5	0.33	3890	246	-	200%

2.5 Contact model

The mechanical contact-impact behaviour of a vehicle crash is characterized as fast impact or crash test problem, where the friction can be neglected and large deformation of the involved bodies may occur. Conventional contact-impact methods of sliding surfaces [13] based on "slave" nodes and "master" surface are widely used in the FEM analyses. Contact-impact algorithms usually consist of two main components. First, the contact detection module realized by means of node through surface penetration algorithms, as depicted in Figure 7a. Then, the contact enforcement technique that can be introduced via penalty or Lagrange multipliers methods.

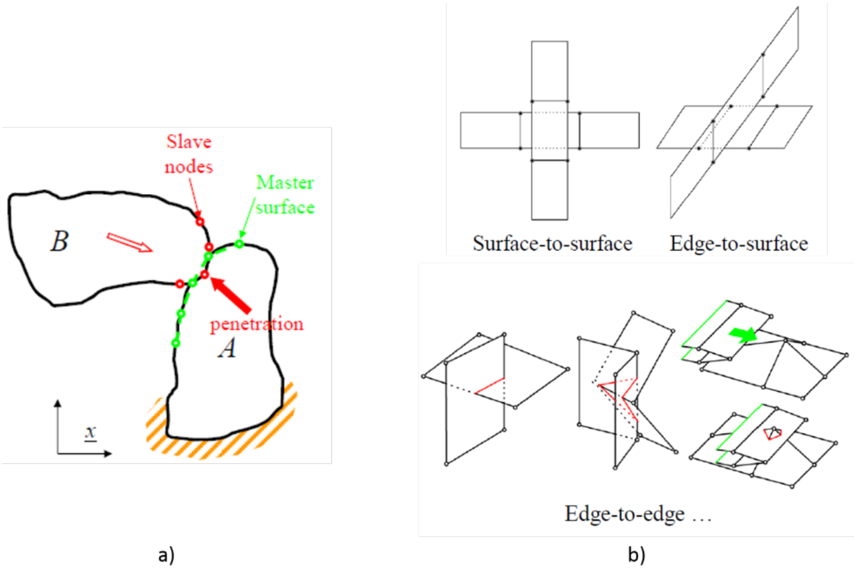
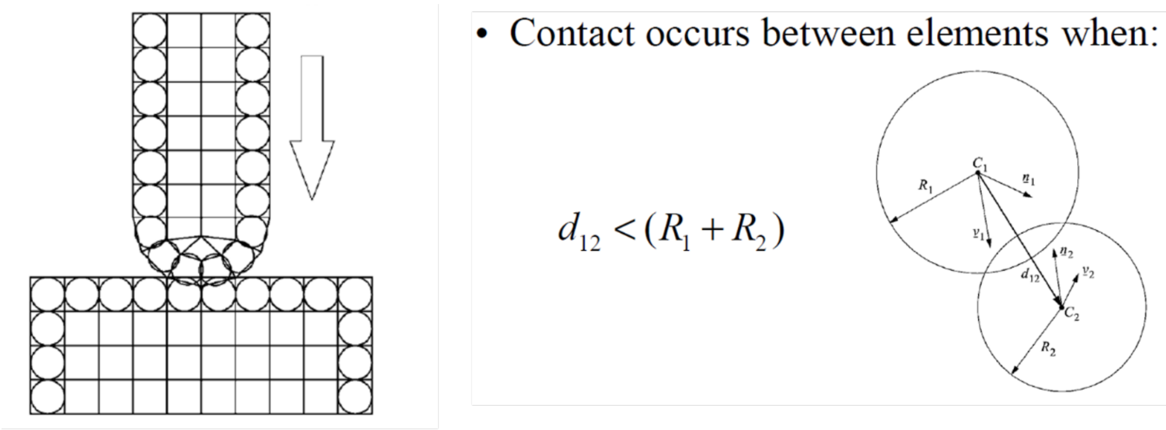


Figure 7: a) representation of conventional contact method b) pathological cases [15]

The conventional techniques can be very efficient but they also suffer from certain drawbacks related to the robustness of the underlying node penetration algorithm. Some cases of undetected contact or spurious penetration by the nearest-node algorithm are presented in Figure 8b. An alternative to resolve the above-mentioned drawbacks is the pinball algorithm introduced by Belytschko and Neal in [14]. The main idea of the pinball algorithm is to enforce the impenetrability condition via a set of spheres (pinballs), which are embedded in the finite elements as shown in Figure 8. For the current study, the sliding surfaces approach has been employed (GLIS directive in EPX) since it has been proven both robust and efficient. The contact relationships have been introduced via the Lagrange multipliers method, in order to obtain a reference solution, independent from any kind of calibration of the penalty coefficients.



a) b)

Figure 8: a) Pinball concept shown in two dimensions b) interpenetration of two pinballs [15]

2.6 Aspects for improvement of the computational cost

The computational cost is always the key parameter for the industrial use of numerical simulations. In crashworthiness analysis, the objective for the automotive industries is to keep the computational cost below half a day. To succeed, the following approaches should be considered.

2.6.1 Parallel computing

The nature of the algorithm of explicit FE codes is suitable for parallel computing through domain decomposition. The whole model is split into smaller sub-domains, as for instance in Figure 9, where each sub-domain can be analysed in a different processor at the same time (in parallel). Explicit FE analysis shows a very high scalability level which means that a big number of processors can be engaged to speed up the calculation. High level of scalability implies that, as the number of processors is increased, the speed-up of the computation is increased in a similar manner. The number of processors that can be used for this type of analysis might range from 16 up to 256, depending on the size of the numerical model and the availability of computational resources.

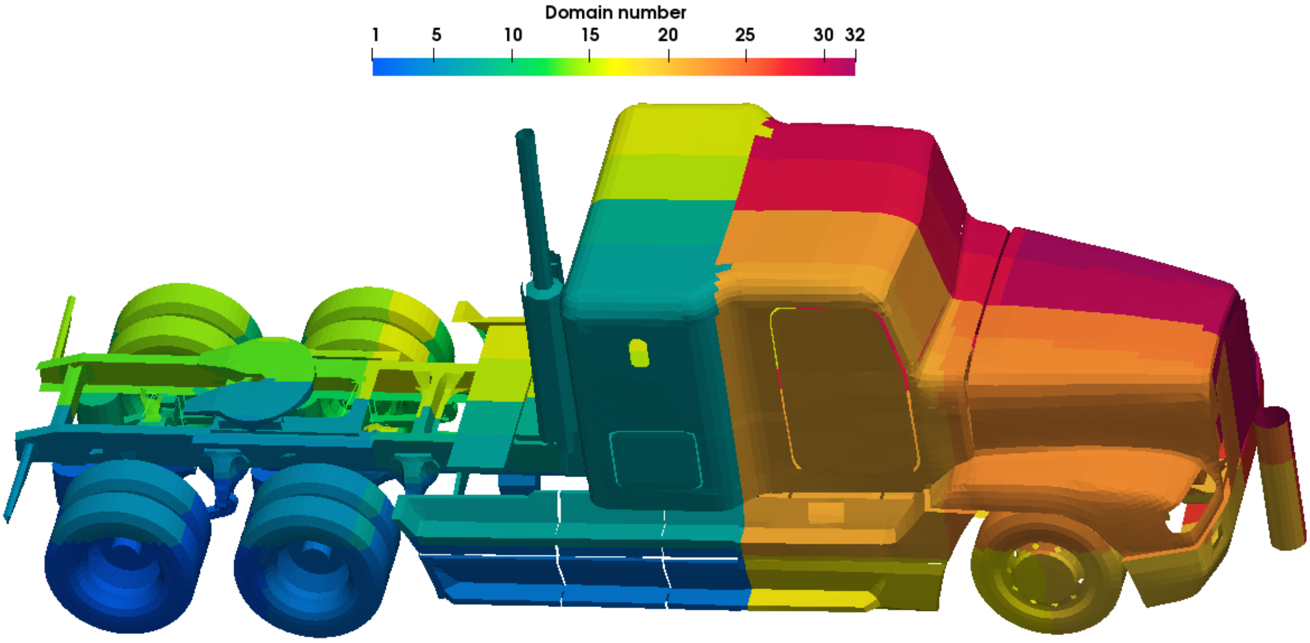


Figure 9: Domain decomposition for the tractor numerical model.

Table 4 presents the performance of the numerical simulation of the tractor model with a varying number of domain decomposition configurations. The first row contains the computational cost for a sequential calculation and serves as a reference point for the speed-up definition. As the number of processors increases, the speed up increases as well (the computational cost decreases). For 4 processors the speed-up is 3.7, which is very close to the highest possible value (4). For more processors, the rate of the speed-up increase until the 64 processors, where the speed-up is the same as with 32 processors.

