REPEATABILITY OF FULL-SCALE CRASH TESTS AND A CRITERIA FOR VALIDATING SIMULATION RESULTS

Malcolm H. Ray[1]

This paper describes a method of comparing two acceleration time histories to determine if they describe similar physical events. The method can be used to assess the repeatability of full-scale crash tests and it can also be used as a criterion for assessing how well a finite element analysis of a collision event simulates a corresponding full-scale crash test. The method is used to compare a series of six identical crash tests and then is used to compare a finite element analysis to a full-scale crash test.

INTRODUCTION

Nonlinear finite element analysis is becoming a useful part of the roadside hardware design and evaluation process. Researchers are using the nonlinear finite element program DYNA3D to simulate collisions between vehicles and roadside hardware.(1) (2) Finite element models have been developed for a variety of vehicles including small and mid-sized passenger vehicles and a pickup truck. (3) Models of roadside hardware like the breakaway cable terminal, the G4(1S) guardrail and a small sign support have also been developed. (3) (4) The number of efforts at using DYNA3D to model roadside impacts and predict the results of crash tests is increasing steadily and finite element analysis should become a standard tool of the roadside hardware designer in the near future.

Building a model that runs to completion with no numerical problems is only the first step in the analysis process. Often the most challenging question the analyst must answer is "how good is the simulation?" Currently there are no guidelines for assessing "how good" a simulation of a

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[1] Assistant Professor, Department of Civil and Environmental Engineering, University of Iowa, 1153 Engineering Building, Iowa City, IA, 52242-1527. 319-384-0523. mhray@icaen.uiowa.edu.

roadside hardware impact should be. Quite often the analyst will visually compare a test response to a simulated response and subjectively compare the two. While such subjective comparisons are useful, there is a need to have more quantifiable criteria for judging the validity of a simulation when compared to a test. The objective of this paper is to present a technique for assessing the quality of a simulation in comparison to a full-scale crash test.

A finite element analysis of a collision event should be expected to produce results that are "as good as running a test." It would be quite remarkable for a series of full-scale crash tests to produce "identical" results since collisions are very complicated events. A simulation, then, need not exactly replicate an acceleration history as long as the response is within the reasonable range of responses expected in a test. Unfortunately, the degree to which full-scale tests are repeatable has never been addressed in roadside hardware crash testing. This paper will seek to answer how repeatable crash tests are for one collision scenario where the repeatability should be quite good.

CRITERIA FOR COMPARING COLLISION EVENTS

There are a variety of techniques for examining the characteristics of two time histories. The NARD Validation Manual, published by FHWA in 1988, lists several techniques for comparing full-scale tests and simulations along with a number of useful check-lists.(5) There are three time-domain criteria in the NARD validation report for comparing test and simulation acceleration histories to each other; each of these criteria will be discussed in the following sections. In all of the following equations f_i and g_i will be the two time histories being compared. The time increment, which is always a constant, is denoted by Δt.

The relative absolute difference of moments is given by the following expression:

$$M_n(f_i) = \frac{\sum_{i=0}^{n} t_i^{\,n} f_i \Delta t}{\{\sum_{i=0}^{n} t_i\}^{n+1}} \tag{1}$$

where n is the order of the moment (0 through 4 typically). The moments of a time history are characteristics of the time history. For example, the zeroth moment corresponds to the average value of the time history. The fact that two time histories have the same value for a characteristic is no guarantee that they are the same. As more characteristics are shared between two time histories, the more likely they are to be the same or related. This is the reason that five moment measures (zeroth through fourth) were suggested in the NARD validation manual.

The logarithmic root-mean-square is given by the following expression:

$$RMS = \frac{\{\sum_{i=1}^{n} (\log(f_i^2/g_i^2))^2\}^{1/2}}{\{\sum_{i=1}^{n} [\log(f_i^2)]^2 + [\log(g_i^2)]^2\}^{1/2}} \tag{2}$$

The correlation coefficient is given by the following expression:

$$r = \frac{\sum_{i=1}^{n} f_i g_i}{\sqrt{\sum_{i=1}^{n} f_i}\,\sqrt{\sum_{i=1}^{n} g_i}} \tag{3}$$

