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# A REVIEW PAPER ON VEHICLE CRASH AND ROAD SAFETY MANUFACTURING

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## Abstract

This survey aims at presenting the current trends and inventions in the area of crashworthiness. Increasing safety of not only cars occupants but also of all the road users is of paramount importance in the world where people's mobility and ease of traveling is more and more common concept. Situation on the road safety and different kinds of vehicle crash modeling are discussed and principles of safety barriers design for the road manufacturers are also presented in this survey.

## 1. Situation on the Road Safety

Transport plays a crucial role in an economy, transferring goods between the place of production and consumption, as well as transporting passengers for work or pleasure. However, transport problems such as congestion, quality of services (such as punctuality and connectivity), affordability and environmental impact put general economic developments at risk [1]. According to [2], Europe's roads have become safer in recent years: the



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number of road accidents involving a personal injury fell by some 12% between 1991 and 2007. More importantly, the number of road fatalities dropped by more than 44% over the same period. Yet much progress remains to be made to achieve the target of halving the number of road fatalities by 2010 compared with 2001 levels. When it comes to the shorter period of time - the decade between 1997 and 2007 - road fatalities in the EU-27 also fell sharply (down 29.9%), from 60267 deaths to 42854 deaths. The road fatality rate, expressed as the number of deaths per million inhabitants, averaged 87 across the EU-27, although there were stark contrasts between Member States. The highest road fatality rates in 2007 were recorded in Lithuania (218 deaths per million inhabitants), Latvia (184), Poland and Estonia (both 146). In contrast, rates were much lower in the United Kingdom and the Netherlands (50 and 43), and particularly in Malta (29). Above data has been taken from [1]. The data included in [3] shows that in 2005, 41600 people were killed on the roads in the EU. This is far from the joint target of no more than 25000 fatalities a year by 2010. About two thirds of the accidents and one third of the road fatalities are in urban areas and affect the most vulnerable road users. The risk of being killed in a road accident is six times higher for cyclists and pedestrians than for car users. Often, the victims are women, children and elderly citizens.

All the above statistics unequivocally prove that there is a lot of work to be done in the area of increasing safety of all road users: car drivers and their passengers, as well as vulnerable road users (VRUs) such as motorcyclists and pedestrians. This task involves a number of correlated issues with many different approaches and methodologies. There are three main ideas proposed in [3]: safer behavior, safer infrastructure and safer vehicles. The first task comprises of the following subjects: to make citizens more aware of their traffic behavior thanks to the education and information campaigns, encouraging safe behavior among cyclists, e.g., by promoting the use of bicycle helmets across Europe or by encouraging research on more ergonomic design of helmets and strict enforcement of traffic rules for all motorcyclists, scooter drivers and cyclists. Infrastructure's safety may be improved by increasing the number of measures in the urban environment as well as by construction of a high quality infrastructure, including good pavements for pedestrians and cyclists. Enhancing visibility, e.g., by providing better lighting, and more visible enforcement officers on the street can help to increase the feeling of security. ITS solutions can also make a substantial contribution by providing rapid and appropriate information and safety-based traffic management. Recommendations for incorporating urban transport safety and security standards in urban infrastructure design could possibly have a positive impact on safer infrastructure. Safer vehicles are of particular importance in urban areas where they share the street with pedestrians, bikes and collective transport. Technologies such as night vision, break assistant, collision avoidance and sleep warning can make a difference to the safety of all street users. An application of on-board Advanced Driver Assistance Systems (ADASs) and improving the existing car design solutions is one approach utilized to make the road transport safer to everyone who is involved in it. The other method, not as direct as installing the ready safety devices in cars, is the virtual experimentation and mathematical modeling of the vehicle. It helps to predict real vehicle behavior, interactions between a vehicle and its occupants, or deformation during a collision – all of that in the virtual environment, without a need of full-scale tests – and providing high degree of models fidelity. In the same time, the results from such an analysis can be used by the specialists who can, e.g., redesign particular car components so that its safety standards can be raised. Therefore, even if almost all the research is done on a computer, then this approach has a huge influence on the vehicles safety.

## 2. Vehicle Crash Modeling

Vehicle crash modeling is one of the paramount challenges in the area of crashworthiness. Having the correct model of a car collision, one does not need anymore to perform complicated and expensive crash tests in such extent as it is currently being done. Nowadays, every new type of a car which is designed and produced must undergo a series of experimental collisions which aims are to assess what the behavior of the vehicle is. Such experiments are performed not only when the car project is finished and vehicle is completely assembled but also throughout the design stage, e.g., to make certain that the initial design safety requirements are satisfied. However, that kind of test will provide just information about a certain type of accident (e.g., vehicle to rigid barrier central impact with a given initial velocity). By the acceleration measurements and monitoring the whole event by high speed video cameras, one obtains the complete dataset necessary for the collision analysis. Afterwards, it is possible to formulate in details responses of both: a car and an occupant during the impact – e.g., to observe at what time the maximum intrusion to the occupant's compartment occurs so that, e.g., the air bag will be activated on time. But if one of the crash parameters changes – e.g., a vehicle hits an obstacle with a different initial velocity, then the results obtained previously are not correct anymore and the whole test has to be repeated. As it has been already mentioned, those tests are complex in terms of facilities and preparations. The data acquisition process has to be carried out with the exceptional care and precision because the acceleration measurements are bases of the analysis of a car's behavior – see [4]. Therefore, crash tests are time-consuming and expensive. Not only a car is destroyed but one needs to be well prepared to destroy it properly. For that reason, it is justified to establish mathematical models of a vehicle collision. Their results could be used instead of the real experiment's responses and whole simulation process should be possible to perform on a typical PC. That is why models are perfect addition to the real crash tests – they simply could decrease their number and help to save the money.