This phenomenon is related to the size of the model and the required time for the communication between the sub-domains. A fraction of the analysis cost is always dedicated to the communication of each sub-domain with the central processor that forms the complete solution. When the size of the sub-domain is becoming small, then the communication time is becoming significant compared to the computational cost (operations on the elements). In the investigated numerical model the total number of elements is about 75,000. If 64 processors are employed then each sub-domain contains approximately 1,150 elements, a rather low number. In the current case, using 32 processors is the best approach, while the speed-up with the use of 16 processors is also a very good compromise (it can be used in case of lack of available processors).

Table 4: Speed-up level for different number of sub-domains for the tractor numerical model

Number of processors	CPU time [h]	Speed-up
1	300	-
4	81	3.7
8	46	6.5
16	24	12.5
32	18	16.7
64	18	16.7

2.6.2 Decoupled links approach

As stated above, the explicit FE algorithm is suitable for MPI calculations since it can demonstrate high scalability level. Nevertheless, in a fast transient analysis, there is an implicit part of the algorithm related to the constraints (boundary conditions, kinematic constraints, contact etc.) of the mechanical system. That implicit part includes solving a system of linear equations (Lagrange multipliers method). When the number of the linked parts is becoming significant, the overall performance of the MPI approach might be affected. Implicit algorithms can rarely exceed a speed-up of 8 (even if a big number of processors is used), therefore as the size of the implicit part is increasing the benefits of the MPI approach are decreasing. In vehicles crash analysis of this implicit part is significant due to the big number of contacting surfaces and kinematic constraints of the several components.

In order to avoid this phenomenon, it is necessary to describe every contact via an explicit approach, which is possible if an appropriate penalty method is used. The kinematic constraints are not anymore described through a system of equations but are introduced through an array of springs based on the material properties of the engaged surfaces. These springs are actually applying a force that (approximately) imposes the kinematic constraint, as for example, a force that is blocking the penetration of two contacting surfaces or keeping together two surfaces that are supposed to be rigidly connected.

It should be highlighted that the penalty approach has several drawbacks that an engineer has to consider before using it. The array of springs that imposes the penalty forces needs to fulfil the requirements for the time-step stability of the explicit algorithm. Special care must therefore be taken to ensure that the minimum time step of the contact calculation is bigger than the analysis time step, otherwise numerical instability can occur. The definition of the stiffness of the imposed springs is related to the material bulk modulus and the area of the involved surface that can be directly identified. The penalty scaling factor needs to be adjusted. The identification of the penalty scaling factor is normally an iterative process requiring several parametric studies. The automotive industry is massively using penalty methods to increase computational efficiency after many calibration tests on the penalty coefficients.

2.6.3 Rigid body components

The most significant parts of the vehicle model (vehicle body, wheels etc.) shall be modelled explicitly with a certain level of accuracy in order to precisely capture their response under impact loading. Other parts can be reproduced in a simpler way, (e.g. the vehicle engine), for which it is enough to model the inertial properties or their kinematics, like in the case of suspension and steering systems. The simplification concerning these parts can take place through a rigid body approach.

Rigid body modelling consists in defining a simplified kinematical system which should behave exactly (or as faithfully as possible) in respect to the actual component. The equivalent kinematic system should be realized by combining simple rigid bodies (small shell or solid elements) by means of different joints, in order to define a sort of “multi-body” component inside the finite element model. Discrete spring and damper elements should be defined in the appropriate locations, in order to model the stiffness and damping properties of the actual part. The advantage of rigid body modelling is the big reduction of computational costs and the possibility to easily modify the stiffness and kinematic properties of the relevant components.

2.6.4 Mesh Quality and mass scaling

Most typical examples of element quality criteria are the aspect ratio, the Jacobian (the value of the determinant of the Jacobian matrix is calculated for each integration point of the element, the reported deviation is calculated as the ratio of the smallest value over the largest), the skewness, the tapering and the crash time step, as presented in Figure 10. Table 5 depicts the typical threshold values of the mesh quality criteria. The first four criteria are applicable for both implicit and explicit solvers while the fifth one is related only to explicit solvers. Usually, a FE numerical model with less than 10% of its elements failing the quality criteria is considered to be acceptable. Special care should be taken though in the regions where the stress intensity is high.

The time step is controlled by the minimum dimension of the smallest element of the FE mesh in combination with its sound speed, therefore, the mesh size shall be a trade-off between the need for geometrical and numerical accuracy and computational cost: large elements guarantee a large time step but poor model accuracy, while smaller elements provide better accuracy but smaller time step.

The time step quality criterion is the most important for an explicit approach since it is directly connected with the computational cost. A smaller integration time step results into a higher number of steps and consequently an increased CPU time. Explicit integration schemes are conditionally stable. Therefore, the integration time step must be small enough. More precisely, it should be lower than the lowest time a sound wave takes to cross a finite element. The critical time step is related to both material properties and the size of the element. The speed of sound is calculated through the formula $U_S = \sqrt{E/\rho}$ where E and ρ are the Young's modulus and density of the material. Therefore, the critical time step for each element is calculated as $\Delta t = L\sqrt{\rho/E}$, where L is the shortest distance in the element.

A useful method for to increasing the critical time step is to apply the mass scaling technique. A small amount of mass is added (via the density of the elements) to a limited number of elements in order to augment the critical time step. Mass scaling should be kept to a minimum (aim at less than 2 %) as mass added to the vehicle on initialisation could affect the impact results. The added mass should not be concentrated in critical areas.

Table 5: Mesh quality criteria thresholds

Quality criterion	**Typical threshold**
Aspect ratio	3
Skewness	45°
Tapering	0.25
Jacobian	0.7
Crash time step	1 microsecond

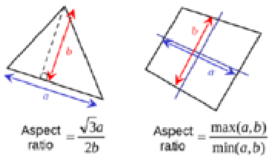
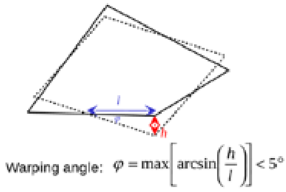
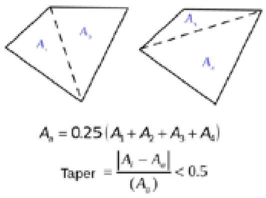
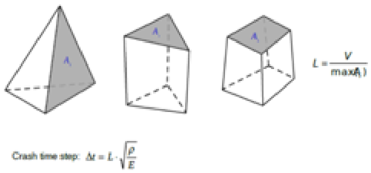
Description	**Example**
Aspect ratio: the ratio of the maximum element edge length to the minimum length.	
Warping angle: Measures how far is a quadrilateral element from being planar.	
Skewness: Measures the deviation of an element's angles from 90° for quadrilateral elements and 60° for triangular elements	
Jacobian: (the value of the determinant of the Jacobian matrix is calculated for each integration point of the element, the reported deviation is calculated as the ratio of the smallest value over the largest	
Taper: The angular distortion of quadrilateral elements	
Crash time step: time needed for the sound wave to travel through an element	

Figure 10: Mesh quality criteria [8].

3 Numerical results

Two vehicle models have been used to apply the numerical framework described in the previous sections. A tractor model [6] (9 tons) impacting a bollard represents the heavy-duty vehicle type, while a Toyota Yaris [4] (1.7 tons) model represents a passenger car. EPX has been employed for all numerical simulations and the Paraview [7] post-processor for the manipulation of results. Typical outputs are a) the state of the vehicle and the barrier geometry for several time frames, b) the velocity time-history of the vehicle, c) the deformation time-history of the barrier and d) the contact and the support forces time-histories on the barrier.

3.1 Tractor model

For the tractor model, the bollard is a hollow cylinder with 1m height and diameter of 0.24m, see Figure 11. In the first study, the tractor is impacting against a rigid bollard (unphysical high stiffness and thickness) in order to estimate the maximum contact and support force of the impact and to represent an ideal protective scenario. Then, a realistic material (high-strength steel) has been assigned to the bollard. Two different thicknesses have been tested for the bollard. In the first case, the bollard is considered stronger having a thickness equal to 5cm while in the second case the bollard is considered weaker and the thickness is 3cm. The bollard is fixed on the ground by blocking all the degrees of freedom of the related nodes. The impact velocity of the vehicle is 20m/s or 72km/h which is a rather severe scenario.

