Verification and validation of models used in computer simulations of roadside barrier crashes

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Abstract

The Finite Element Method (FEM) is now regularly used by engineers to analyse the crashworthiness performance of roadside safety barriers. In particular, the improvements in non-linear Finite Element (FE) codes and the available access to supercomputing facilities have now allowed engineers to simulate in detail crash tests between vehicles and roadside safety barriers. Computer FEM simulations allow investigating the performance of new designs or retrofitted modifications to existing systems. However, it is essential that the numerical model is accurately verified and validated to provide reliable results. In particular, quantitative methods should be used to pursue an objective assessment of the level of Verification and Validation (V&V). The quantification of the V&V process is particularly important in the certification process for roadside hardware by regulatory authorities. This paper provides an overview of the guidelines for V&V of numerical models used for simulating roadside hardware crashes that were recently proposed under the National Cooperative Highway Research Program (NCHRP) 22-24 in the United States. After an initial description of the general concepts of the V&V process, the quantitative methods that objectively measure the level of validation of numerical models used to simulate the crash performance of roadside safety hardware, such as guardrails or concrete barriers are discussed. In particular, it is shown how the acceptance criteria were assessed for those selected validation metrics, based on an analysis of the typical scatter of results from a repeated series of identical or very similar vehicular full-scale crash tests. An example application for the proposed V&V procedures is also provided. Designers, policy decision makers and regulators will benefit from the use of the described V&V procedures, which provide a quantitative process and measurable level of the numerical model's reliability.

Introduction

In the past two decades, the improvements in non-linear Finite Element (FE) codes combined with progressively more accessible supercomputing facilities have allowed complex dynamic events such as vehicles crashes into roadside safety barriers to be simulated. Accurate simulations of crash tests now allow investigating the safety performance of either new designs or retrofit modifications for existing systems to be investigated in detail. Simulations can now provide designers with a tool to better understand the dynamics of the system as well to help reduce the costs associated with otherwise more extensive, and thus more expensive, experimental testing.

Various efforts regarding computer simulation of full-scale crash tests into roadside safety hardware have been made in recent years. Detailed simulation efforts were made since the late 90's to model impacts involving guardrail systems (Plaxico, Patzner, & Ray, 1998; Tabiei & Wu, 2000). Further examples of the use of simulations in roadside safety include modelling full-scale crash tests with reinforced concrete barriers (Abu-Odeh, 2006), impacts into lighting and utility poles equipped with breakaway bolted connections (Reid & Hiser, 2005), dynamic component tests used for the development of guardrails (Eskandarian, Marzougui, & Bedewi, 1997) or wire-rope cable barriers (Stolle & Reid, 2011). Yet other applications of simulations in roadside safety included modelling the interaction of vehicle tires with curbs or safety-shape barriers (Orengo, Ray, & Plaxico, 2003; Reid, Boesch, & Bielenberg, 2007).

Recently, the US Federal Highway Administration (FHWA) has proposed a procedure to formally accept improved versions of roadside safety hardware that require only minor changes with respect to previous successfully-tested designs for cases in which these analyses are purely based on numerical simulations (FHWA, 2012). Following is an overview of the steps involved in this proposed process:

- Develop a model of the roadside safety hardware that has already been tested and approved through dynamic testing. This is referred to as the *baseline* model;
- Validate the results of the computer simulation of the baseline model against the already-existing crash test(s);
- Modify the baseline model to replicate minor changes in the structure and perform the simulations of the new configuration;
- Evaluate the results of the new design configuration using the same requirements for the crash tests. If simulation results indicate acceptable performance according to the test guidelines for roadside hardware design, the new design configuration can be approved for use.

An objective assessment of the baseline model through a rigorous Verification and Validation (V&V) process is essential to guarantee that the entire proposed acceptance procedure can deliver reliable results.

Verification and Validation

In order to provide reliable results, it is essential that a numerical model should be accurately verified and validated. A rigorous definition of both the concepts of V&V for numerical simulations as recently formulated by the American Society of Mechanical Engineers (ASME) (ASME, 2006) is provided in the following.

Verification is defined as the process of determining that a computational model accurately represents the underlying mathematical model and its solution.

Validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

In practice, verification is the process of checking that the numerical model has been properly implemented, while validation ensures that the results obtained from the model are consistent with the real world. In particular, the question at the root of the validation exercise in roadside safety is whether the simulation replicates the physical experiment and, consequently, whether it can be used to explore and predict the response of new or modified roadside hardware in the real-world.