### 2.1. Finite element method (FEM)

In the last ten years, emphasis on the use of analytical tools in design and crash performance has increased as a result of the rising cost of building prototypes and the shortening of product development cycles. Currently, lumped parameter modeling (LPM) and finite element method (FEM) are the most popular analytical tools in modeling the crash performance of an automobile [5-8]. Since the early 60s, the finite element method (FEM) has been used extensively for linear stress, deflection and vibration analysis. However, its use in crashworthiness analysis was very limited until a few years ago [9-11]. The availability of general purpose crash simulation codes like DYNA3D and PAMCRASH, an increased understanding of the plasticity behavior of sheet metal, and increased availability of the computer resources have increased the use of finite element technique in crash simulation during the last few years [12-14]. The major advantage of a FEM model is its capability to represent geometrical and material details of the structure. The major disadvantage of FE method is its cost and the fact that it is time-consuming. To obtain good correlation of a FEM simulation with test measurements, extensive representation of the major mechanisms in the crash event is required. This increases costs and the time required for modeling and analysis. When it comes to determining crush stiffness coefficients, in [15], it is presented a method which employs CRASH3 computer program. Vehicle structure was modeled as a homogeneous body and then the comparative analysis of the crash responses of vehicles tested in both: full-overlap and partial-overlap collisions were done. Even in the domain of FEM analysis which could be considered as the most robust and authoritative tool in vehicle crash simulation, there are continuously being done upgrades and researchers tend to simplify the models as much as possible. In [16], a Bogie instead of a real car was modeled in software and its behavior was compared to the real experiment's results. In [17], the multibody occupant model was constructed and its response for the crash pulse was compared with the full-scale FE model (LS-DYNA3D), proving that such a simplification is justified. [18-20] illustrate how the complicated, complete mesh model of a car can be further decomposed into less complex arrangements. Solutions used by them are as follows – accurate modeling of just an occupant, seat belt and airbag while representing the front-end car structure as a spring-beam element, designing particular car components so that they satisfy the prescribed strain/stress constraints or compensating nonlinearities in FE model by using the plastic hinges and nonlinear springs in the modal model. [21] presents a feasibility study of using numerical optimization methods to design structural components for crash. The presented procedure required several computer programs, which included parametric modeling (Pro/ENGINEER), automatic mesh generation (PDA PATRAN3), nonlinear finite element analysis (RADIOSS), and optimization programs. Both single and multiple objective formulations were used for numerical optimization, which resulted in better designs. It was found that crash optimization was feasible but costly and that finite element mesh quality was essential for successful crash analysis and optimization. [22] describes in detail a procedure for rapid simulation and design of the frame of an automotive structure. They developed a simplified program, called *V-CRUSH*, for rapid simulation of the structure. The program used special collapsible 3D thinwall beam elements and was used to design full front-end frame for a light truck. The frame was divided into several substructures that were designed and tested. Experiments were also performed on the structures. Correlation between the experimental and simulation results was very good. Above brief overview of the literature has been done according to [23].

FEM is suitable not only for creation and simulation of a 3D car model but it has a strong potential in safety barrier investigation as well. ANSYS and LSDYNA-3D software has been employed in [24] to perform realistic and predictive virtual crash simulations for analyzing the large-deformation dynamic responses of elastic or inelastic structures using implicit as well as explicit time integration schemes. Simulation and testing have shown marked improvements compared to the current generation of energy absorbing barriers (EABs). The analysis consists of a crash deformation profile, acceleration records at different locations, and energy absorptions by different components. A method which joins together FEM and ANN (artificial neural networks) is described in [25]. An accident without tire marks can be reconstructed by such approach, making it possible to determine the impact velocity. Thanks to the neural network, the relation between the initial crash parameter and the deformation in particular points is mapped correctly, therefore the number of FEM simulation cycles is reduced. The results of this procedure coincided with a typical traffic accident analysis.

### 2.2. Lumped parameter modeling (LPM)

The use of lumped parameter modeling in crashworthiness began in the aerospace industry and was gradually extended to the auto industry. The first successful lumped parameter model for the frontal crash of an automobile was developed in [26]. From then on, this technique was extensively used throughout the auto industry for various car models. In a typical lumped parameter model used for a frontal crash, the vehicle can be represented as a combination of masses, springs and dampers. The dynamic relationships among the lumped parameters are established using Newton's laws of motion and then the set of differential equations is solved using numerical integration techniques. The major advantage of this technique is the simplicity of modeling and the low demand on computer resources. The biggest challenge in this method, is obtaining the values for the lumped parameters, e.g., stiffness, and damping. In [27-29], basic mathematical models are proposed to represent a collision together with their analysis according to [30]. [31] describes Ford's Energy Management System that used CRUSH (Crash Reconstruction Using Static History) lumped mass modeling capability. In that system, the energy absorbing (EA) structural components were represented by nonlinear springs. Force-displacement characteristics of the EAs were obtained through static crush tests. Those were inputted directly to the program. Using the system, barrier loads and passenger compartment loads were calculated and compared with the test results in a frontal crash.