This expression is equivalent to the more common statistical definition of the correlation coefficient as expressed by:

$$r = \frac{\sum_{i=1}^{n} (f_i - \bar{f})(g_i - \bar{g})}{\sqrt{\sum_{i=1}^{n} (f_i - \bar{f})^2 \sum_{i=1}^{n} (g_i - \bar{g})^2}} \tag{4}$$

if the assumption is made that the average of the f and g functions is zero and both functions have an equal number of points (e.g. paired data are being compared). The assumption that the average of both functions is zero is not generally true for accelerometer data from crash tests so the second form of the expression will be used in this paper. A correlation coefficient near unity indicates high positive correlation indicating that the two time histories have the same shape. High correlation does not guarantee that the time histories are the same since they could be identical curves offset from each other. High correlation indicates that one curve can be linearly transformed into the next. For purposes of comparing time histories, this means that the shape of the curves are very similar even if the magnitudes and timing are offset.

Analysis of Time History Residuals

Usually the first information an analyst obtains about a crash event are acceleration time histories. If two time histories are sampled at the same rate and start at the same time, one method for comparing time histories would be to measure the residuals between each pair of data. Since the data are sampled (and filtered) at the same frequency, each data point can be paired with a data point of the other time history. The difference between the two data points is the residual. A statistical analysis of the resulting residuals will provide a good measure of the correspondence between the two time histories.

If the two curves are identical, each pair would be identical and the residual at every point would be zero. Unfortunately, even two accelerometers at the same location in the same test will not provide truly identical samples due to random vibrations, experimental error, and sampling errors. One method for exploring the relationship between two time histories is to make the assumption that they represent the same physical event and then perform statistical tests to either support or disprove that assumption.

If the two time histories were the same and the only differences were random experimental and data acquisition errors, the mean residual should be equal to zero. The residual measures the difference at each instant in time between two time histories that are assumed to be the same. The line passing through the point where the sum of the residuals is zero is, by definition, the average response. Likewise, the standard deviation of the residuals can also be calculated.

If the two time histories are assumed to represent the same event, the differences between them (e.g. the residuals) should be attributable to random experimental error. If a time history is digitized at 2000 Hz, there will be 100 data points in a 50-msec long event. The residual at each point in time is an independent random error event. If the residuals are truly random, then the residuals should be normally distributed around the mean error of zero.

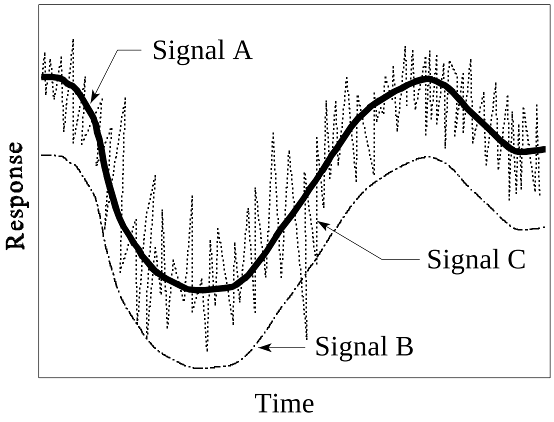

Figure 1 Examples of signal correlation.

Figure 1 shows several possible scenarios to illustrate this technique. Assume that time history A is a true measure of a particular physical event and time history B is another measured time history that is thought to represent the same event. Time histories A and B have the same shape but time history B is always less than time history A. This would result in an average residual that is less than zero. Even though the shape of the curve is identical, time history B cannot be the same as time history A since the average residual is nonzero. Time history C, though it is much more variable or noisy than time history A, has a mean residual of zero, indicating that the time histories could be the same.

Once the mean and standard deviation of the residual distribution are known, a paired two-tailed t test can be performed where the t statistic is defined as follows:(6)

$$T = \frac{\bar{e}}{\sigma_e / \sqrt{n}} \qquad \textbf{(5)}$$

where $\bar{e}$ is the average residual between two curves, σ_e is the standard deviation of the residuals and n is the number of paired samples. If the t statistic is in the range:

$$-t_{\alpha,n-1} \leq T \geq t_{\alpha,n-1} \qquad \textbf{(6)}$$

where $t_{\alpha,n-1}$ can be found in a table of critical t statistics it can be concluded that there is no significant difference between the two time histories at the α level. A statistical test, like the t test, cannot prove that the two histories are identical. What the test does indicate is there is no statistically significant reason for rejecting the hypothesis that the curves represent the same response. One advantage to the t-test approach is that it requires only two curves -- the test curve and the simulation curve. In actual practice, an analyst will not have any information about the variability of the test data and will have to depend on the response of one test and one simulation to decide how well the simulation predicted the response of the test.