In particular, the assessment of the level of V&V of a numerical model should be pursued through the use of quantitative comparison metrics. Using measurable metrics to quantify the level of V&V would allow for an objective assessment of the model, with all the consequent benefits that this implies. Not only designers, but also decision makers and regulators will benefit from the use of rigorous and objective V&V procedures. Specifically, when required to take a decision based purely on the outcomes of simulations, an assessment process based on quantitative criteria that are unambiguous and mathematically precise would provide policy decision makers and regulators with a measurable level of the numerical model's reliability.

Objectives and Methods

The main objective of this paper is to describe the guidelines for the V&V process used to assess the accuracy of numerical models used for simulating crash scenarios typically used for testing roadside safety hardware and to provide an example of how the process is used. These guidelines were recently developed under the National Cooperative Highway Research Program (NCHRP) Project 22-24 in the United States of America (USA) (Ray, Mongiardini, Plaxico, & Anghileri, 2011). After an initial description of the general concepts of the V&V process, the quantitative methods that objectively measure the level of validation of numerical models used to simulate the crash performance of roadside safety hardware, such as guardrails or concrete barriers are discussed. In particular, it is shown how the acceptance criteria were assessed for those selected validation metrics, based on an analysis of the typical scatter of results from a repeated series of identical or very similar vehicular full-scale crash tests. An example application for the proposed V&V procedures is also provided. This example highlights the robustness of the proposed V&V method in assessing the predictive capability of a numerical model.

Verification Process

The verification of a model is the initial step. It can be considered the equivalent of a final checkup of the model, to check that everything has been implemented in the model as planned Although based on the general laws of dynamics, and given their complexity and the many parameters involved, full-scale crash tests typically performed to assess roadside safety hardware are difficult to model analytically using specific formulas. Although engineering design methods have been determined to calculate impact loads and the deformation of barriers (Jiang, Grzebieta, & Zhao, 2004), these methods do not allow to predict in detail the vehicle kinematics during a crash. Although based on the general laws of dynamics, given their complexity and the many parameters involved, full-scale crash tests typically performed in roadside safety cannot be analytically modelled through specific formulas.

Hence, because of the limitations and difficulties related to an analytical approach, it is not possible to verify of numerical models used in roadside safety in the strict sense of the term. However, verification that the numerical model produces stable solutions is possible. Indeed, during numerical simulations non-physical energy may potentially be created as a result of numerical inaccuracies in element formulation, contact definitions, or the addition of non-physical mass in case a mass-scaling technique is adopted. While it is typical to expect some of these deficiencies in the analysis, the resulting error has to be limited to a reasonable level in order to have a minimal effect on the solution. Element stability in terms of unexpected deformation can also be checked. This is done by checking that there are no solid elements whose volume may become negative when subject to extreme deformation at any stage of the simulation or that there any elements with so-called shooting nodes, which are large unrealistic node displacements due to contact instability.

The next step is to then verify that basic laws of conservation are satisfied during the entire duration of the analysis. This can be achieved by performing a check that global quantities such as energy and mass remain constant throughout the simulations. Indeed, in general, events such as full-scale crash tests are modelled as a closed system, which means that no energy or mass is added or removed during the analysis. In particular, the total energy should be equal to the initial kinetic energy of the impacting vehicle.

Validation Process

Although necessary, the verification step discussed in the previous section is not sufficient to completely assure the regulator the model is accurately replicating the physical event of interest. A further level of confidence needs to be established which is provided by the validation step. In general, the validation process involves a comparison between experimental and numerical results in order to assess how well the simulation replicates the real event of interest. The physical quantities considered in such comparisons can be of different nature but, in the specific case of roadside safety, they are usually limited to accelerations, velocities, and displacements. In particular, these quantities of interest are often measured as a function of time (e.g., acceleration time history of the vehicle's centre of mass during the impact event) rather than being a single value.

Although a mere visual comparison provides a general assessment of how well the experimental and numerical curves match, it would be inevitably restricted by subjective interpretation of the assessor. As such, a quantitative and measurable type of comparison is needed in order to make an objective assessment. Note that, being the quantities of interest are mostly time histories, it is not always possible to perform a direct comparison between the quantities of interest measured during an experimental test with those computed in the corresponding numerical simulation. This issue can be resolved by considering comparison metrics, which are mathematical measure that quantifies the level of agreement between any two curves (i.e., simulation versus experimental values).

Comparison Metrics

A variety of validation metrics can be found in literature but essentially they can be grouped into two main categories: (i) deterministic metrics and (ii) stochastic metrics. Deterministic metrics do not specifically address any probabilistic variation of the results, i.e., curves are assumed to be repeatable since input parameters are deterministically imposed and hence it is considered that both the test and the simulation can be perfectly repeatable. On the other hand, stochastic metrics considers the likely variation in both experimental and simulated curves due to the uncertainty of the input parameters. Although more representative of the variation of a system response due to their capability of taking into consideration the uncertainty of some parameters (e.g. material variation, probabilistic variation of vehicle assembly tolerance dimensions, barrier construction tolerances, etc.), stochastic metrics would require a much larger effort.