### 2.3. Crash pulse approximation

[32] and [33] provide brief overview of different crash modes. Since models' formulation is based on the crash pulse analysis, it is of great importance to approximate the measured car acceleration correctly. In [34], there are presented basic mathematical functions (like sine, haversine or square wave pulse) used to simplify the crash acceleration graph. Results obtained from this research show that one can follow those easier characteristics and still get satisfactory accuracy of the crash pulse analysis. Another manner of expressing the measured acceleration signal as an

approximation is wavelet application. Haar wavelets have been employed in [35] to create the equivalent plot of the crash pulse. Results have confirmed that this method allows us to split the signal into a couple of Haar wavelets components and then to combine them together in order to get the characteristic which resembles the real recorded acceleration very well.

### 2.4. Energy approach and occupant modeling

[36-39] talk over commonly used ways of describing a collision - e.g., investigation of tire marks or the crash energy approach. As it has been already stated, a car's occupant is one of the main concerns of car safety research programs. It is extremely important to assess what factors have influence on the crash severity of an occupant. As in the case of a vehicle crash simulation, also here we can distinguish two main ways of examining occupant behavior during an impact. [40] focuses on finding the relationships between the car's damage and occupant injuries. On the other hand, [41] employs FEM software to closely study the crash severity of particular body parts. An interesting research has been done in [42]. They have examined what the influence of occupants' body mass index (BMI) is on their injuries resulting from a collision. Their study was based on the data obtained from 10941 drivers who were aged 18 years or older involved in frontal collision crashes. Sex-specific logistic regression models were developed to analyze the associations between injury and the presence of driver obesity. In order to confirm the findings from real-world data, computer models of obese subjects were constructed and crash simulations were performed. According to real-world data, obese men had a substantially higher risk of injury, especially serious injury, to the upper body regions including head, face, thorax, and spine than normal weight men. In the high-BMI range, men were more likely to be seriously injured than were women for all body regions except the extremities and abdominal region. The findings from the computer simulation were generally consistent with the real-world results in the present study – software utilized was MADYMO (Mathematical Dynamic Models).

Currently, there are only a few researches concerning modeling interactions between a car and a pregnant woman. One such an example is shown in [43]. The aim of this study is to develop a numerical model of the whole human body, in order to investigate car crash scenarios and to evaluate alternative security systems to improve protection of both: the woman and the fetus. A 3D reconstruction based on a set of MRI images led us to a good spatial representation of the pregnant woman in driving position. The anatomical precision will make progress possible in the field of traumatology of the pregnant woman. It is well known fact that an occupant experience large accelerations during a collision. This is in particular dangerous for the head and neck, since those body parts are especially susceptible to injury. In [44], a detailed 3D head-neck FE model was developed and validated under static and dynamic conditions and was used to characterize the head response under various simulated vehicular impact conditions. The FE model has reasonably predicted the effects of impact direction in the primary sagittal and frontal segmental motion and curvatures of the head-neck complex under various impact conditions. On the other hand, a modal analysis of a human neck in vivo has been done in [45]. An experimental and theoretical modal analysis of the human head-neck system under frontal head impact, simulating low speed rear-end impact motion, has been successfully constructed. Based on those new validation parameters, they have compared the human and crash test dummy frequency response functions and evaluated their biofidelity.

Another key issue is occupant protection in rollover crashes. Although rollover crashes account for a small percentage of all crashes, because of their high proportion of fatal injuries, it is important to focus on preventing serious injury to occupants in this type of collision. [40] shows a study concerning this subject. The purpose of this research was to determine occupant, vehicle, and crash characteristics predicting serious injury during rollover crashes. They compared occupants with serious or greater severity injuries with occupants without injury or with only minor or moderate injury. An identification of predictive variables for serious injury associated with rollovers has been made by the means of, e.g., logistic regression. A detailed analysis of a rollover crash event is presented in [46]. Occupant protection using safety restraint systems is a major step in passenger safety. Belt tensioners could protect passengers from ejection while various airbags would protect the passenger from serious injuries. In order to trigger such safety restraint systems, a dynamic stability criterion have to be formulated, which reliably predict and detect vehicle rollover situations. In this paper, a couple of various vehicle rollover models are evaluated. Although the occupant safety is of high importance, one cannot neglect the need of designing vehicles which in case of collision with pedestrian will cause their less possible injury. The reconstruction methodology of this type of accidents has been elaborated in [47]. To identify the pre-impact conditions of pedestrian and vehicle, they have applied the appropriate optimization algorithms (in particular, the genetic algorithm performed that operation in the shortest time). Their application to the real-world accidents has been tested – results obtained proved that this method may improve the procedure of determination of pre-impact conditions in vehicle-to-pedestrian collision.