Once the mean and variance of the residual distribution are known, they can be used to plot an envelope around the average response. For example if the standard deviation of the residuals is multiplied by 1.6449 and then added to the average response the upper bound 90th percentile envelope response is obtained assuming that the residuals are normally distributed. Likewise subtracting yields the lower-bound 90th percentile response.

The analysis of variance leads to the following criteria evaluating two time histories:

$$
\begin{aligned}
\bar{e} &\cong 0 \\
\sigma_e &\leq \sigma_{crit} \\
\frac{\bar{e}}{\sigma_e/\sqrt{n}} &\leq t_{\alpha,n-1}
\end{aligned}
\qquad \textbf{(7)}
$$

(1) The average residual between two time histories averaged over the event should be essentially zero.
(2) The standard deviation of the residuals should be less than some accepted reasonable value.
(3) The absolute value of the t statistic should be less than the critical t statistic for a two-tailed t-test at the 5 percent level (90 percentile).

Ensuring that the two time histories are correctly paired is critically important in this technique. If the start of one event is off-set from the second time history, incorrectly large residuals may result. When there is uncertainty about pairing the time histories, the most probable starting point can be obtained using the method of least squares:

- Make a trial estimate of the starting point on each time history,
- Square each individual residual and sum them to obtain the summed squared residual.
- Move the pairing point of one time history a small amount forward or backward from the initial point. Recalculate the summed-squared-error and iteratively search the region where the summed-squared-error is at a minimum. This is the most likely pairing point according to the method of least squares.

In crash test analyses, however, this is not normally a serious problem since impact switches are always used to coordinate a variety of electronic and film data channels. Usually the crash test analyst will know quite precisely when in time the impact occurred and will be able to correctly pair time histories.

An analysis of the residuals should only be performed on <u>measured</u> time histories and should never be performed on histories mathematically derived from primary measurements. For example, accelerations are usually measured directly in a full-scale crash test. Velocities and displacements are derived quantities since they are usually found by integrating the experimentally measured accelerations. Residuals (random experimental error and random vibrations) do not accumulate in an acceleration trace when the acceleration is the measured quantity; since residuals are independent there is no relationship between the residual at one instant in time versus the residual at another instant in time. However, when the acceleration curve is integrated, the residuals are accumulated in the velocity history. An error in measuring acceleration will be integrated and added to the velocity curve such that all the error in the acceleration curve will accumulate in the velocity history. Integrating once more to obtain displacements will further compound the accumulation of error. An analysis of variance, therefore, should only be used on measured experimental data.

REPEATABILITY OF FULL-SCALE TESTS

Description of Test

Before exploring the issue of how similar the response of a test should be to a simulation to judge it "validated," the issue of the repeatability of identical crash tests must be explored. Only in rare cases will the analyst have more than one experimental result for a particular impact scenario. Exploring the variability of repeated crash tests will, however, provide invaluable information on the likely variability of tests.

Full-scale crash tests are an assembly of complicated and interdependent events. Normally a developer of roadside hardware has resources for only a few tests, therefore identical tests are a great rarity. The degree of repeatability of a full-scale crash test is a function of the type of test and the vehicle and barrier interacting in the test. Some tests, like rigid pole impacts with identical vehicles, should have a high degree of repeatability. Other tests, for example gating terminal tests, will probably not be very repeatable.

A series of six identical full-scale crash tests were performed at the Federal Outdoor Impact Laboratory (FOIL) between 1991 and 1994.(7),(8),(9) Each test involved a 1988-1992 Ford Festiva impacting a rigid instrumented pole at 32 km/hr on the center-line of the vehicle. The Ford Festiva in these model years was exactly the same platform with only very minor non-structural differences. The tests were all performed at the same facility, with the same personnel, using the same data acquisition and reduction techniques. This particular test should be one of the most repeatable full-scale tests possible.