Simulations with FE explicit codes, which are the only suitable to reproduce in detail the deformation of structures under impact loads, require large and complex models with long computational times. Recently, the availability of supercomputers has made it possible to reduce the computational time necessary to simulate typical vehicle-barrier impacts within 24 hours, thus making parametric runs of these models more affordable than in the past few years. Although the advances in supercomputing allow to simulate a vehicle–to-barrier crash test, a validation of models that may account for a stochastic variation of the relevant parameters of interest, is still practically unaffordable in roadside safety. Unfortunately, to validate a model that accounts for the stochastic variation of relevant parameters of interest, multiple repetitions of experimental tests under the expected variation of the input parameters would be required to gather information about the stochastic distribution of the results. Given the large cost of a full-scale roadside safety barrier crash test (likely in excess of US$80,000), this approach would be extremely expensive. Further, for a dynamic full-scale roadside safety barrier crash test, an accurate control of the parameters of interest would be prohibitive, e.g. varying the mechanical resistance of each of the barrier posts or the soil strength, the different dimensions of the barrier and impacting vehicle that accounts for dimension tolerances, the construction material variations, etc. For this reason, only deterministic metrics were considered as a feasible solution for V&V of roadside safety barrier crash models assessing the barrier's crashworthiness.

Validation metrics also require appropriate acceptance criteria that are representative of the typical scatter of the experimental results in the specific field/application where they will be employed. In practice, to consider a simulation as good as another experiment, the maximum difference between simulation and experimental results would be expected to be within the same scatter range observed when compared experiments in that field. Therefore, validation metrics require two parts: (i) a deterministic metric and (ii) an acceptance criterion fit for the specific case of roadside safety. Also, within roadside safety, acceptance criteria may vary according for the specific crash scenario (e.g., impact against deformable guardrails, rigid barriers, end terminals, etc.).

Selected Metrics for Roadside Safety Hardware

Various deterministic metrics originally developed in different scientific fields were reviewed. The Sprague & Geers (Sprague & Geers, 2003) and the Ray's ANOVA (Ray, 1996) metrics were selected as the most suitable for the specific case of validating simulated crash tests into roadside safety hardware. The mathematical definition for each of these metrics is summarised in Table 1. The Sprague & Geers metric is a two-part metric since it is calculated by analysing two components of the simulation and test curves being compared, i.e. the magnitude (M) and phase (P) difference. The other two metrics selected were the average and the standard deviation of the residuals between the experimental and simulated curves. These last two metrics provide an analysis of the results scatter.

Table 1. Comparison Metrics and Acceptance Criteria for V&V in Roadside Safety [1,2]

		Formulation	Acceptance Criteria
Sprague & Geers	***Magnitude Component (M_{SG})***	$M_{SG} = \sqrt{\frac{\sum c_i^2}{\sum m_i^2}} - 1$	≤ 40%
	Phase Component (P_{SG})	$P_{SG} = \frac{1}{\pi} cos^{-1} \frac{\sum c_i \ m_i}{\sqrt{\sum c_i^2 \sum m_i^2}}$	≤ 40%
ANOVA (based on residual error*)	***Average ($\bar{e}^r$)***	$\bar{e}^r = \frac{\sum_{i=1}^{n}(m_i - c_i)/m_{max}}{n}$	≤ 5%
	Standard Deviation (σ^r)	$\sigma^r = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(e^r - \bar{e}^r)^2}$	≤ 35%
	(*) normalized to the peak of the measured values		

(1) m_i and c_i are the values at the i^{th} sampled point of the measured and computed curves, respectively.
(2) Both the measured and computed curves are assumed to have the same constant sampling rate.

Determination of Acceptance Criteria for Roadside Safety Hardware

An analysis of ten repeated full-scale crash tests was performed. The scatter in the metric values obtained from this analysis provided a good basis for determining reasonable acceptance criteria for these metrics. In fact, using this approach, it was possible to define the acceptance based on actual probabilistic variation of the experimental results.

All ten crash tests were performed on the same type of rigid concrete barrier (Anghileri & Mongiardini, 2005). For five of the tests, 2000 model Peugeot 106 test vehicles were used, while for the other five tests different vehicle makes and models were used. For all ten tests, the vehicles were compliant with the standard 900-kg small test vehicle specified in the European crash test standard EN 1317 (CEN, 1998). The plot of the vehicle's lateral acceleration time histories that were used to determine the acceptance criteria, along with the corresponding 90th percentile corridor, is shown in Figure 1. Further details concerning the ten repeated full-scale crash tests and the selection of the deterministic metrics is described by Mongiardini (Mongiardini, 2010).