### 2.5. Neural networks, fuzzy logic and linear parametrically varying (LPV) models

Vehicle crash investigation is an area of up-to-date technologies application. [48-50] discuss usefulness of such developments as neural networks or fuzzy logic in the field of modeling of crash events. Those two intelligent technologies have extremely high potential for creation of vehicle collision dynamic models and their parameters establishment – e.g., in [51], values of spring stiffnesses and damping coefficients for lumped parameter models (LPM) were determined by the use of radial basis artificial neural network (RBFN) and the responses generated by such models were compared with the ones obtained via analytical solutions. Results confirmed usefulness of this method – correlation with the reference experimental car’s behavior was good. In [52], artificial neural networks (ANN) were used to predict the speed on highways. Training of the network was based on the data gathered by the radar gun and inputs consisted of geometric parameters (e.g., length of curve) and traffic parameters as well (e.g., annual daily traffic). Study presented there proved that the network can be used for that predictive application. On the other hand, ANN can be applied to predict injury severity of an occupant by less direct measurements – using statistical data. [53] presents a method for crash severity assessment based on the number of such inputs, like, e.g., driver age, alcohol use, seat belt use, vehicle type, time of the crash, light condition or weather condition. The output obtained from the network was simply crash severity classified into three levels: no injury, minor injury, severe injury. Results confirmed that ANN is a powerful tool in the area of crashworthiness analysis. Above overview of the neural networks application for the vehicle crash modeling has been done according to [54]. What is more, neural networks are also extremely efficient in modeling nonlinear dynamic problems. Advanced recurrent artificial neural networks have been used for this application in [55]. Their task was to predict the acceleration curves of the impacting objects. To illustrate their usability, each problem which they were used for was firstly solved numerically for several impact scenarios and those results were used as the training datasets for the networks. After the teaching and testing stage, it was stated that they are capable to store nonlinear characteristics of the impacting objects, i.e., to model nonlinear multi-body impacts. Fuzzy logic together with neural networks and image processing has been employed by [56] to estimate the total deformation energy released during a collision. A vision system has been developed to record a crash event and determine relevant edges and corners of a car undergoing the deformation. Then suitable algorithms (expert system, neural network) compare the deformation to the original 3D model of a car and make it possible to estimate the energy equivalent speed and absorbed energy as well. One of the paramount challenges in increasing occupant's safety is the development of an active, real time seat belt controller [57]. This is due to the fact that at the moment, there are no appropriate sensors which could monitor the desired occupant's body parts. Authors proposed a virtual experiment in which the standard FE dummy model has been simplified and the developed control algorithm was changing the belt tension according to the car's and occupant's decelerations during a collision. Thanks to the sensitivity analysis, the dummy model consisted of 11 rigid bodies and 14 kinematic joints instead of 37 rigid bodies and 37 kinematic joints (full FE model) and still maintained the fidelity. Hence the calculated occupant injury criteria were almost the same for both: full MADYMO model and the simplified one. In the most up-to-date scope of research concerning crashworthiness, it is to define a dynamic vehicle crash model which parameters will be changing according to the changeable input (e.g., initial impact velocity). One of such trials is presented in [58] – a nonlinear occupant model is established and scheduling variable is defined to formulate LPV (linear parametrically varying) model. Responses of this model for different values of scheduling variable proved its correlation with LTI (linear time invariant) models as long as the mass of the occupant is constant (the same dummy is being used). In addition to this work, in [59], one can find a complete derivation of vehicle collision mathematical models composed of springs, dampers and masses with piecewise nonlinear characteristics of springs and dampers. A vehicle is modeled as so-called fixed and extendable front-end structures which provide different behavior of the whole model and therefore increase its fidelity. Simulation results showed that offset collisions produced larger car's deformation and less occupant's deceleration than full frontal collisions.

An innovative approach has been adapted in [60]. They have developed a vehicle simulator in which a signalized intersection has been replicated. It has been done to verify if the traffic risk patterns in the driving simulator were similar to the real intersection data. The results showed that both speed data: real and simulated, follow normal distributions and have equal means for each intersection. What is more, surrogate safety measures from the simulator were used. It has been found that subjects at the right-turn lane with the high rear-end crash history record exhibit more risky behavior than the ones at the right-turn lane with the low rear-end crash history record. An application of support vector machine (SVM) models to predict vehicle crashes has been done in [61]. The study showed that SVM models predict crash data more effectively and accurately than traditional negative binomial (NB) models. In addition, SVM models do not over-fit the data and offer similar, if not better, performance than Back Propagation Neural Network (BPNN) models.

## 2.6. On-board safety devices

When it comes to crashworthiness, vehicle crash modeling is obviously not the only issue which improves occupant safety. There is a number of Advanced Driver Assistance Systems (ADASs), e.g., LKA (Lane Keeping Assistant) or ACC (Adaptive Cruise Control) which are on-board elements of vehicles and which support drivers by providing them with warnings or, even in some cases, taking the action, e.g., Brake Assist (BA) system which automatically stops a car when it is approaching an obstacle (another vehicle or pedestrian). To be able to efficiently test those various ADASs, vehicle hardware-in-the-loop (VeHIL) experimental setup has been applied in [62]. Another key concepts are so-called vehicle Collision Warning and Collision Avoidance (CW/CA). [63] describes a tracking algorithm which interchanges the commonly applied joint probabilistic data association (JPDA) algorithm used for solving the ambiguity of multi-target data association problem. The method described is helpful in tracking, e.g., another road users and predicting their paths to avoid possible collision. The similar research has been done in [64] - they have developed a control system which maintains a desired distance from the preceding vehicle as well as is capable to avoid the collision with vulnerable road users (VRUs), like cyclists or motorcyclists. Work done by [65] talks over almost the same problem - i.e., collision avoidance and autonomous driving. They use a full-scale test vehicle with a variety of sensors (like video sensing or laser rangefinders) and evaluate its performance in an urban environment. Results have proved that such a car can detect, track or avoid other cars, pedestrians, curbs or roads.