Acceleration History Criterion

Table 1. Analysis of variance for the residuals of two redundant accelerometers.

e (g's)	-0.02
σ_e (g's)	1.35
t	-0.25
Max residual (g's)	5.29

Even when two independent measurements of the same collision event are obtained, there will usually be differences between the resulting time histories. Table 1 shows statistics for the time histories derived from two redundant accelerometers located at the same location, aligned in the same direction for a 32 km/h impact with a rigid pole (test 94F001). The time histories are very similar although there are small differences due to experimental error and random vibrations. The mean residual and the standard deviation of the residual between these two time histories were found to be -0.0219 g's and 1.3446 g's, respectively. Even though the time histories "look" nearly identical, the maximum residual between the two time histories is 5.29 g's. The t statistic for this case indicates that the two curves describe the same phenomena since the t statistic is much less than the critical t statistic of 2.58 indicating 90 percent confidence that two time histories cannot be statistically distinguished.

Next, data from six nearly identical full-scale tests were obtained from the Federal Outdoor Impact Laboratory (FOIL).

The values recommended by the NARD validation manual were compiled for the six identical tests. Table 2 shows the zeroth through fourth moments and the maximum ratio of the absolute differences. The NARD validation manual suggests that values less than 0.2 represent acceptable correlation. There are six tests shown in table 2 which represent 720 possible combinations. Instead of calculating the absolute difference ratio for each combination, the absolute difference was calculated for maximum and minimum moments. This would represent the worst combination since the difference between the moments is maximized. As shown in table 2, the maximum absolute differences are all less than 0.2 until the fourth order moment is reached. The absolute difference increases as the order of the moment increases. This is because higher moments represent a higher and higher degree of correspondence. The results in table 2 indicate that even for identical repeated tests, the fourth order moment may not be a discerning quantity.

Table 2. Absolute zeroth through fourth moments of the impact direction accelerometer signals from six identical tests.

	0th	1st	2nd	3rd	4th
91F049	-7.47	-0.4211	-0.1488	-0.0445	-0.0032
92F032	-7.47	-0.4193	-0.1524	-0.0480	-0.0064
92F033	-7.37	-0.4195	-0.1512	-0.0489	-0.0081
94F001	-7.43	-0.4220	-0.1493	-0.0449	-0.0036
94F002	-7.46	-0.4329	-0.1577	-0.0506	-0.0073

The correlation coefficients for the six tests were also calculated and are shown in table 3. All the correlation coefficients listed in table 3 are very close to one indicating that the six time histories are highly correlated with each other.

Table 3. Correlation coefficients for six identical tests with respect to the average x acceleration history.

	$r_{g/f}$
91F049	0.9705
92F032	0.9772
92F033	0.9736
94F001	0.9712
94F002	0.9867
94F011	0.9721

As shown in figure 2, there is variability between tests although all six of the tests display the same basic response and they clearly represent similar events. The average acceleration history can be determined by averaging the acceleration value at each sampling point of these six tests as shown in figure 2. Once the average response has been calculated, the residual of each sampling point in each curve can be calculated. The residual is the absolute instantaneous value of acceleration from the test subtracted from average response at that time.

