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Frontal crashworthiness characterisation of a vehicle segment using curve comparison metrics

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ABSTRACT

The objective of this work is to propose a methodology for the characterization of the collision behaviour and crashworthiness of a segment of vehicles, by selecting the vehicle that best represents that group. It would be useful in the development of deformable barriers, to be used in crash tests intended to study vehicle compatibility, as well as for the definition of the representative standard pulses used in numerical simulations or component testing.

The characterisation and selection of representative vehicles is based on the objective comparison of the occupant compartment acceleration and barrier force pulses, obtained during crash tests, by using appropriate comparison metrics. This method is complemented with another one, based exclusively on the comparison of a few characteristic parameters of crash behaviour obtained from the previous curves.

The method has been applied to different vehicle groups, using test data from a sample of vehicles. During this application, the performance of several metrics usually employed in the validation of simulation models have been analysed, and the most efficient ones have been selected for the task. The methodology finally defined is useful for vehicle segment characterization, taken into account aspects of crash behaviour related to the shape of the curves, difficult to represent by simple numerical parameters, and it may be tuned in future works when applied to larger and different samples.

1. Introduction

Thanks to the efforts made by vehicle manufacturers, public authorities, consumer organisations and research institutions, the safety of vehicles and roads has increased significantly in the last decades. Looking at vehicles, they are equipped with both active and passive safety systems, which are increasingly more sophisticated and efficient. However, accidents are still unavoidable and, in some cases, the consequences result in serious injuries and deaths. Therefore, safety system research and improvement should not cease.

Crash tests are one of the primary tools for the improvement of vehicle safety systems. Crash tests attempt to reproduce the conditions of an actual collision, and Anthropomorphic Test Devices (ATDs) are often used to study the dynamics, efforts and damage levels suffered by the occupants during the event. The use of this technique enables to improve the performance of the restrain systems, airbags and the structure of the vehicle to mitigate the injuries resulting from collisions.

Full-scale impact tests are expensive, since a whole vehicle is required, so sled tests (Hault-dubrulle et al., 2011; Beeman et al., 2012) and numerical simulation (Danelson et al., 2015; Bose et al., 2010) are usually carried out in the preliminary phases of the design of vehicle's safety systems. To do so, it is essential to know the dynamic conditions to which occupants are subjected, i.e. the pulse of acceleration of the passenger's compartment.

On the other hand, in a vehicle to vehicle collision, the occupant's injuries depend in the first instance on the way in which the forces are transmitted between the two structures, which affects in a decisive way the performance of the retention systems and other protection devices. Deformable barriers are developed to be used in impact test, reproducing the stiffness and aggressiveness of the frontal structure of a standard vehicle, that could collide with the vehicle whose crashworthiness and safety systems are to be tested. By characterising the vehicle's stiffness, the developed barrier could reproduce the same consequences in the partner vehicle than those potentially produced by the vehicle that it tries to emulate (Sánchez and Abellán, 2015).

On the other hand, deformable barriers could be also developed to represent the standard stiffness, deceleration pulse and occupant protection level of the frontal structure of a vehicle of a certain group.

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Those barriers are useful to test the aggressiveness of different vehicle designs in car to car collisions.

Each vehicle model has different characteristics and structures, even if they have similar dimensions and weights and can be considered as belonging to the same group, so their behaviour during a frontal collision may differ. If a random representative vehicle is chosen, the crashworthiness and/or aggressiveness of the sample vehicle might not be representative of the rest of the vehicles in the same segment. In that case, the safety systems and tools developed and optimised based on the characteristics of that particular vehicle, could lose effectiveness or even be invalid for most vehicles of the same segment in actual collisions.

In this work, a new method is developed for the crashworthiness characterisation of a group of vehicles, and for the selection of a vehicle whose behaviour during the collision is representative of its segment. The method, based on the objective comparison of the shapes of the acceleration and force curves, is applied to different groups of vehicles to evaluate the robustness of the method, and the most appropriate metrics to be used in each case. The new method presented here, is compared and complemented with another one based on the comparison of only certain characteristic parameters of crash behaviour, also obtained from the previous curves

2. Background

2.1. Crashworthiness characterisation

In the literature, some proposals can be found for characterising the frontal crashworthiness of a vehicle through certain parameters, obtained from acceleration and stiffness curves measured during crash tests. In some works, parameters as the maximum acceleration of the occupant compartment, crash pulse duration, average acceleration, change in velocity or the maximum displacement are used. Parameters derived from the stiffness curves (Nusholtz et al., 2005) as the initial stiffness, the dynamic and the static stiffness (Appel, 1996) or the energy necessary to produce a given deformation (Patel et al., 2007) are also commonly used.