## 2.7. Vehicle simulation and crashworthiness patents

Patent [66] contains a preliminary description of a way to minimize vehicle occupant injury in a collision. A method, computer program product and an apparatus for minimizing occupant injury by optimizing occupant restraint properties and/or actions and other safety measures in real time, during pre-crash and crash phases is developed. The safety or restraint system (and related method and computer program product) may use three catalogs and a database linking these catalogs. They may include a catalog of possible occupant states, a catalog of possible collision scenarios, and a catalog of potential restraint control laws. The database may provide an assessment of injury outcome for each possible combination of occupant state, collision scenario, and restraint control law. In addition to the catalogs, the method may require four computational components: an occupant identifier, a collision identifier, a restraint law optimizer, and a restraint controller, all of which are specific to the vehicle in which the system is installed. A useful invention is shown in [67]. The purpose of this tool is to create a simulation-based environment that allows a product-based restraint engineer, with a modest understanding of complex software programs, to use complex math models, i.e., MADYMO, to solve product-based issues. The MADYMO simulation software, which is widely available, currently requires an experienced simulation modeling expert to model a complex simulation such as a vehicle crash modeling and then interpret the results. As with other modeling software, the MADYMO software format and its nature are complicated and require training and extensive use for a current user to become effective. This invention provides an interface for the most basic components of simulation software such that a product engineer would also be able to utilize and benefit from the results of simulation. By following the abstract of [68], the main purpose of this new design is “creation of a dynamic model of the dummy mounted on a seat of a vehicle and a dynamic model of a restraint body, which binds the dummy on the seat and includes at least a seat belt with a force limiter and a knee bolster. Subsequently, they are mathematized by using equations of motion and spring characteristics of the dynamic model identified by a dummy thread test and a knee bolster static compression test are substituted into the equations of motion and a forcible deceleration waveform is inputted to the vehicle to calculate actions of the dummy, especially, its breast at the time of a vehicle collision. Thus deceleration characteristics and movement amount of breast of the occupants at the time of the collision are predicted”. A similar objective as the one of [68] is specified in [69]. Its aim is “to provide a technology for clarifying the relation between an occupant deceleration at the head-on collision and a ride-down effect, and simulating what kind of car body front part rigidity is required for occupant protection based on the ride-down effect. This simulation apparatus comprises a car body front part characteristic for setting a buckling characteristic of the car body front part at the collision in a dynamic model as a nonlinear spring; a seat belt characteristic for setting a seat belt as a linear spring or a nonlinear spring; an occupant deceleration operation part which is also responsible for changing the characteristic of the nonlinear spring showing the buckling characteristic of the car body front part as a parameter; a ride-down effect index value; and an output part for outputting set pointer information of the car body front part rigidity based on the ride-down effect from the minimum value of the occupant deceleration".

## 3. Safety Barriers Design

By following the information provided in [70], an early type of known barrier consists of a rail or the like which separates for example the two roadways of the highway, thus forming a practically uninterrupted rigid element. This type of barrier has the serious disadvantage in the case of a violent shock due to a vehicle striking the said safety rail, and under certain conditions of approach angle of the vehicle to the said rail, that the vehicle is sent back on the roadway from which it comes, the trajectory followed by the vehicle being practically the same as for a reflection, the safety rail being the reflecting surface. It is quite obvious that in this case, the vehicle thus projected back on the roadway constitutes a very serious risk of accident for the other vehicles which subsequently pass.

### 3.1. Guard-rail type of the safety barrier

An early interesting idea has been elaborated in [70]. It completely describes a safety barrier which was used for motorways as well as its manufacturing procedure and which significantly helped to reduce the effect of the vehicle going back to the roadway after the rebound from a barrier. Gradual braking of the vehicle which strikes against the safety barrier is permitted because the barrier does not have the disadvantage of the safety rails which are fixed in the ground and which are particularly rigid, which have the effect of throwing the vehicle back on the roadway, and which increase the damage of the vehicle concerned since the vehicle absorbs almost the whole of the energy due to the shock. Another characteristic feature of the modules resides in the actual composition of the material which constitutes them. Each module must be made of a material capable of disintegrating or bursting under the effect of an internal tension on the modules, this tension being due to the linear element, which is stretched during a shock which follows the impact of a vehicle against the safety barrier. In the case where one of the constituents is rubber, it is particularly advantageous to use rubber obtained from used pneumatic tyres. This has the advantage on the one hand of disposing of used pneumatic tyres which are difficult to destroy and therefore constitute a pollution, and on the other hand of producing a safety barrier at reduced cost.

A particular problem exists where a road bridge crosses another road or the track of a railway. In these circumstances, it becomes even more desirable to prevent a vehicle passing through or over a crash barrier. Usually, vehicle crash barriers of metal construction comprise one or more rails extending parallel with the road surface and supported, on their side away from the road, on vertical posts firmly anchored on top of a wall or in the ground. It is desirable that the rails do not distort upon impact sufficiently to create a “pocket” between one support post and the next so that the vehicle concerned strikes that next post head on. A solution to that has been presented in [71]. In the invention, there is provided a vehicle crash barrier of metal construction and comprising at least one rail, extending generally parallel with a road surface, and mounted on spaced-apart generally vertical supports located on the side of the rail remote from the road characterized in that the rail is hollow and is divided into at least two closed compartments by a web extending between the supports and a part of the surface of the rail remote there from so as to transmit an impact load on the surface directly to the supports. A sight barrier in the form of sheet-like cladding may extend from the rail to a location generally level with the base of the supports. The upper end of the sight barrier is preferably located inwardly of the outermost part of the rail or rails and the lower end of the sight barrier preferably has a part lying sufficiently close to fastenings for the supports as to prevent access thereto and includes a section welded or riveted in place so that disassembly of the crash barrier cannot be carried out quickly and simply – this is of a great importance because it is desirable that such crash barriers should not be capable of easy disassembly as well as it is also advisable, particularly on bridges over railway tracks that a sight barrier is provided to discourage pedestrians from straying on to the bridge.