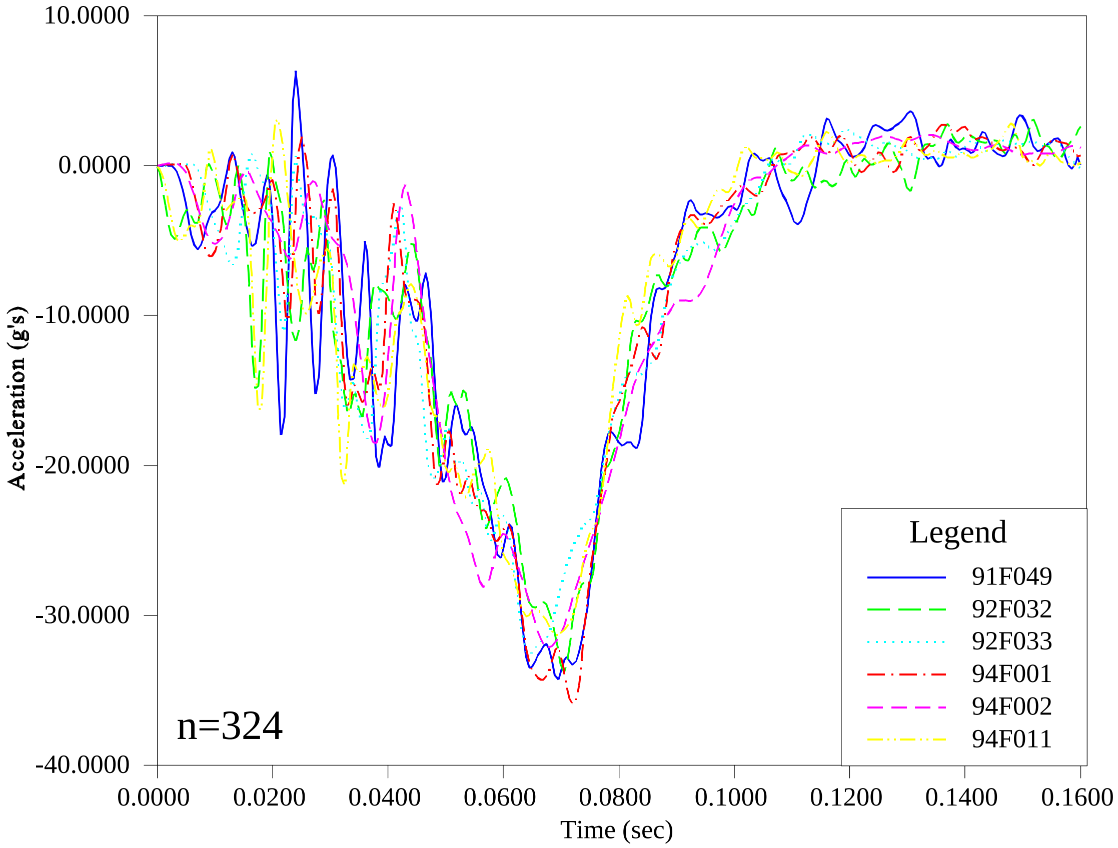

Figure 2. Acceleration history of six identical rigid pole impacts at 35 km/hr.

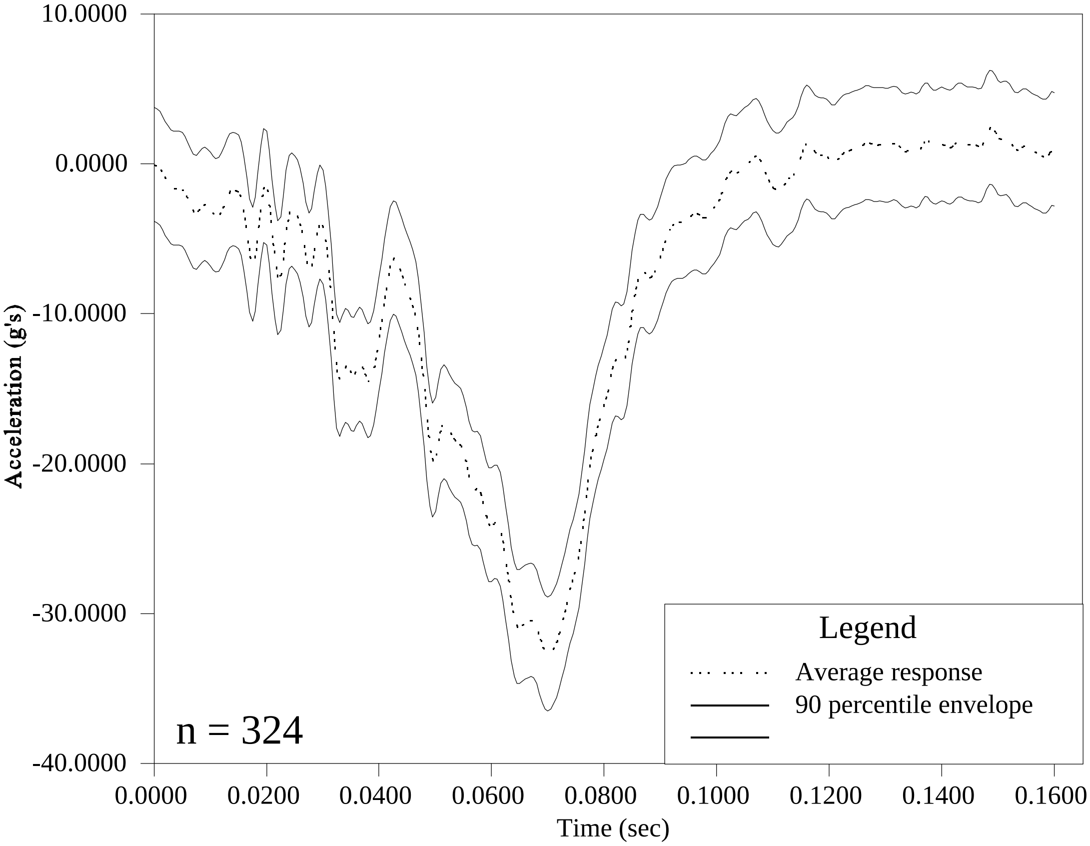

Figure 3. Average acceleration response of six tests and the 90th percentile confidence envelope.