Comparison of Multiple Pairs of Curves

In a typical full-scale crash test, where multiple channels are usually collected, such as three components for the acceleration of the vehicle's centre of mass and other three components for the vehicle rotational speed. Depending of the specific impact conditions, some of the collected channels may be more relevant than others. For example, in a redirection impact against a guardrail, the vehicle's lateral and longitudinal accelerations, and the yaw rate are likely to be predominant. To avoid introducing subjectivity into the selection of the channels to be compared during the validation process, a weight assigned to each of these six channels is automatically computed based on their relevance. The proposed method determines the weight for each channel based on a pseudo momentum approach using the area under the curves. More detail about this method are described by Mongiardini et al. (Mongiardini, 2010; Ray et al., 2011).

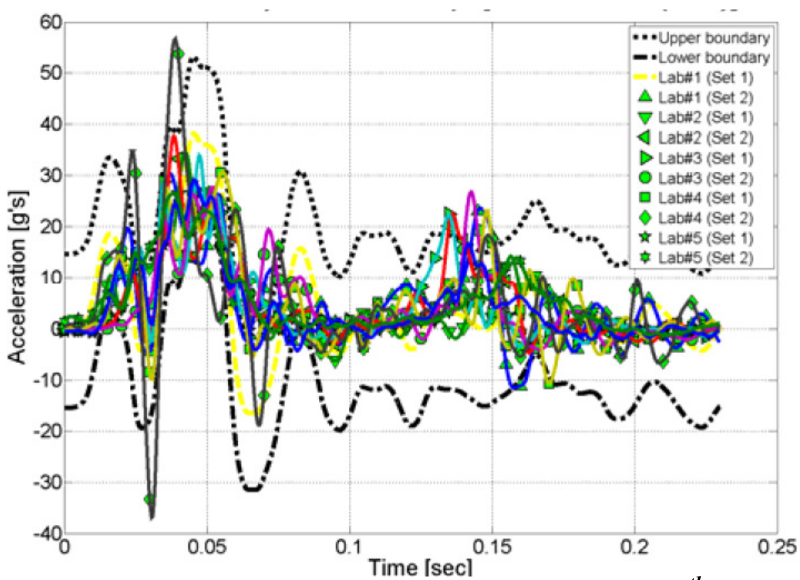


Figure 1. Lateral Acceleration Time Histories and Corresponding 90th Percentile Envelope for the Ten Repeated Full-Scale Crash Tests

Comparison of Phenomena Required by Testing Standards

The last step of the proposed validation process is to compare the phenomena observed in both the crash test and the numerical simulation. Since numerical models in roadside safety are used to simulate crash test scenarios according to the relevant testing standards, the same physical phenomena used to assess the performance of the hardware safety device are considered.

Documenting Relevant Phenomena Implemented in the Model

When a model has been validated for a particular application, it may not be appropriate for use in other situations that vary significantly from the intended original scenario. In many cases, models that have been developed and validated by one analyst are then obtained and used by others, who may use these models for entirely different purposes if they do not understand the modeler's original intent. It is therefore important that users other than the original developer(s) of a model fully understand whether the various components of the model accurately simulate the phenomena that are important to their application. With this in mind, a Phenomena of Interest Ranking Table (PIRT) was included as a compulsory part of the proposed V&V procedure to provide a means of communicating to other users the specific phenomena that the model was validated for during its development. The PIRT should list all the physical tests that were used to validate the various components and subassemblies of the model and provides a quantified assessment of their validity. In particular, a separate PIRT table should be prepared for both the vehicle and the roadside safety hardware being simulated and analysed.

Example Case

The case described in the following is an application of the proposed V&V procedures applied to an FE model that reproduces a typical scenario in roadside safety: an impact into a deformable guardrail system. The purpose of this example case is to both describe a practical example of how the proposed procedures should be applied and, at the same time, evaluate whether they are capable of adequately assessing the model's capacity to replicate the desired physical event.

The benchmark case involved an FE model of a ¾-ton pickup truck impacting the most common guardrail system in the USA, the modified G4(1S) (Ray, Plaxico, Weir, & Council, 2005), which is shown in Figure 2. The objective of the research leading to the simulation effort described in this benchmark case was to analyse the safety performance of a guardrail system when placed behind a curb. Since that project aimed at investigating different configurations varying both the curb height and the offset distance, it was not feasible to perform full-scale crash tests for each scenario of interest. Instead, the use of Finite Element (FE) simulations represented a convenient and more efficient alternative to performing full-scale crash tests for this sort of parametric study.