According to [72], one of the types of safety barriers is so-called "guard-rail" type. They comprise a horizontal, longitudinal member, or stringer, which may consist of a strip of corrugated sheet iron mounted on uprights or posts. These safety barriers present quite safe and predictable results in the event of impact of a vehicle at angles of trajectory which are not too wide. However, for reasons of convenient access to the roadway or for other reasons, it is unthinkable to build a continuous guard-rail all along a road between the points of start and arrival of the road itself. Consequently, the guard-rail will inevitably be built in more or less long stretches that have end portions. Whilst statistics have shown a rather satisfactory behavior of the guard-rail in the case of impact against an intermediate portion thereof, they have also shown an increasing incidence of impact of vehicles against the end parts, or terminals, of the barrier, having consequences that are almost always serious or tragic because the stiffness of the barrier is high in its longitudinal direction, and because of the very high kinetic energy, due to the whole speed of the vehicle. In addition, the height of the ends may be dangerous. The invention discussed in [72] talks over the new terminal which comprises a longitudinally extended strip made up of a number of barrier segments provided with elongated slots in which screws for joining the segments together are screwed at a calibrated tightening torque; it further comprises a headpiece of the terminal applied on an outermost segment; each segment is mounted on an upright or post, which is made up of two half-posts, the bottom one of which is driven into the ground for a substantial portion of its height, and the top one is mounted on the bottom one by means of a predictably breakable transverse pin, i.e., a pin having a preset breaking strength, and preferably presenting a groove which engages with a peg of the bottom half-post. According to a further characteristic of the invention, at least between the bottom half-post, which supports the end segment and/or the headpiece, and the adjacent top half-post a tie rod is mounted, which comprises in its length a weakened section with a predictable or preset breaking strength. One of the advantages of such a solution is its simple replaceability. After impact, the terminal may be restored relatively easily by replacing the barrier elements that have been deformed, the tie-rod element, the calibrated pins, and by restoring the top half-posts on them.

### 3.2. Vehicle crash barriers

One of the recent developments in the area of crash barriers design is presented in [73]. It is a pivoting crash barrier for arresting an impacting vehicle without causing excessive injury to the driver. It has an easily replaceable expendable gate which houses multiple plastically deformable cables mounted within for absorbing the energy of the impacting vehicle. The crash barrier design causes the cables to deform as a unit, rather than separately. It is pivotally supported on a horizontal shaft by an operator unit positioned on a first side of a roadway. An engagement stanchion engageable by the outer tip of the lowered gate supports the lowered gate on the second, opposed side of the roadway. The upper sections of both crash barrier stanchions consist of operator heads that can pivot about the vertical axes of their respective mounting posts after the shearing of restraining shear pins whenever a vehicle impact occurs. This swiveling reduces the tendency for the components of the crash barrier other than the gate to sustain significant damage during vehicle impacts. The crash barrier gate further has a latch on the engagement stanchion side that prevents inadvertent gate unlatching from uplift forces to the gate and a simplified method of balancing the crash barrier with counterweights.

A crash barrier is a device that prevents an unauthorised vehicle from driving through a vehicle entrance. Crash barriers are commonly used where there is a threat from car bombs and as such are located some distance (typically 30m to 50m) away from the highly occupied building being protected. One of such barriers was developed in [74]. Since it can be utilized for the protection purposes (e.g., against terrorist attacks), it is of key importance to simplify its assembly and mounting procedure to make it easy and quick to install. A typical, temporary, quick and unrated crash barrier is a cable barrier and consists of two reinforced concrete blocks which each have a loop of reinforcement protruding from the surface (used as a lifting lug). A cable barrier of this type can be varied in width simply by undoing the friction U-grips at one end, reducing the distance between the loops located at either end of the steel cable and moving the concrete blocks closer together. The main disadvantage with a cable barrier of this type is that the friction grips are expected to fail before the cable and at a load that is not possible to accurately determine. To compensate those disadvantages, this invention provides an inexpensive rated cable type crash barrier that is easily stored and whose width can be varied.

### 3.3. Mobile safety barriers

The use of mobile barriers in lane dividing sections in order to guarantee opening for the passage of vehicles is known. The information included in [75] indicates that these barriers can consist of sections sliding on supports that can be fixed in appropriate housings in the ground. The overall longitudinal extension of the sliding sections can be up to 16 metres, with the supports, aligned as much as possible, positioned at a distance of around 1.5 metres apart. Their opening foresees the sliding of the sections to open a central gap followed by the temporary removal of around 20 supports from their respective housings and their loading on a motor vehicle for transport to a place relatively far away from the mobile barrier so that road maintenance work can be carried out in the vicinity of the barrier. To date, mobile barriers consisting of cables stretched from one end to another of a gap and sustained by appropriate supports are also used. There must be at least three cables and the tension must be adequate to counter any impact and ensure safety. To open the gap, each cable must be loosened so that it can be released from the supports. The cables must then be rolled up into reels with an overall weight that exceeds 100 kg and loaded, by means of a crane, onto a motor vehicle which carries them away from the opened gap. One drawback is represented by the fact that the opening of each of the previously described mobile barriers requires the closure of at least one road lane adjacent to the barrier itself. Invention described in [75] aims to provide an automatically retractable road safety barrier that can be fitted to any gap requiring the minimum amount of space due solely to its actual presence in the working position. This was achieved by: a framework erected in working position that can be retracted to a rest position, consisting of reciprocally hinged elements; a chamber, cut out from below a road surface, to house the said framework in the rest position; means of support and of temporary blocking of the framework in the erect or working position; means for the movement of the said framework from the working position to the rest position and vice versa; a source of motion kinematically connected to said means of movement and equipped with appropriate means of control.