If the cumulative density function of the residuals for the six identical tests are plotted, figure 4 is obtained. The residuals appear to be normally distributed as would be the case if experimental errors and random vibrations were independent random events. The cumulative density function of the residuals is exactly the curve that would be obtained by plotting the cumulative density function of a normal distribution with a mean of 0 g's and a standard deviation of about 2 g's, the test statistics from table 4.

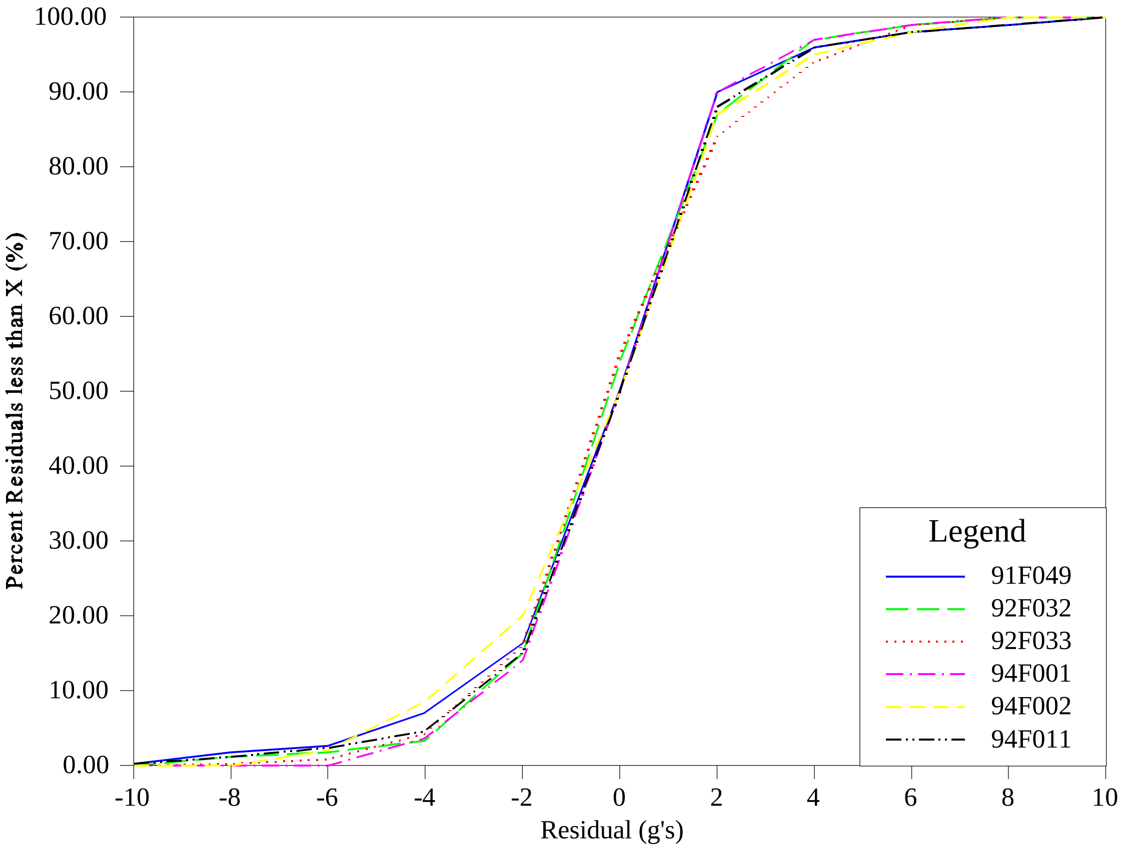

Figure 4. Cumulative density function of residual accelerations from six identical tests.