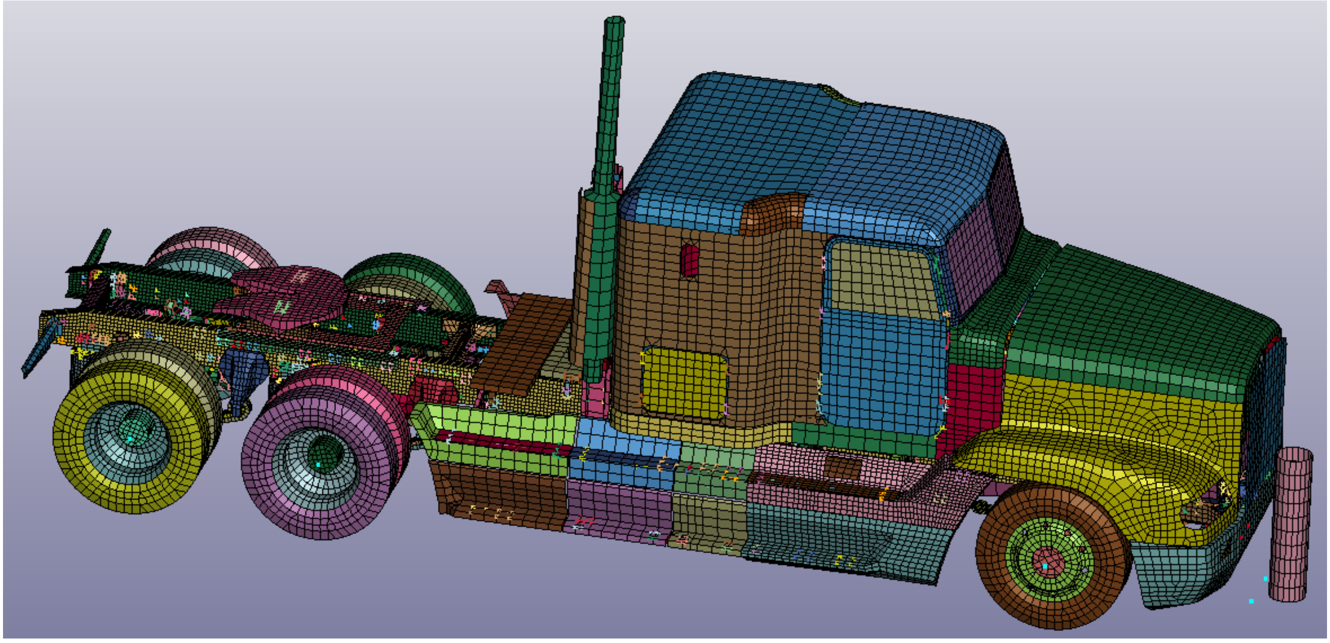


Figure 11: Tractor vehicle numerical model [6] impacting a bollard.

Figure 12 depicts the contact force applied on the protective structure, during the impact of the tractor for different types of bollards. The blue curve corresponds to the rigid barrier. That scenario represents the maximum force that the bollard may undergo during the impact with the vehicle. That force history can be used as an input in the case where only the barrier would be modelled. That approach would be rather conservative since the contact force is decreasing for deformable barriers. The red curve (stronger bollard) exhibits lower peaks than the rigid one and higher peaks than the weaker one.

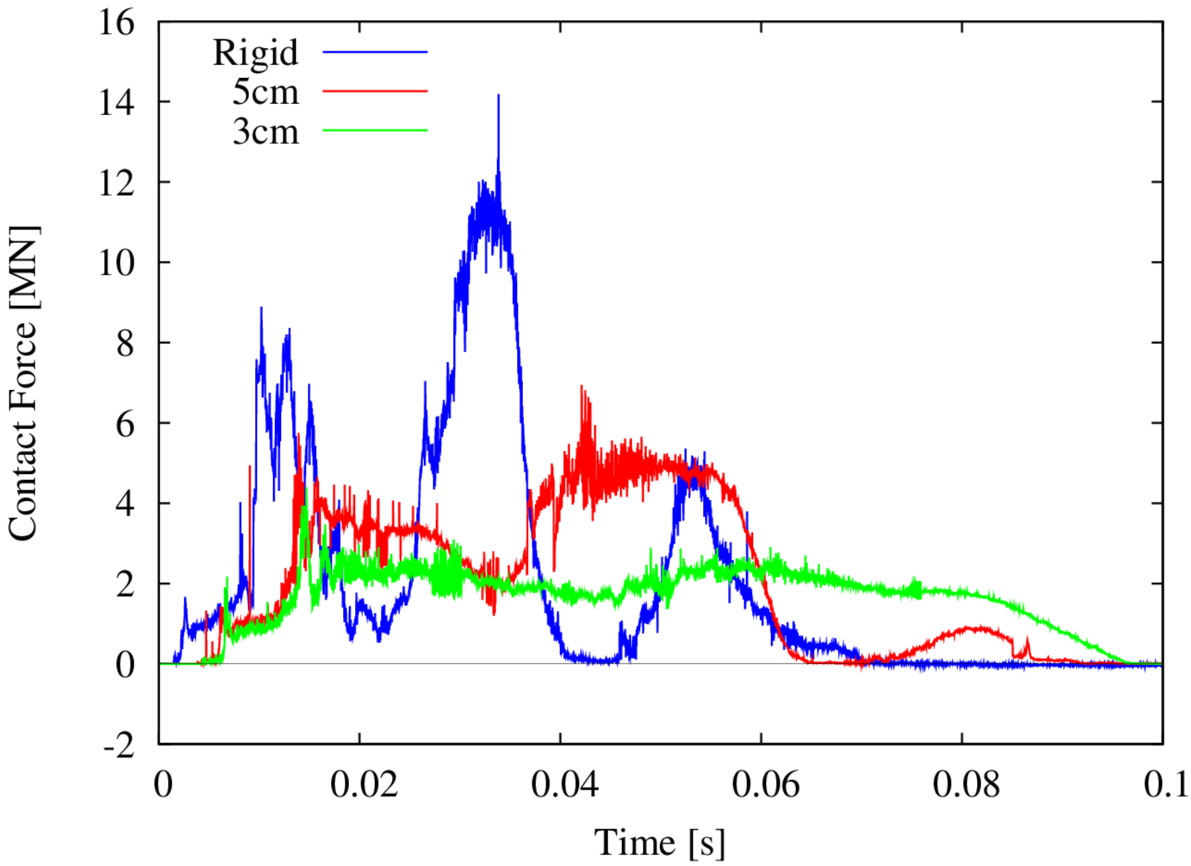


Figure 12: Contact force for the impact on different bollard types.

Similar remarks can be extracted from Figure 13, which presents the support forces observed at the bottom of the protective structure, during the impact of the tractor, for different bollard types. The rigid bollard receives the highest contact force and gives the highest support response. The support force in the stronger deformable bollard perceives a higher level than the weaker one but much lower than the rigid case. There is an obvious difference in the impulse of the support force for the different cases. There are two explanations for this behaviour: first, the change in the momentum is not the same for the different cases, for example in the case of the weaker bollard the vehicle is not stopped after impact. Second, the deformable cases are absorbing part of the energy of the system through plastification of the structure. The support force is an essential quantity for the design of the protective structure as it provides an estimation of the foundation requirements.

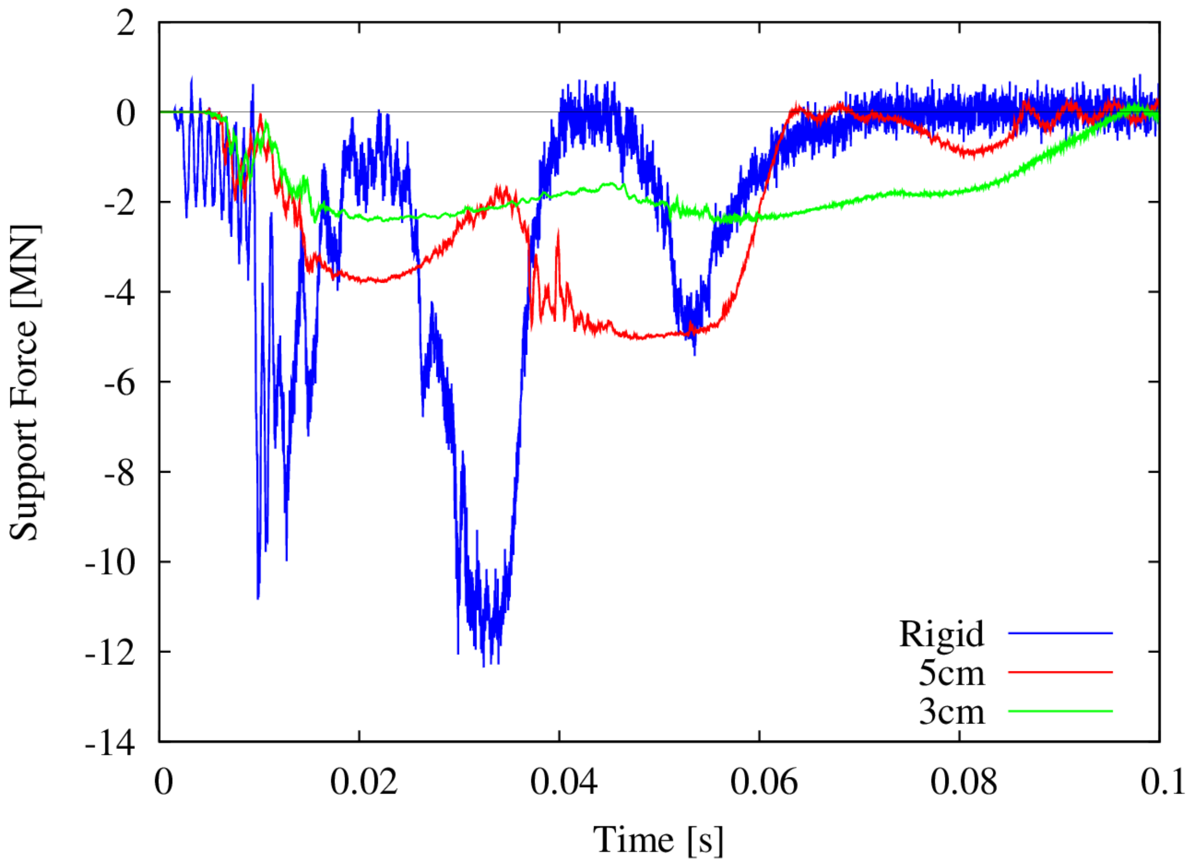


Figure 13: Support force for the impact on different bollard types.