### 3.4. Design improvements

To make the existing safety barriers safer for the vehicles occupants, it is not always needed to redesign them completely, but sometimes, it is just sufficient to apply a small solution which can significantly improve the performance of a barrier. An example of such a methodology has been developed in [76]. The spacer designed has a fixation part for fixing it with a handrail and a plate for fixing it with a post. The plate is mounted between two fixed wings and a vertical folding absorbs effect of shock on the handrail. The plate has a split defining upper and lower fixing zones. It permits a rotation of the spacer with respect to the post under the effect of shock. The results have confirmed that application of such an energy absorber can successfully decrease the impact severity for car passengers, since vehicle’s kinetic energy is dissipated in a higher degree than for the collision with a roadside safety barrier without a spacer.

### 3.5. Safety barriers performance evaluation

When it comes to performance evaluation of safety barriers, [77] presents an experimental testing method which helps to assess whether they conform to the safety norms and standards. It shows a test methodology and a first-of-a-kind evaluation of the crash performance of strong post W-Beam barrier that has sustained minor damage. Pendulum tests were conducted on a two-post section of strong post W-Beam barrier sections with five different types of damage. Based on the experiment's results, it was concluded which type of collision causes the most severe damage to the barrier. In [78], representative nonlinear finite element models of the bolted test coupons have been constructed. When compared to the laboratory results the initial stiffness, maximum force and displacement of the bolted connections are similar to the finite element model predictions. Current investigations have moved onto strain rates comparable to those observed in actual vehicle crash tests. Explicit dynamic finite element (FE) models have been constructed and validated, using experimental data produced using a series of high strain rate laboratory tests for a number of bolt configurations.

It is also of key importance to verify the behavior of a connection joint in a safety barrier during an impact. This has been done in [79]. The results showed that there is significant deformation of the barrier material surrounding the slotted holes in the safety barrier beam of tested components. The mechanical fasteners faired slightly better but they sustained some damage to the threaded portion of the bolts that were in contact with the barrier section. The results show changes in the safety barrier beam material microstructure in the area of the slotted holes where the mechanical fasteners were subjected to shear loads due to tension forces in the safety barrier beam.

In [80], concrete specimens containing shredded waste tire chips were evaluated using laboratory and field tests. For the dynamic tests, on the other hand, 6 New Jersey shaped concrete barriers were constructed using the identical mix designs used in the static tests. Results of the study showed that tire addition reduced the compression strength and modulus of elasticity of specimens. Dynamic impact tests show that increase in tire percentage has significant effect on the reduction in vehicle peak deceleration forces and thus impact severity. Based on the static and dynamic test results, it can be concluded that specimens with 20 to 40% aggregate replacement gives the best impact performances without significant reduction in concrete strength. Concrete barriers containing larger amounts of tire can be used at highway applications where concrete fracture is desired for energy dissipation, such as crash cushion and end treatment applications. In [81], by making extensive use of nonlinear dynamic finite element impact simulation, several cycles of concept refinement were carried out using simulation rather than expensive full scale crash testing. Issues such as ensuring stable vehicle redirection during impact, properly accounting for frictional effects (and associated energy dissipation), and monitoring system energy parameters are discussed together with corresponding example simulations. Results obtained from full scale crash testing of the barrier validate the simulation methodology and demonstrate successful barrier performance.

[82] describes the computational analysis and experimental crash tests of a new road safety barrier. The purpose of that research was to develop and evaluate a full-scale computational model of the road safety barrier for use in crash simulations and to further compare the computational results with real crash test data. The impact severity and stiffness of the new design have been evaluated with the dynamic nonlinear elastoplastic analysis of the 3D road safety barrier within the framework of the finite element method with LS-DYNA code. Comparison of computational and experimental results proved the correctness of the computational model. The tests have also shown that the new safety barrier assures controllable crash energy absorption which in turn increases the safety of vehicle occupants.

### 3.6. Acoustic performance of safety barriers and their interactions with soil

Median barrier is used to prevent cross-median crashes on divided highways. Although it is well documented that crash frequencies increase after installing median barrier, little is known about median barrier crash severity outcomes. [83] estimates a nested logit model of median barrier crash severity using 5 years of data from rural divided highways in North Carolina. Vehicle, driver, roadway, and median cross-section design data were factors considered in the model. A unique aspect of the data used to estimate the model was the availability of median barrier placement and median cross-slope data, two elements not commonly included in roadway inventory data files. The estimation results indicate that collisions with a cable median barrier increase the probability of less-severe crash outcomes relative to collisions with a concrete or guardrail median barrier. Increasing the median barrier offset was associated with a lower probability of severe crash outcomes.