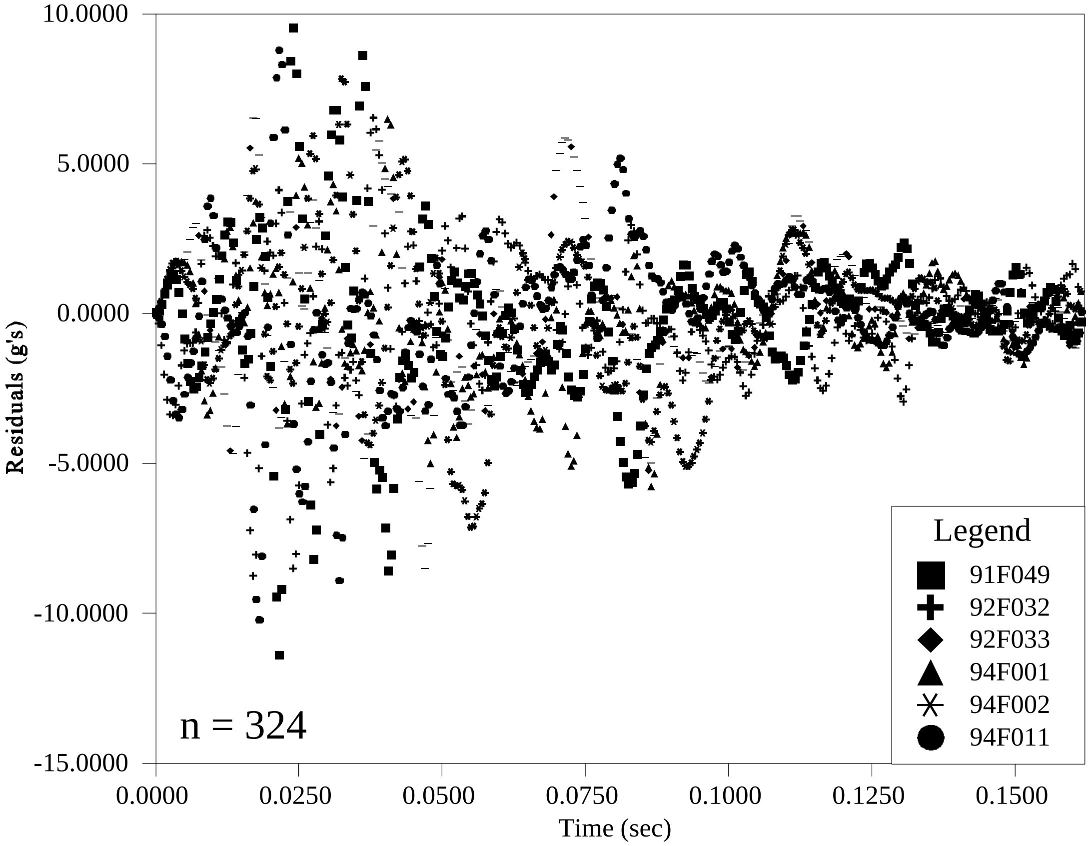

Figure 5. Residual acceleration for six identical tests as a function of time.

If the instantaneous residuals for each test are plotted as a function of time, however, it can be seen that there is some time dependency of the magnitude of the residuals as shown in figure 5. The region between time 0.01 and 0.03 sec show the largest residuals. Physically this corresponds to the part of the collision where the bumper-radiator-core support assembly has collapsed but has not as yet made contact with the engine block.

This <u>should</u> be a noisy part of the impact since the response will be dominated by many small unrepeatable events. The major response of the vehicle, however, is determined by the primary masses and load carrying assemblies like the engine, the frame systems and the main body. When these systems are encountered, the residuals are generally less than 3 g's. Although the magnitude of the residual seems to be a function of time, the randomness of the residuals is still apparent. For example, the residuals are symmetrically distributed about the 0-g line indicating that positive and negative residuals are equally probable (i.e. the distribution is heteroscadastic).

Statistically, the magnitude of the residual is not completely independent of time as shown in figure 5. The assumption that the residuals <u>are</u> independent random events, however, should be retained since it does help to explain most of the impact event. If repeated tests were always available, the analyst could determine the functional relationship between the residuals and time. Since ultimately the analyst will have only one test and one simulation, the independence of the residuals is vital to testing hypotheses about the responses of a test and simulation.

The average response of the test data should by definition be zero or, for practical purposes close to it. As shown in table 4, the actual average residual was 0.17 g's which is less than one percent of the peak acceleration so for all practical purposes is zero. For the six tests shown in figure 2, the standard deviation of the residuals varies from 1.92 to 2.63 g's, a little less than 10 percent of the peak acceleration. The average standard deviation of the residuals for these six tests was found to be 2.3 g's.