Figure 14 shows the average vehicle velocity time-history during the impact with different bollard types. This diagram contains the most important information of the study, which is the velocity of the vehicle after its impact with the protective structure. The final velocity of the vehicle indicates the effectiveness of the selected barrier. In the case of the rigid bollard, the vehicle is stopped little before 60ms and then it has an oscillating rebound velocity in the order of 1m/s. In the case of the stronger deformable barrier, the vehicle is stopped little before 80ms and there is no rebound velocity. In the case of the weaker deformable barrier, the vehicle is not stopped and has a velocity of 3m/s after its impact. In the latter case, the design of the protective structure is ineffective and fails to fulfil its task to block the vehicle.

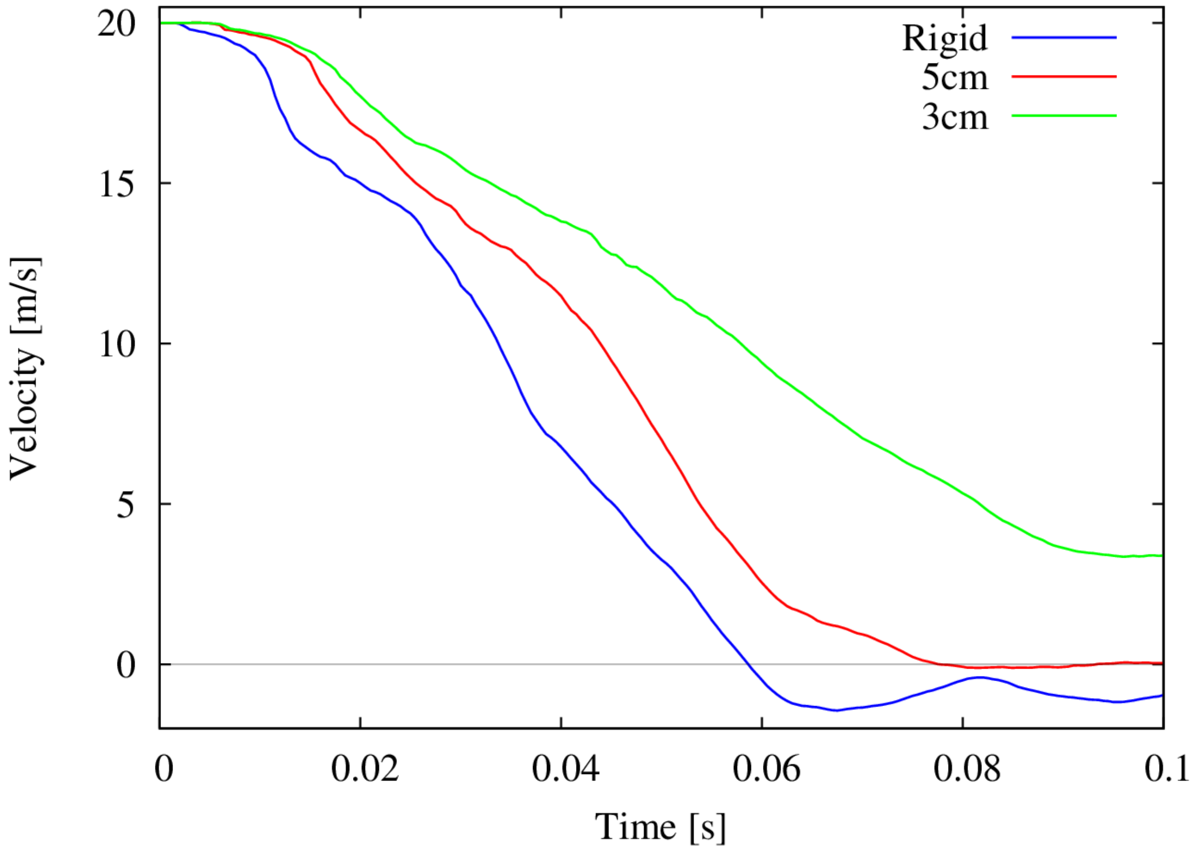


Figure 14: Tractor velocity history during the impact on different bollard types.

Figure 15 depicts the horizontal displacement time-history of the top of the barrier during its impact with the tractor. As expected, the deformation in the case of the rigid barrier is negligible, just small oscillations in the order of a fraction of mm were observed. In the case of the flexible barriers, the permanent deformation is from medium for the stronger type (around 0.2m), to significant for the weaker type (0.6m). The barrier permanent deformation is better observed in Figure 16 where the final state of the protective structure for each case is presented. The figure presents also the damage observed on the protective structure. The damage is a quantity related to the plastic strain of the structure and is 0 in the case where the case is intact and 1 in the case where the structure is failing (the element is eroded). The weaker bollard is exhibiting a higher damage level than the stronger case, as expected. Actually, in the weaker bollard case, the bollard has deformed to such a degree that the vehicle can pass over. The state of the vehicle and the barrier for the stronger and the weaker bollard type for several time frames is depicted in Figure 17 and Figure 18.

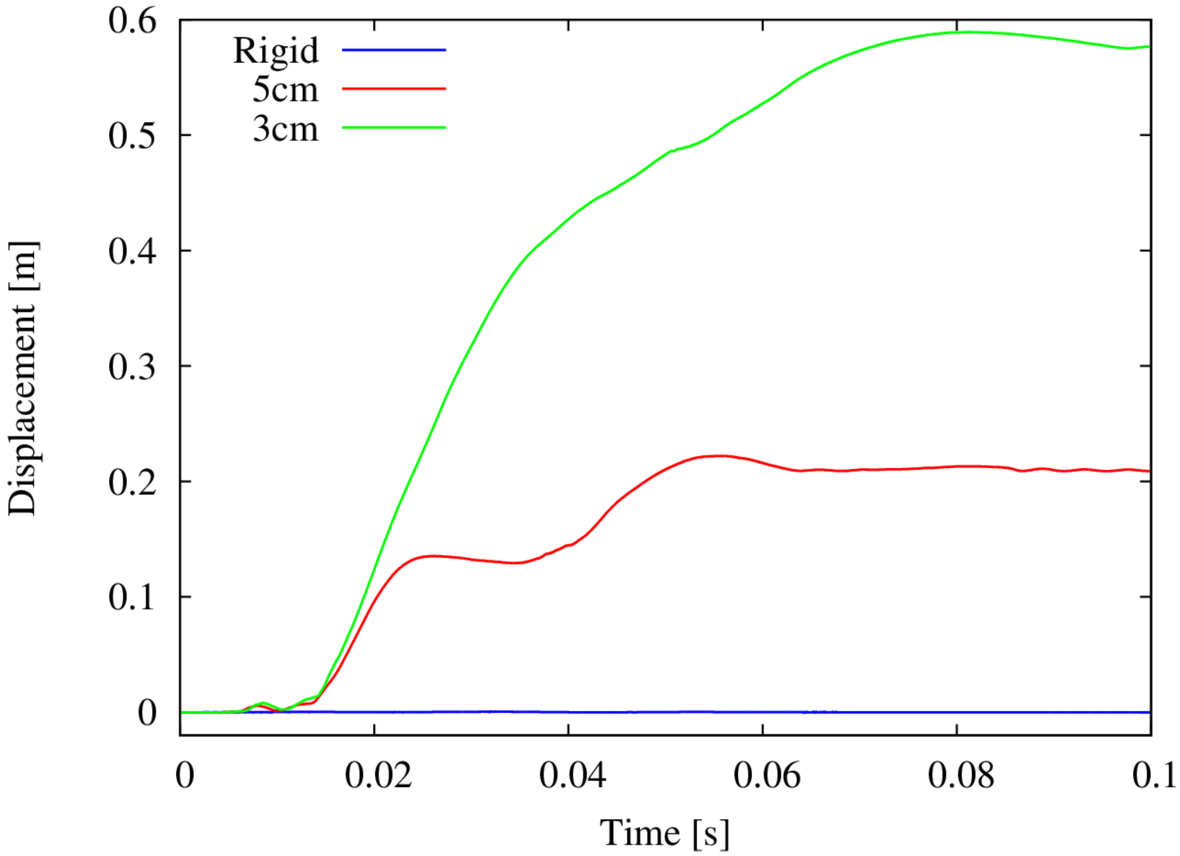


Figure 15: Top horizontal displacement for different bollard types.