Although vehicle dynamics simulations have been used in vehicle design and crash reconstruction for long time, their use for highway design is rare. [84] investigates the safety of highway medians through iterative simulations of off-road median encroachments. The commercially available software CarSim was used to simulate over one hundred thousand encroachments, representing the entire passenger vehicle fleet and a wide range of encroachment angles, departure speeds, steering inputs, and braking inputs. Each individual simulation output was then weighted using data from previous studies to reflect the probability of each specific accident scenario occurring in a real-life median encroachment. Results of this analysis illustrate the relative influence of median cross-section geometry on the resulting accident outcomes. The simulations indicate that the overall safety of a highway median depends on the occurrence of both vehicle rollover and median crossover events, and the cross-section shape, slope, and width are all shown to greatly affect each of these incidents. An evaluation of the simulation results was conducted with vehicle trajectories from previous experimental crash tests. Further assessment of the aggregate simulation results to actual crash data was achieved through comparison with several databases of crash statistics. Both efforts showed a strong agreement between the simulations and the real-life crash data.

The primary objective of the work described in [85] was to examine the roadside performance of a multiple edge profile. The profile consists of vertical side panels 0.5m deep which are attached to the posts of an existing barrier without increasing its overall height. The profile was tested at three sites adjacent to the motorway. It was concluded that the screening performance of simple barriers 2 and 3m high located adjacent to a motorway can be significantly improved by the RTB profile by an amount depending on site conditions.

The desired safety behavior is ensured not only by the guardrail structure itself, but also by the interaction between the gravel and the guardrail post. The interaction of gravel with a Sigma-post of a standard Swedish guardrail was studied in experiments and numerical analysis in [86]. The aim of that work was to measure the strength of the single post embedded in gravel and use the data to validate a computer model for the investigation of the soil-post interaction. The numerical results showed that the LS-DYNA soil and concrete model and the Cowper-Symonds steel model effectively captured the soil-post interaction since the calculated strength of the post agreed with the corridors of the test data.

### 3.7. Impact severity assessment

The occupant impact velocity (OIV) and acceleration severity index (ASI) are competing measures of crash severity used to assess occupant injury risk in full-scale crash tests involving roadside safety hardware, e.g., guardrail. Delta-V, or the maximum change in vehicle velocity, is the traditional metric of crash severity for real-world crashes. [87] compares the ability of the OIV, ASI, and delta-V to discriminate between serious and nonserious occupant injury in real-world frontal collisions. Vehicle kinematics data from event data recorders (EDRs) were matched with detailed occupant injury information for 180 real-world crashes. Cumulative probability of injury risk curves were generated using binary logistic regression for belted and unbelted data subsets. By comparing the available fit statistics and performing a separate ROC curve analysis, the more computationally intensive OIV and ASI were found to offer no significant predictive advantage over the simpler delta-V.

The study [88] describes a 3D computer simulation of the kinematics impact of motorcycle and dummy rider with W-Beam guardrail inclined at angles 45 and 90° to the initial direction of travel. The simulation is based on the test procedure recommended by ISO 13232 on the configurations for motorcycle-car impact. The focus of this study is on the rider’s kinematics and acceleration vs. time history. Multibody model of motorcycle and finite element model of guardrail were developed in commercially available software. A research which also investigates motorcyclists' injuries is [89]. It reports on the findings of a retrospective case series study of fatal motorcyclist-roadside barrier collisions. Cases were retrieved from the National Coroners Information System (NCIS), the coronial case files of Australian jurisdictions, and the Crash Analysis System (CAS) of the New Zealand Transport Agency. Seventy seven (77) motorcycle fatalities involving a roadside barrier in Australia and New Zealand were examined. The fatalities usually involved a single vehicle crash and young men. The roadside barriers predominantly involved were steel W-beams, typically on a bend in the horizontal alignment of the road. A majority of fatalities occurred on a weekend, during daylight hours, on clear days with dry road surface conditions indicating predominantly recreational riding. Speeding and driving with a blood alcohol level higher than the legal limit contributed to a significant number of these fatalities.

## 4. Conclusions

This brief survey aimed at presenting the current trends and inventions in the area of crashworthiness. Increasing safety of not only cars occupants but also of all the road users is of paramount importance in the world where people's mobility and ease of traveling is more and more common concept. Thanks to the rapid growth of computational power of computers, it is possible to perform complicated vehicle collision simulations without the need of carrying out a full scale crash test. However, time-consuming FEM virtual experimentation is not considered to be the only methodology utilized for creating vehicle collision models. People tend to find an efficient and reliable way to identify the parameters of mathematical models of different crash scenarios. Such systems should produce results which are similar to the real cars behavior during an impact. What is more, the coefficients of those models should be changeable so that one model can be capable of representing a couple of collisions. One needs to remember that the outcome of this approach will not be as accurate as a FEM simulation. However, it will help to assess the overall structural and geometrical features of a vehicle's prototype. Due to the advances in manufacturing technology and electronics, the ADAS (Advanced Driver Assistance Systems) become more and more popular. At this time, every produced car is equipped with some of those devices and it is impossible to find a new vehicle without, e.g., ABS. The number of lives which were saved thanks to those systems is difficult to assess, although one can try to recall how many times they helped us in our own driving. Apart from the developments which make cars safer, the improvement of road infrastructure itself makes the difference to decreasing number of car accidents. Currently, the safety barriers which are going to appear on the roads have to be not only as safe as possible (e.g., preventing a vehicle from leaving a roadway or having a high crush energy absorption rate), but also be easy to maintain, install or replace. Stiffness is not the only factor which makes a safety barrier appropriate to be used – it should also protect a vehicle from sending it back to the roadway or be designed in such a way that the motorcyclists' injuries are minimized if they happen to hit it. The last key issue is the capability of safety barriers to protect vulnerable objects or – to be more precise – to prevent suspicious vehicles from entering a safety zone. We clearly see that the safety barriers can be successfully used for the civil as well as for the military applications.

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