And there are also studies where these parameters are used for the crashworthiness characterisation of a group of vehicles. For example, Hackney (1993) proposes to characterise the crash by the maximum deceleration, the time in which the peak deceleration is produced and the pulse duration. Sánchez Lozano (2001) points out as the most relevant parameters describing the crashworthiness of a vehicle: the shape and duration of the deceleration pulse, the mean deceleration, the peaks of the deceleration, the time for those peaks, the energy absorbed and mean acceleration until the seat-belt tensioners are triggered, the maximum and mean force levels, the maximum frontal deformation, the permanent deformation of the frontal, the change of velocity, and the total absorbed energy by the vehicle structure.

The selection of the most appropriate among these parameters depends on the purpose. When the objective is to study the vehicle occupant protection, those parameters related to the pulse of acceleration will take a greater importance. If the aim is the study of compatibility and aggressiveness towards the rest of road users, those parameters related to the force transmitted by the frontal structure and its stiffness will be more important.

When attempts are made to characterise the behaviour of a group of vehicles, using various parameters, it may not exist any vehicle whose settings are similar to the average values of the group, due to the differences between models and the heterogeneity in their response. Thus the selection of a vehicle that represents the average crashworthiness of a group becomes complicated.

Furthermore, the use of simple parameters, as the peak deceleration, doesn't take into account the pulse shape or the existence of other local maximums which have influence in occupant injuries and the performance of the safety systems (Moorhouse, 2013; Donnelly et al., 2014).

It is necessary therefore to develop a method to characterise the crashworthiness by comparing the shape of the acceleration and force pulses. In the field of the design of Anthropomorphic Test Devices (ATDs) it is a common practice to characterise the biomechanical response of Post-Morten Human Subjects (PMHS) during an impact by the normalisation of the force pulses or the force-displacement curves (Moorhouse, 2013; Donnelly et al., 2014). Using these techniques, the different curves obtained from PMHS with different characteristics, are mathematically adjusted to make them collapse to a single curve. The resultant curve defines the typical behaviour taking into account the various features of the tested subjects, and it can then be modified to adapt the response to specific characteristics: such as desired mass or dimensions. Normalised curves are often used in the definition of the target behaviour of the ATD's (Schwer, 2007).

But vehicles of the same segment vary considerably in the size and arrangement of the elements of their front and their frontal structure. Therefore, acceleration and force curves obtained in vehicle impact test show greater oscillations that produce worse results in the normalisation curve than the curves obtained from PMHS response. So these normalization techniques might not be directly applicable, and other possible tools should be explored.

2.2. Curve comparison metrics

The comparison of two curves can be performed by representing both curves and qualitatively assessing how much they match each other. This comparison "by eye" has important limitations, as it is a subjective process and very complicated to apply to curves such as those obtained in an impact test.

The metrics commonly used in the validation of computational models, may be useful in these cases. There are several metrics, also used to study the repeatability of the crash tests, that allow an objective and quantitative assessment of how much two curves are similar (Schwer, 2007). These metrics quantify the similarity between two curves by different methods:

- Comparison of the signals in the frequency domain (Basu and Haghighi, 1988). The pulses generated in a collision have a short duration and multitude of oscillations, which produces soft power spectra, hindering the application of this type of metrics.
- Determining the correlation between the signal data. Correlation coefficients employed in statistics (e.g. NARD or Pearson coefficients) or factors defined primarily to compare curves may be used (Basu and Haghighi, 1988).
- Comparison of the mean values of the signals, or the average value of the point-to-point differences between signals. In this group we can include the metrics of Oberkampf (Oberkampf et al., 2002), the Vectorial Norm (Sarin et al., 2010), RMS and RMS_{log} (Basu and Haghighi, 1988), the Velocity of the Residual Errors or some others based on statistical tools like ANOVA (Ray, 1996; Ray and Hiranmayee, 1998). The methods based on the comparison of the average values of the signals don't take into account the shape of the pulses and the moments in which the peaks occur. On the other hand, the methods based on the correlation between curves and the point-to-point differences of the signals are very sensitive to the phase differences between signals. It is usual to perform a signal synchronization process before applying these comparison metrics in order to improve the sensitivity to the phase differences.
- Techniques derived from voice and image recognition. For example, metrics based on DTW (Dynamic Time Warping) use algorithms for signals synchronisation that assign a cost function to the variations that should be a signal to synchronise it with the other (Sarin et al., 2010). This method is also very sensitive to the initial synchronization of the pulse being compared and to the differences in phase.
- Combined metrics, that combine the results of comparing different characteristics of the curves. In this group they are included the