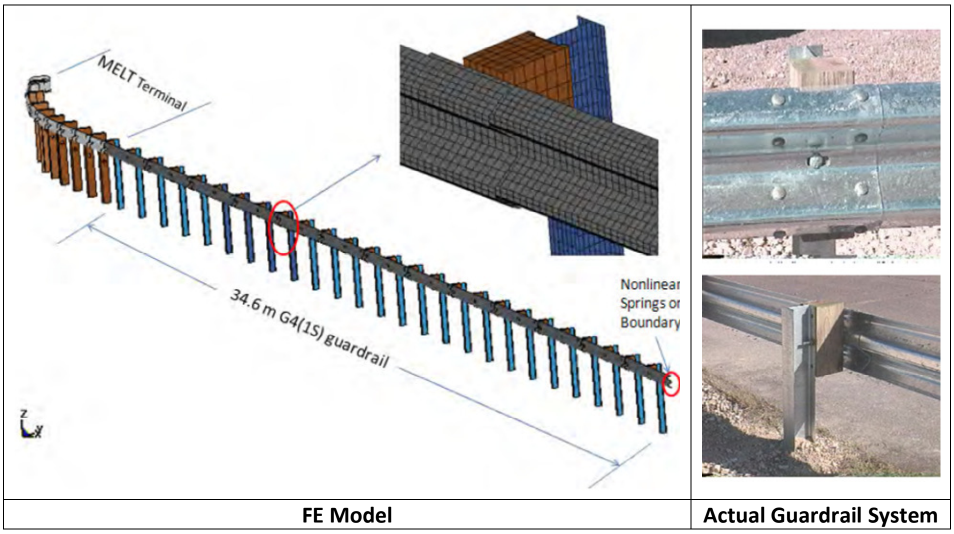


Figure 2. G4(1S) Guardrail: FE Model and Actual System

Baseline Analysis

Solution Verification

As discussed in the previous sections, the initial step of the proposed V&V process consists in the verification of the model stability through a check of the global energies, mass, and element stability during the simulation. Both the total energy and mass remained constant throughout the entire duration of the simulation and no element showed numerical instability. Table 2 shows a summary of the proposed global verification assessment based on the criteria previously discussed.

Validation

Various component validations were initially made for both the vehicle and barrier models to ensure the model's capability to replicate physical phenomena relevant for this type of full-scale crash test. These component validations should be summarised in a PIRT.

Table 2. Verification of the Baseline Model

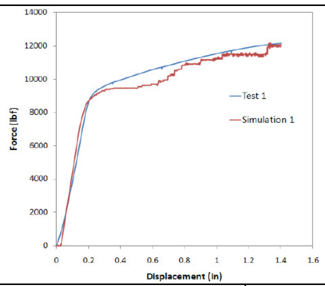
		Model Entity	Stage of Simulation	Verification Criteria	Quantity Value	Pass? (Y/N)
Verified Quantity	***Total Energy***	Global	Throughout	≤ 10% Total Init. Energy @ t=0	1.3%	Y
	Hourglass Energy	Global	Termination	≤ 5% Total Init. Energy @ t=0	0%	Y
			Termination	≤ 10% Total Internal Energy @ end	0%	Y
		Specific Parts	Throughout	≤ 5% Total Init. Energy @ t=0	0%	Y
	Added Mass	Global	Start	≤ 5% Total Mass @ t=0	0%	Y
			Throughout	≤ 10% Total Mass @ t=0	0%	Y
		Specific Parts	Throughout	≤ 10% Mass of Part @ t=0	0%	Y
		Global (Moving Parts Only)	Throughout	≤ 5% Mass of Moving Parts @ t=0	0%	Y
	Shooting Nodes?	Global	Throughout	Y/N	N	Y
	Solid Elements w/ Negative Volume?	Global	Throughout	Y/N	N	Y

As an example, Table 3 summarizes the validated physical phenomena for the barrier model. The component validation for the first phenomenon listed in the barrier PIRT is shown in Table 4. A detailed description of all the items listed in the barrier PIRT as well as the vehicle PIRT can be found in the final report describing these proposed V&V procedures (Ray et al., 2011).