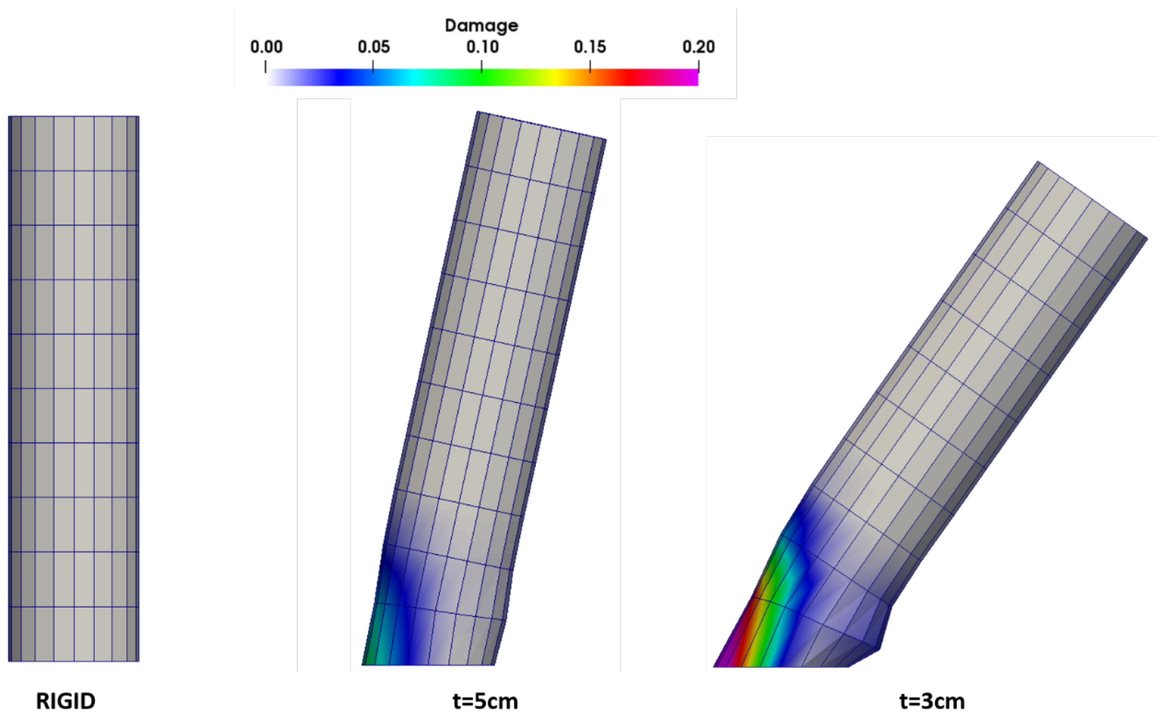


Figure 16: Deformation and damage level for different bollard types.

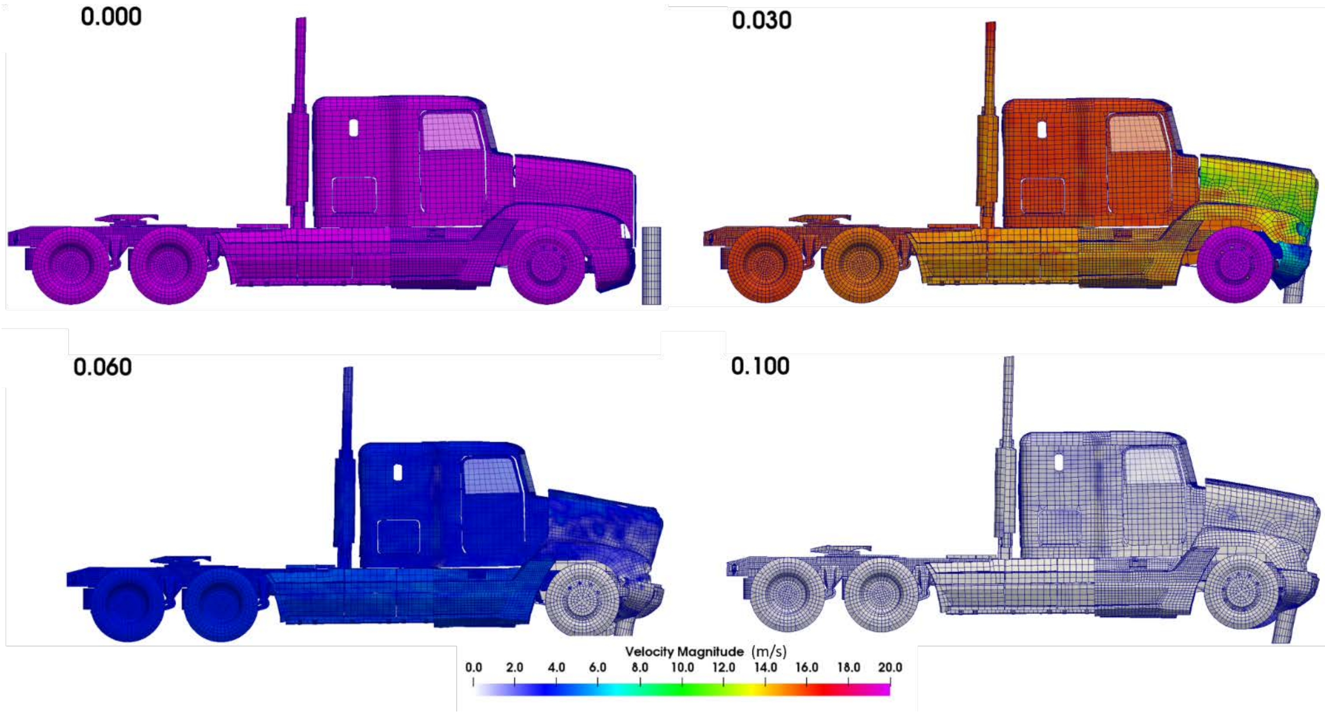


Figure 17: Response of the tractor impacting on a strong bollard (5cm) for several time frames.

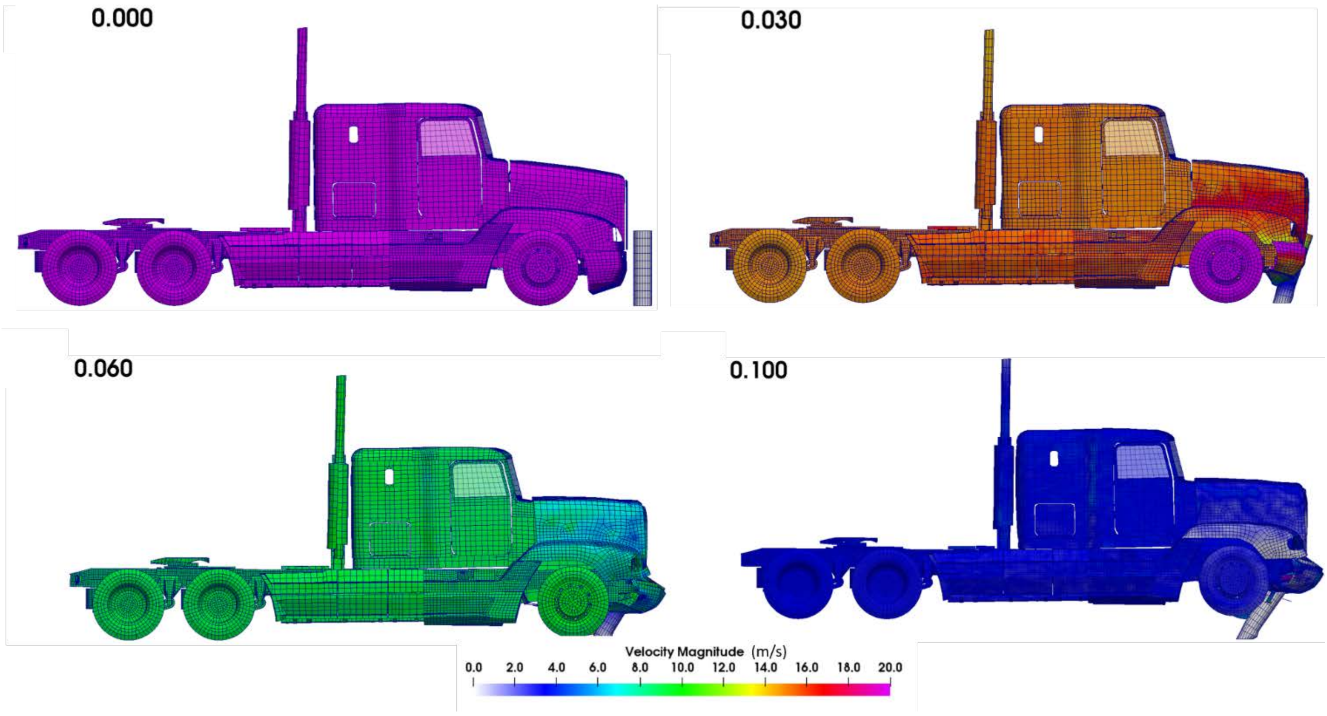


Figure 18: Response of the tractor impacting on a weak bollard (3cm) for several time frames.

3.2 Yaris model

The Yaris vehicle model has been used for conducting a parametric study on the maximum permissible distance between two barriers and their capacity to stop the vehicle, see Figure 19. The barriers are represented by hollow cylinders of 0.4m diameter and 1m height. The barriers are fixed on the ground (by blocking the degrees of freedom of the relevant nodes) and their behaviour is nearly rigid by using a very stiff material (unphysical high stiffness and thickness). The distance between the two barriers, practically the area the vehicle can pass through (air gap), varies from 120 cm up to 140 cm. The impact velocity of the vehicle is 20m/s or 72km/h and is perpendicular to the plane of the two axes of the barriers and its mid-point is placed exactly at the mid span, which is a rather severe scenario. The study has two objectives, first to determine whether the barriers are capable of blocking the vehicle and second to estimate the penetration distance. The penetration distance is defined as the maximum post impact distance between the barrier (its front or rear face depending on the testing procedure) and the vehicle's reference point, as described in [2].

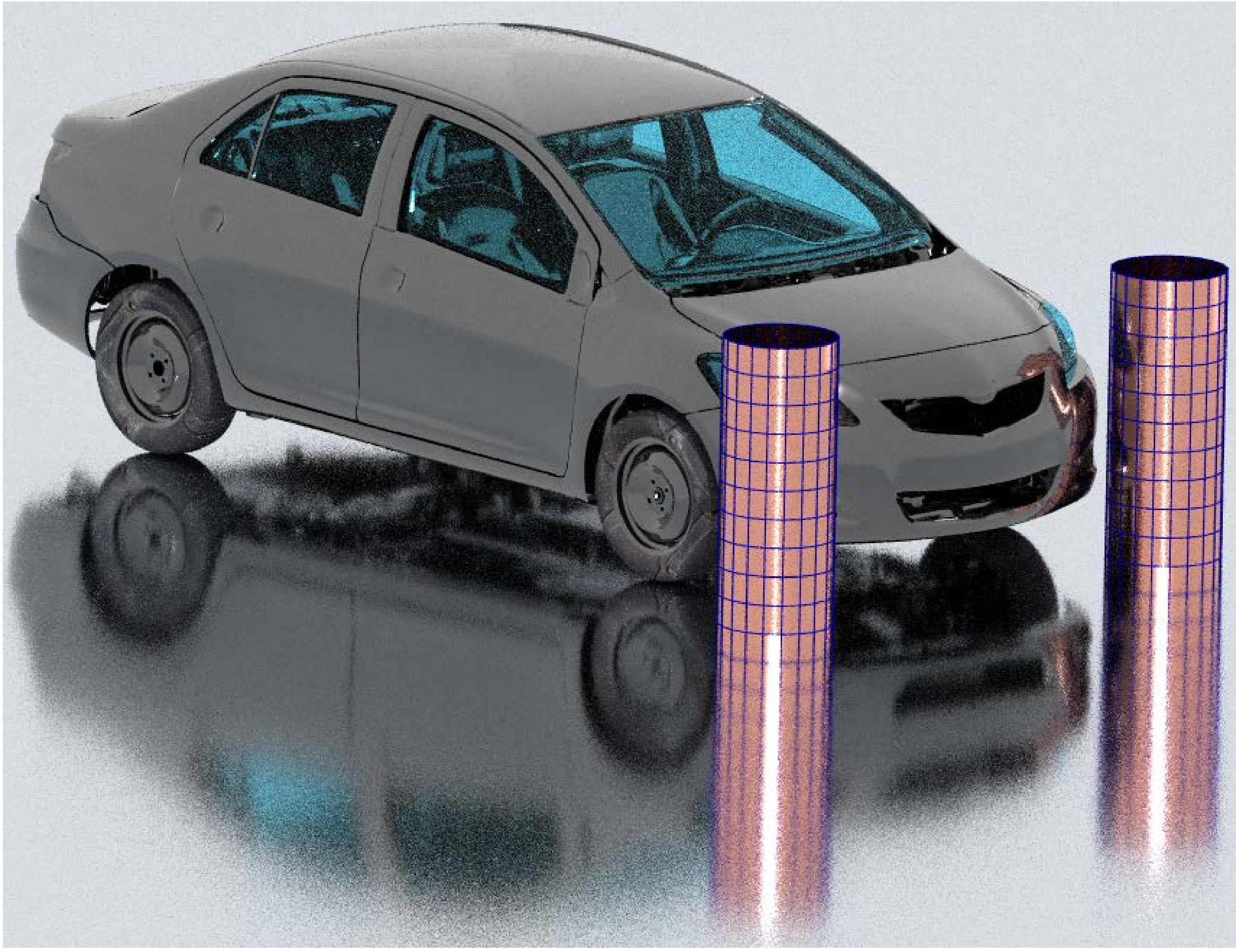


Figure 19: Yaris vehicle numerical model [4] impacting two barriers.

Figure 20 depicts the velocity time-history of the vehicle model during the impact on the two barriers for 120 cm, 130 cm and 140 cm air gap. For the case of 120 cm the vehicle reaches zero velocity after 70 ms, which means that it was blocked by the barriers. The span between the two barriers is small enough and they are able to decelerate the vehicle efficiently. In the case of 130 cm again the vehicle is blocked after 100 ms, a little later than the previous case. For the case of 140 cm the deceleration of the vehicle is not very steep. The vehicle reaches a velocity of 7 m/s at 180 ms which is the final time of the calculation. The calculation was stopped since the major part of the vehicle has passed the barriers and its velocity still has a considerable value. That practically means that in this case the vehicle is passing through the barriers and entering in the protected zone. It should be noted that the steering system of the vehicle has been damaged since the front wheel axle has been broken, therefore the vehicle is not able to make manoeuvres inside the protected zone and will eventually stop.

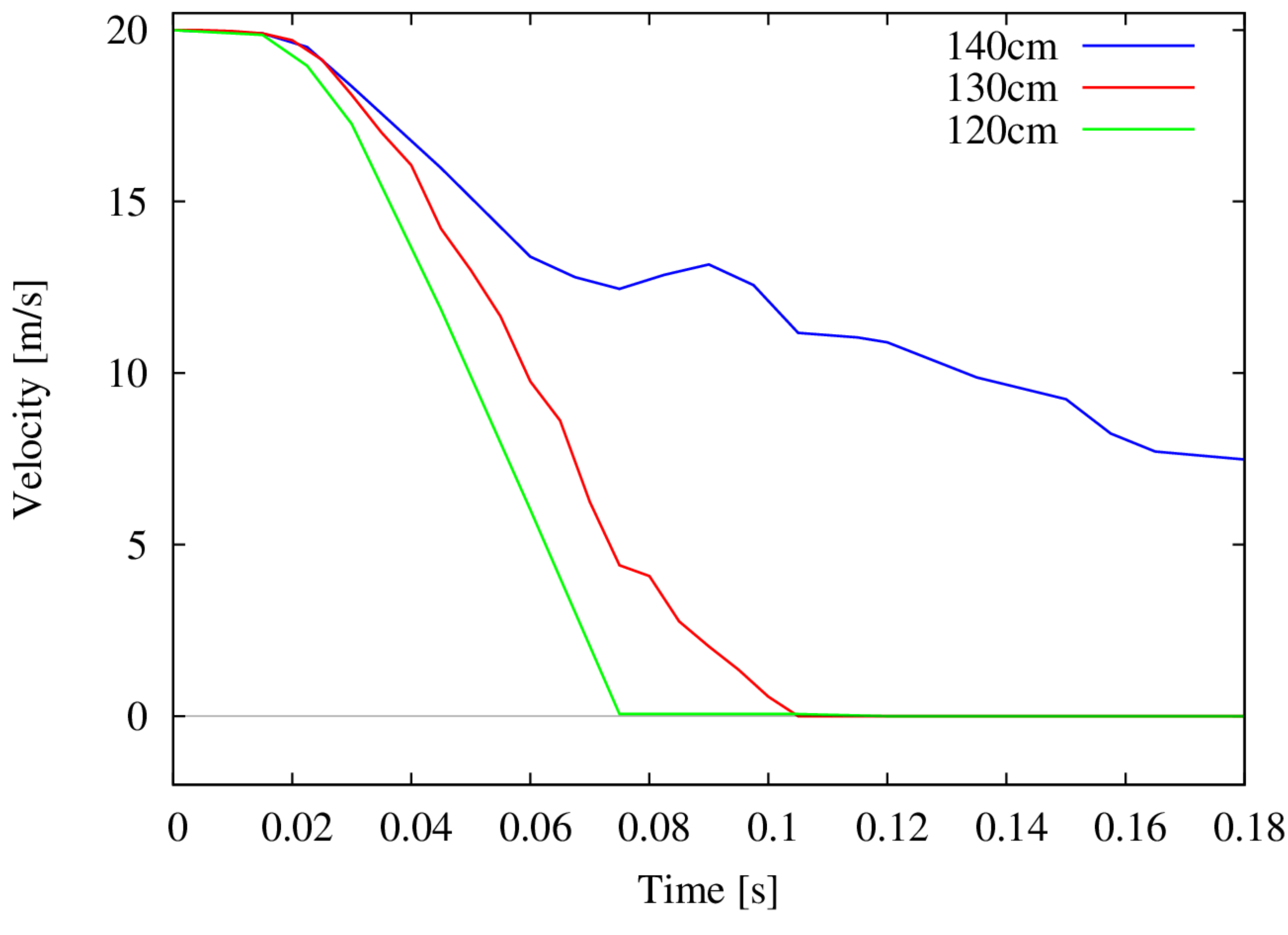


Figure 20: Yaris velocity history during the impact for three different barrier configuration.