Table 3. Phenomena Importance Ranking Table (PIRT) for the Barrier G4(1S) Model

	Validated Phenomenon
1	Three-Point Bend Test of W150x13.5 Post About Weak Axis
2	Load-to-rupture of splice connection under quasi-static axial loading
3	Pull-through of post-bolt-head connection to w-beam using axial load machine
4	Full-scale bogie impact tests of the W150x13.5post embedded in 1,980 kg/m^3 soil
5	Full-scale bogie impact tests of the W150x13.5post embedded in 2,110 kg/m^3 soil
6	Full-scale bogie impact tests of the W150x13.5post embedded in 2,240 kg/m^3 soil

Table 4. Description of Component Validation for Phenomenon#1 in Barrier PIRT

Plastic deformation of guardrail posts due to bending about weak axis			
Three-Point Bend Test of W150x13.5 Post About Weak Axis (Force-Displacement Curve)			
 			
Sprague&Geers Metric	***M***	***P***	**Pass?**
	3.6	1.1	Y
ANOVA Metrics	***Mean Residual***	***STD of Residuals***	***Pass?***
	0.03	0.03	Y

An initial visual comparison of the simulated and experimental vehicle kinematics was performed, as shown in Figure 3.

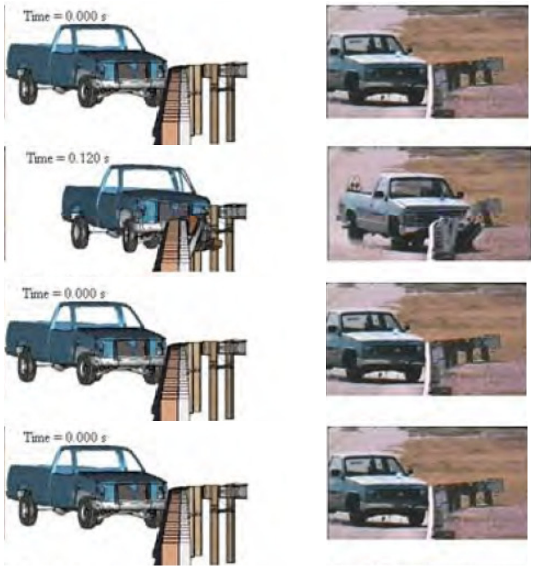
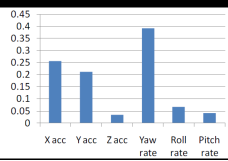


Figure 3. G4(1S) Guardrail: FE Simulation and Actual Full-Scale Crash Test

Further, the time histories of the accelerations and rotational rates were quantitatively compared calculating the Sprague & Geers and the ANOVA metrics. The computed metric values for the lateral and vertical accelerations, and the pitch rate slightly exceeded the acceptable limits. However, the metric values for the most relevant channels (i.e., the longitudinal acceleration and the yaw rate) were acceptable, as summarised in Table 5. This result was reflected also by the simultaneous comparison of all the six channels through the use of weighting factors that were computed using the methodology previously outlined. Plots of the time histories for the accelerations and rotational rates can be found in Appendix.

Table 5. Comparison Metrics for Baseline Model (1)

Single Channels	Sprague&Geers		ANOVA		Pass?
	M	*P*	*Mean Residual*	*STD of Residual*	
X Acceleration	21.5	33.3	0.02	0.34	Y
Y Acceleration	43.9	35.7	0.05	0.27	N
Z Acceleration	21.1	43.0	0.02	0.32	N
Roll Rate	35.3	32.7	0.02	0.27	Y
Pitch Rate	13.3	48.0	0.05	0.36	N
Yaw Rate	11.7	8.7	0.04	0.12	Y
Multichannel Weights					
Weighted average	**Sprague&Geers**		**ANOVA**		**Pass?**
	M	*P*	*Mean Residual*	*STD of Residual*	
	22.9	25	0.03	0.24	Y

(1) Underlined values exceed the corresponding acceptable limits.

Prediction of Modified Model

The main idea behind V&V is to guarantee the reliability of a numerical model so that it can be used to simulate crash scenarios with a similar accuracy to those for which the model was validated. As such, to prove the robustness of the proposed V&V procedures, the initially validated baseline model was modified to simulate a slightly different scenario involving the presence of a curb located in front of the guardrail system. The simulation using this modified model was eventually compared to the corresponding full-scale crash test.

The validated baseline model was modified by placing below the barrier's W-beam rail a 6-inch (152-mm) tall Type-B curb complying with the American Association of State Highway and Transportation Officials (AASHTO) standard. The modified model was able to accurately simulate both the vehicle kinematics and the barrier deformation observed in the full-scale crash test, as shown in the sequential views of Figure 4.

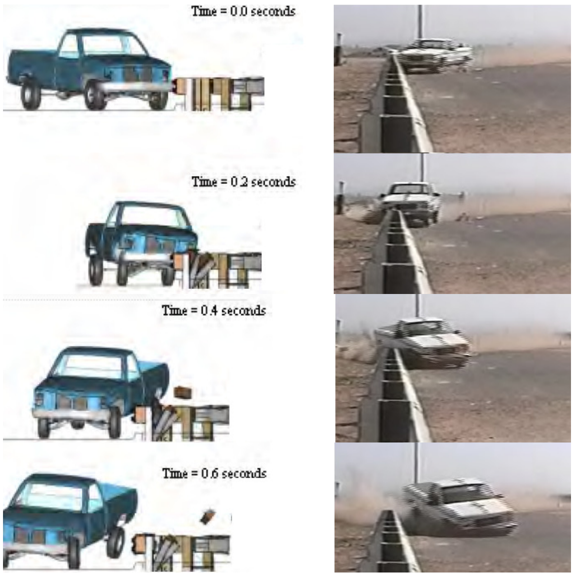


Figure 4. G4(1S) Guardrail with 6-in. Curb: FE Simulation and Full-Scale Crash Test

Summary and Conclusions

This paper provided an overview of recently-developed procedures for the V&V of numerical models used to simulate typical crash scenarios that are used for assessing the safety performance of road safety hardware. The advancements of computer technology and the development of complex and efficient codes now allow to simulate in detail crash events. Ultimately, the reliability of the simulation results relies on a properly verified and validated model. This is even more important for those cases in which official acceptance of modification to road safety hardware by government agencies can be based purely on simulation analysis, such as it has been recently proposed in the USA for minor variations of existing designs that were previously successfully tested.

The adoption of a standardised and rigorous method for the V&V of numerical models in roadside safety would benefit both designers and decision makers. In particular, the objective and quantitative assessment of the validation level guaranteed by the use of comparison metrics will allow designers to better identify the accuracy of their predictions. The quantitative nature of this V&V process also provides decision makers with the capacity to take decisions based on a measurable level of the numerical model's accuracy.

The proposed V&V procedures, which were developed as part of the NCHRP Project 22-24, require an initial verification of the numerical model based on the conservation of energy and mass during the simulation. Thereafter model validation is assessed throughout both qualitative and quantitative methods. In particular, the use of quantitative comparison metrics provides a measurable and objective assessment of the validation level. Acceptance criteria for the metrics used to quantitatively compare experimental and numerical curves were defined based on the scatter of results expected in full-scale crash tests in roadside safety. The relevant physical phenomena that the vehicle and roadside safety hardware models proved to be able to replicate were then listed in the respective PIRT tables. The PIRT tables allow other users to understand whether they can consider the model for simulating other similar events that require the same phenomena for which the model has proven to be validated.

A practical application of the proposed V&V procedures was provided with an example case involving a FE model for assessing the safety performance of a guardrail system. This example case proved that the proposed procedures are capable of adequately assessing the model's capacity of replicating the type of physical event for which the model was validated.

The proposed V&V procedures would primarily be used for making decisions on incremental hardware improvements. A typical implementation of these V&V procedures in the approval process would require the relevant regulatory authority to be provided with the following documentation:

- V&V report documenting the comparison between the full-scale crash test of the baseline hardware and the corresponding simulation analysis. This crash test is defined as *benchmark* case.
- PIRT's for the roadside safety hardware and the vehicle models tested in the benchmark case.

The V&V report and the PIRT's for the hardware and vehicle models tested in the benchmark case should then provide decision-makers with sufficient information to be confident that the extrapolation to the modified system is reasonable.

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Appendix

Plots of the accelerations and rotational rates used to validate the baseline model described in the example case.