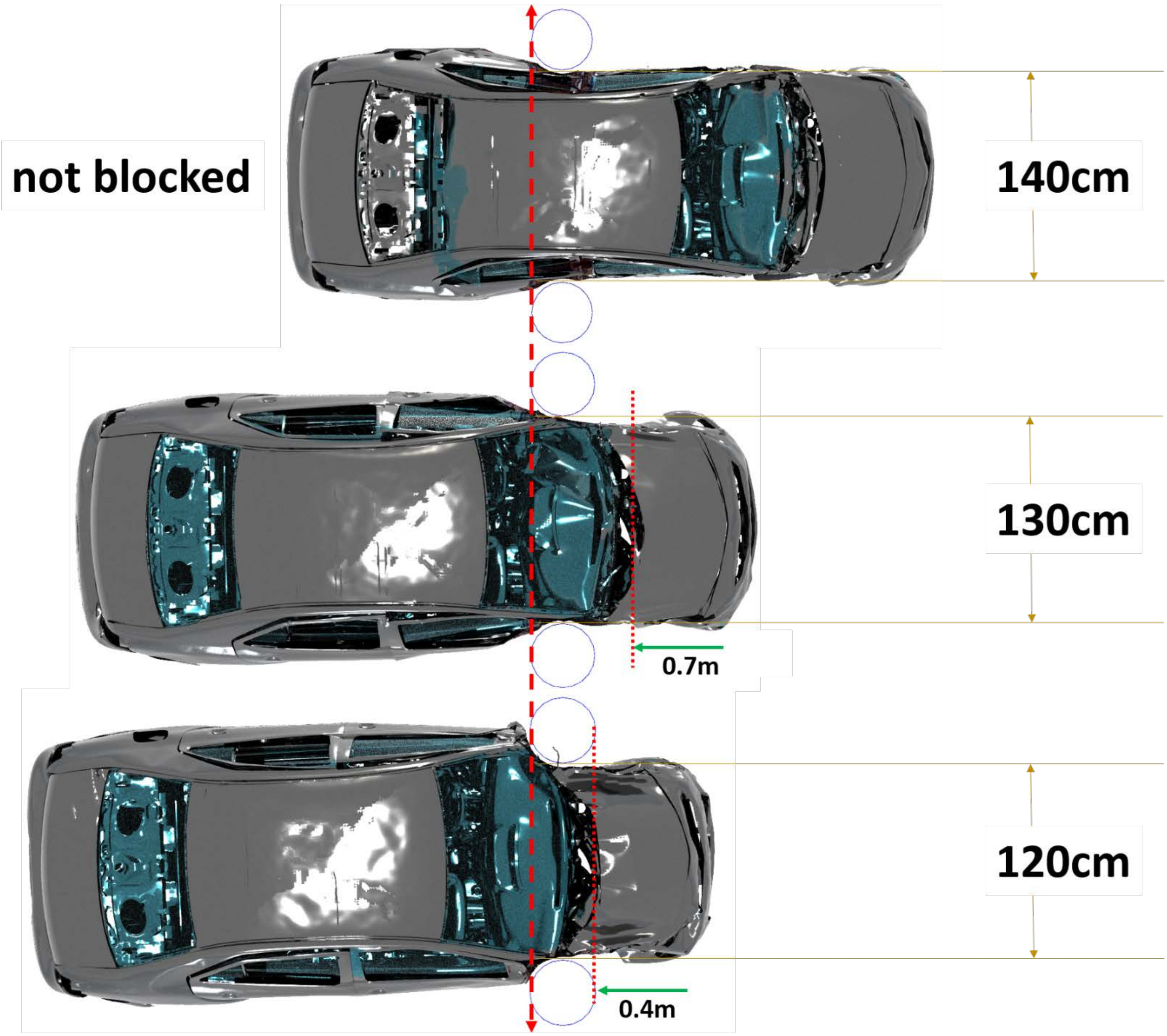


Figure 21: Comparison of penetration distance for three different barrier configurations.

A better understanding of the penetration distance can be obtained in Figure 21. The dashed red line indicates the plane passing through the back face of the barriers. The dotted red line indicates the vehicle reference point (where the windscreen meets the front trunk according to [17]) when it reaches zero velocity. The distance between the two red lines defines the penetration distance of the vehicle. For the 120 cm case the penetration distance is around 0.4 m, indicating the area where people is not protected. For the 130 cm case the penetration distance is a little higher up to 0.7 m, but the objective of the barriers to stop the vehicle has been accomplished. In the 140 cm case the vehicle is not stopped close to the barriers and what is depicted in the figure refers to the final time of the calculation (after 180ms). In this case the vehicle passes through the barriers, but its front and back wheel axes are destroyed, so the actual (final) penetration distance is much higher.

The presented parametric study may be very useful for the local authorities, owners and urban designers that are responsible for selecting and placing the security barriers. Since the configuration with an air gap of 140 cm requires a relatively big penetration distance, reflection is needed from the decision-makers to guarantee that such a distance between the barrier and the public is acceptable. On the other hand, both 120 cm and 130 cm configurations proved to be effective in blocking the vehicle at much smaller penetration distances. The penetration distance is rather small for both cases, consequently another parameter like for example the cost can be decisive. Selecting a higher air gap between barriers means that the number of the needed elements would be lower. A lower number of barriers in combination with placement and maintenance cost can have a significant effect on the total budget of the project.

4 The potential role of numerical simulations in the assessment of security barriers

In the previous chapters we have presented a numerical framework to perform impact analysis of vehicle models against HVM protective measures. Such framework could be employed to simulate the performance of security barriers impacted by vehicles and consecutively providing recommendations for the design of security barriers under certain loading scenarios. Numerical simulations are not yet foreseen in the standards that are currently used for the performance assessment of security barriers (see following sections). Nevertheless, some standards are already introducing numerical simulations in the field of vehicle collisions, like for example CEN/TR 16303 [8] that regards the computational mechanics of crash testing against vehicle restraint systems. The scope of this document is to establish accuracy, credibility and confidence in the results of crash test simulations to roadside safety devices through the definition of procedures for verification and validation in roadside safety applications. Several areas are covered, like vehicle modelling and verification, validation procedures and analyst qualifications, while focus is primarily on the effects of the vehicle impact on the passengers.

Similar documents focusing on the effectiveness and the performance assessment of HVM security devices through numerical simulations can significantly assist both producers and private/public authorities that are active in the field. Such an initiative requires the support of different stakeholders, like local security authorities, site owners, operators, counter-terrorism security advisers and the manufacturers of such protective systems.

The development of dedicated standardisation in the use of numerical models for simulating vehicle impact against HVM measures, the creation of common vehicle numerical models is also required. This would allow the use of the same vehicle model for all barrier performance assessments, resulting in easily compared results.

4.1 Advantages from the use of numerical simulations

As already mentioned, a validated numerical framework for assessing the performance of HVM barrier systems under vehicle impact can facilitate the certification process of products. A clear and cost efficient numerically assisted certification process may enhance competitiveness among producers and invest in the production of for more effective HVM systems, while consumers may benefit a heightened security for their assets.

There are various documents (IWA 14-1 [17], PAS 68 [16], CWA 16221 [20], ASTM F2656 [19]) regarding the performance rating of Vehicle Security Barriers (VSBs) through impact testing. The review of these standards is beyond the scope of the current work, as it is included in [2], but a closer look on their scope can reveal the added value of numerical simulations on the performance evaluation of VSBs.

IWA 14-1 & 14-2

IWA 14 is an ISO International Workshop Agreement that combines and updates elements from PAS 68, PAS 69, ASTM F 2656 and CWA 16221. IWA 14-1 [17] is the International Workshop Agreement which specifies the essential impact performance requirements for a vehicle security barrier (VSB) and proposes a test method for rating its performance when subjected to a single impact by a test vehicle (not driven by a human being). IWA 14-2 provides guidance for the selection, installation and use of vehicle security barriers (VSBs) and describes the process of producing operational requirements. Figure 22presents an overview of the information included in specification.