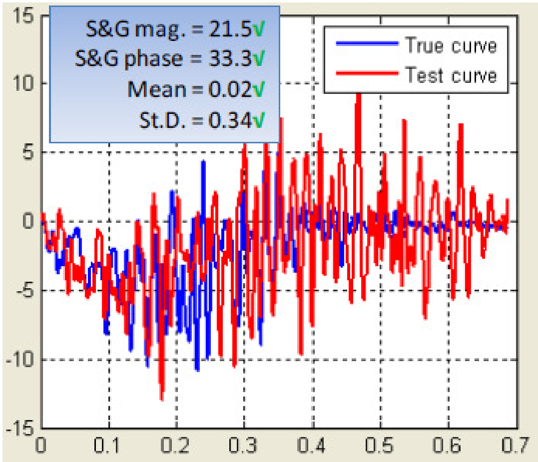

Figure A-1. X-channel acceleration-time history data used to compute metrics

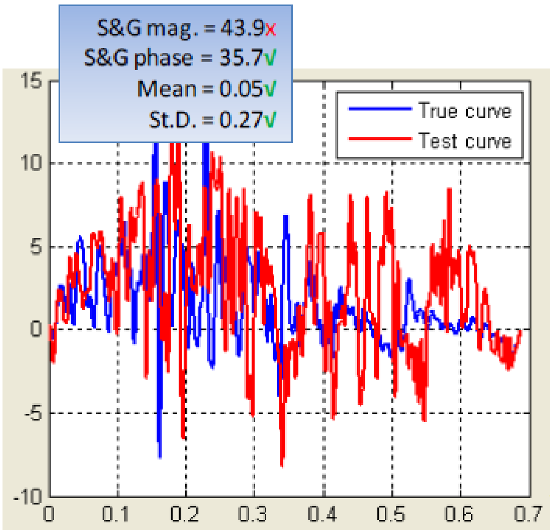

Figure A-2. Y-channel acceleration-time history data used to compute metrics

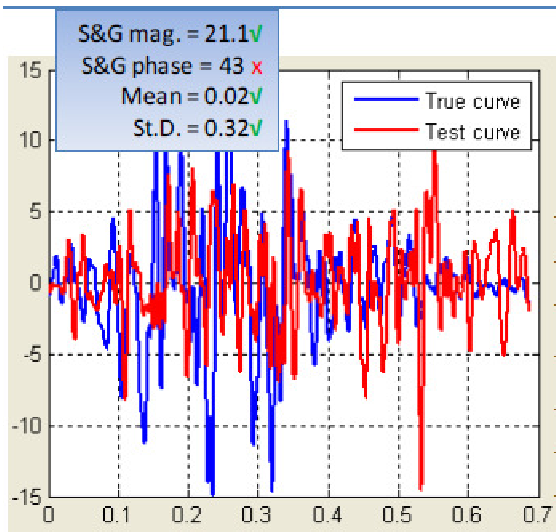

Figure A-3. Z-channel acceleration-time history data used to compute metrics

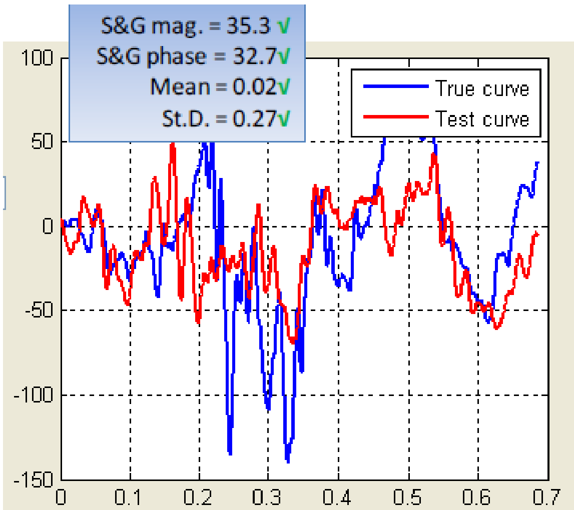

Figure A-4. Roll-Channel angular rate-time history data used to compute metrics

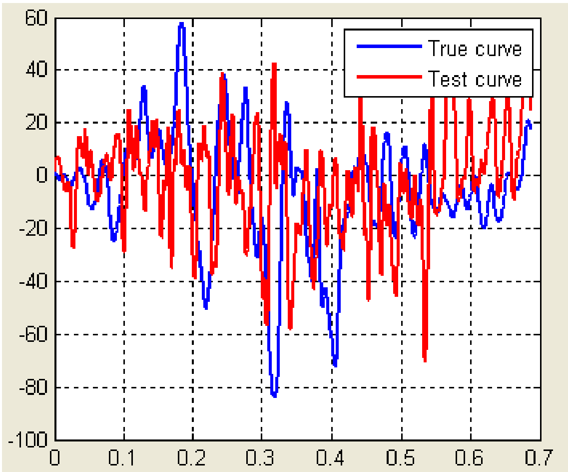

Figure A-5. Pitch-Channel angular rate-time history data used to compute metrics

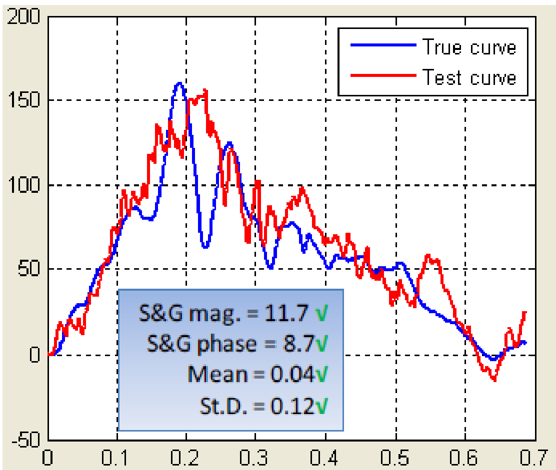

Figure A-6. Yaw-Channel angular rate-time history data used to compute metrics