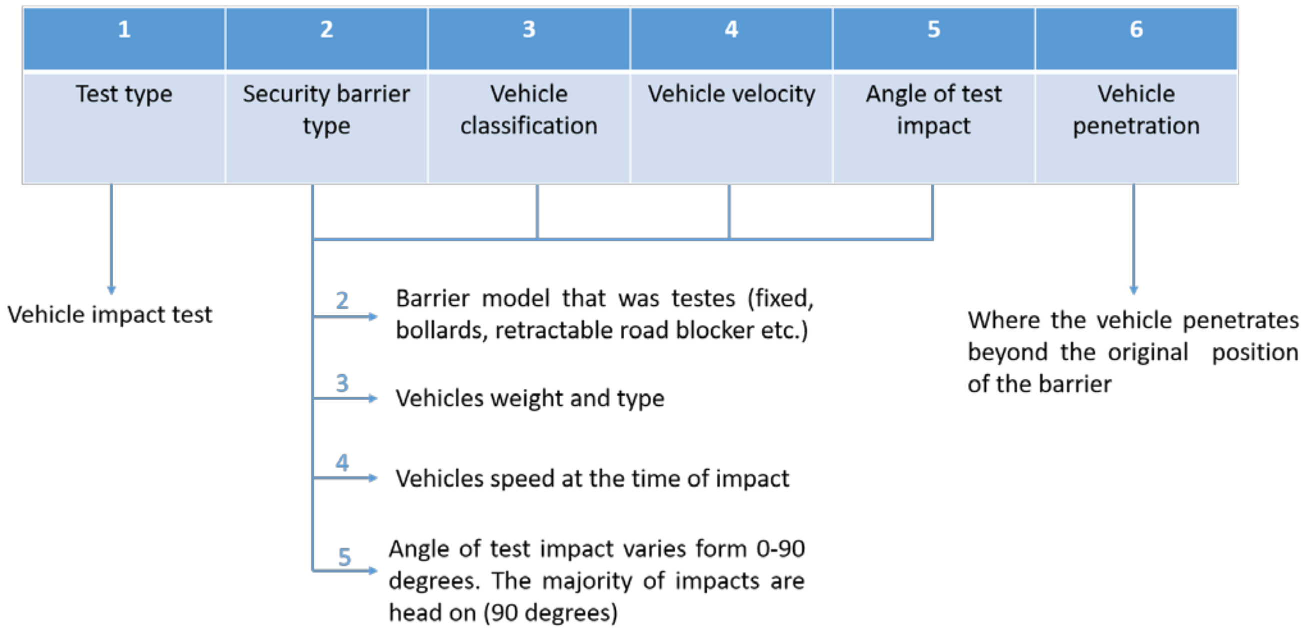


Figure 22: Test certification code of IWA 14.

By reviewing the abovementioned four documents the following the following remarks can be made:

1. The evaluation of the performance rating of VSBs and consequently their certification may also be performed with a single physical impact test. Depending on the desired protection level, a specific vehicle type is accelerated at a predetermined speed before impacting the examined VSB, which means that the test takes place only once under one specification/scenario (e.g. vehicle mass, speed, angle of impact etc.). It is clear that duplicating the same physical test or investigating additional scenarios would significantly increase the cost. Moreover, physical tests characterized by excessive deformation of the involved structures need a certain number of repetitions (at least two, while the most commonly adopted strategy suggests three repetitions). Performing only one physical test

means that the accuracy of the results cannot be guaranteed. Moreover, a single vehicle type is tested, which does not necessarily mean that all vehicles of the same classification would behave identically.

2. Part of the existing documentation (e.g. PAS 68) already allow the use of FE analysis procedures as a design method, yet it is not clear how these procedures can be validated and implemented in the design process. In the last decades, the automotive industry has paved the way by extensively using numerical simulations to improve the crashworthiness of its products; a systematic approach that should also be exploited by the HVM industry. The first step in building confidence on such an approach requires an extensive validation of the numerical analysis results against those from physical vehicle impact tests on protective barriers. Subsequently, computational methods may be employed to analyse additional attack scenarios, thus minimizing the cost that would be required in case of an actual physical crash test.

Parametric studies with numerical simulations might also provide feedback to design inquiries, like:

- Definition of the maximum distance between two barriers to avoid encroachment incidents.
- Evaluation of optimum VSB height for different vehicle types.
- Influence of site, environmental and weather conditions (e.g. friction variation)
- Foundation restraints, depending on the soil characteristics and the presence of any underground services over which the barrier will be placed (excavation depth, material type, weight etc.).
- Assessment of vehicle penetration distance and/or dispersion of the produced debris.

4.2 Simplification / harmonization of the adopted vehicle numerical model

There are fundamental differences between the crashworthiness analyses of the vehicle industry and those regarding security barrier impact tests. The vehicle industry focuses mainly on the safety aspects that are related to car crashes by examining mainly the behaviour of the vehicle and the potential consequences on the driver's health, whereas the primary objective of barrier impact tests is the definition of the robustness and effectiveness of the protective structure. This implies that the barrier analysis concentrates on different aspects, like the geometrical details, the barrier material characteristics and its boundary constraints. Clearly, in this type of analysis the numerical complexity should focus on the barrier and not on the vehicle model and its interiors. On the other hand, the representation of the vehicle, should be accurate enough to guarantee that its response is identical to that of the real vehicle.

As a result, a simplified numerical model should strike the right balance between simulating both the vehicle and the barrier, even though the main focus needs to be on the barrier model that is the most significant part in the analysis. Therefore, several parts of the vehicle numerical model can be omitted or substituted by simpler components. In this regard, experts of the automotive industry could provide valuable input on how to simplify a numerical vehicle model without sacrificing the accuracy of its global response when impacting a VSB. The term accurate vehicle global response incorporates the evaluation of the precise impact load acting on the barrier, while at the same time predicting with accuracy the vehicle penetration distance. The formation of an expert group, to shape recommendations on simplifying numerical vehicle models, can open the discussion for the construction of validated numerical models within the European automotive industry. These vehicle models should be freely available so as to be adopted by a wide audience, including, but not limited to, the industry, researchers and designers. As already mentioned in the previous section some numerical models already exist in the USA, but similar vehicle models are still missing in the European market representing in particular European type of vehicles.

The simplification process of numerical vehicle models can eventually lead to the formation of generic harmonized numerical models that will correspond to different vehicle weight classes of. Such an action would facilitate the cost efficient performance assessment of VSBs, since it would allow the simulation of different vehicle types impacting a single barrier type, and not the use of only one vehicle as is usually the case in physical tests (resulting in the certification of a single impact scenario).

An additional simplification proposal might entail the substitution of the vehicle model with a prescribed impact load, identical to the one generated from the physical crash test. Such an approach is for example already well-established regarding the impact of aircrafts against critical infrastructures. The consequences assessment of an aircraft's potential impact into a building may be examined through a predefined contact load that is imposed on the investigated structure. This approach significantly reduces both the computational and design cost, since the aircraft numerical model can be omitted. A similar concept in the field of protective barrier systems could promote a cost efficient robustness evaluation of a VSB. However, the simplified technique of using a predefined impact load for assessing the performance of VSBs has some inherent limitations when compared to the FE vehicle model approach, as the behaviour of the vehicle and its various parts when impacting the barrier cannot be predicted. The question of the penetration depth of the vehicle can also not be answered with such a simplified model. Nevertheless, such techniques may be successfully employed for analysing impact scenarios under relatively low kinetic energy values, where the deformation of the vehicle and the protective barrier is not excessive.

5 Conclusions

In the current document, a **numerical framework for studying the impact of vehicle FE models against protective barriers** has been presented as part of a HVM analysis. The necessary steps to be followed for the numerical simulations, such as the material modelling, the contact algorithm and the computational efficiency have been discussed as a reference point for future studies. Special attention has been paid on the presentation of the existing vehicle models freely available on the internet. These models can serve as a starting point for a potential analysis of the capacity of a protective structure to block a speeding vehicle. However, the level of detail of these vehicle FE models is very high and can be an inhibitor for the study, since its objective is the performance of the protective structure and not of the vehicle's interior.

The present document aims to demonstrate areas where the engagement of **numerical simulations can contribute to the evaluation of the performance of security barriers**, by providing cost-efficient insight for different impact scenarios**. Validated numerical models may be used to certify alternative impacting scenarios** (changing the vehicle velocity, its type or its angle of impact) without significantly increasing the total budget. Another point that is stressed out in the document is the **formation of generic harmonized numerical models for the various vehicle classes**. The goal of that procedure is to develop generic models for each vehicle class that can be independent from the unique characteristics of each commercial brand. Finally, additional vehicle FE model simplifications can be studied in order to further reduce the computational cost and focus the numerical complexity on the barrier model, which is the most important aspect of the study.

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