The 90th percentile envelope is formed by adding 1.6449*2.3=3.8 g's to the average response to obtain the upper boundary and subtracting 3.8 g's from the average response to obtain the lower boundary. If 100 tests were performed, 90 of them should fall within the nearly 8-g wide envelope shown in figure 2.

Table 4. Test statistics for six paired t tests.

Test	e	σ_e	$t_{0.005,380}$
91F049	-0.21	2.63	-1.45
92F032	-0.21	2.10	-1.82
94F001	-0.11	2.39	-0.83
94F002	-0.17	1.92	-1.54
94F011	-0.20	2.48	-1.47
92F033	-0.15	2.33	-1.18

Two-sided paired t-tests were performed between the six experimental acceleration curves and the averaged response. Table 4 shows the resulting statistics. The critical t statistic for α=0.005 and 380 degrees of freedom (essentially ∞) is 2.58. Since all the t statistics in table 4 have absolute values much less than the critical value, the chance that these paired time histories are not essentially the same physical event is less than 10 percent.

These six tests, then, all would satisfy the three criteria listed earlier in this paper: the average residual is close to zero, the standard deviation is reasonably small and the t statistic suggests the residuals are statistically indistinguishable.

Energy Balance Criterion

Crash tests are generally performed to assist engineers in learning how energy is dissipated in a collision event. The designer of a vehicle or a roadside barrier is attempting to manage the pre-collision kinetic energy in such a way that the vehicle occupant is protected.

The conservation of energy is one of the fundamental principals of mechanics. The total energy of a system during a collision is the instantaneous sum of the kinetic energy and the strain energy of each particle in the system. Kinetic energy is the energy of motion of the particles whereas the strain energy produces distortion and displacement of the particles. At the start of a collision event the kinetic energy is generally at its maximum value whereas strain energy is zero. The impact event transforms kinetic energy into strain energy required to deform the vehicle structure and overcome the frictional forces in the collision. Other sources of energy dissipation in automobile collisions are relatively minor and are neglected in this paper.

The initial kinetic energy is easily calculated as:

$$T_o = \frac{1}{2} m \, v_o^2 \qquad \textbf{(8)}$$

where m is the mass of the vehicle and v_o is the initial velocity of the vehicle. The kinetic energy at each instant of time is also easily calculated based on the instantaneous velocity observed in a crash test.

Strain energy is not measured directly in a full-scale crash test but when the impacted device is an instrumented rigid pole or wall the work done on the vehicle can be calculated based on the measured force history. Since the work done on a structure must equal the strain energy dissipated the strain energy history can be obtained from:

$$U = W = \int_0^t F\, du \simeq \sum_{i=1}^{n} F_i (u_i - u_{i-1}) \qquad \textbf{(9)}$$

where U is the strain energy, W is the work done on the structure, the F_i are the instantaneous forces on the rigid barrier and the u_i are the generalized displacements resulting from the application of those forces. Instantaneous values for the force, F_i, are measured directly in rigid pole and rigid wall tests. The displacements can be obtained in several ways but the easiest method is to integrate the F_i history twice to obtain the instantaneous displacements.

Since kinetic energy is a function of the square of the initial velocity, the energy balance is more sensitive to small variations in the initial conditions than is the acceleration history. To help remove the effect of the initial conditions it is sometimes convenient to divide both the kinetic and strain energy histories by the initial kinetic energy, the resulting histories are called the relative strain and relative kinetic energy histories. The relative strain energy (or work) can be plotted against the relative kinetic energy to obtain an energy balance like that shown in figure 6.

The energy histories should display several important characteristics. First, the initial kinetic energy should be essentially equal between tests or in comparison to a simulation. The initial kinetic energy is simply a function of initial conditions and if it is not reasonably similar (e.g. 5 percent or so) the tests may not be equivalent collision events. Second, the time when the maximum strain energy occurs should coincide with the time when the minimum kinetic energy occurs. The relative strain energies should agree very closely. At all instants of time the sum of the relative kinetic and strain energy should be close to one.

Performing an energy balance is in principle possible for any impact event, however, it is more difficult to perform the required calculations as the event becomes more complicated. For simple symmetrical center-on frontal impacts with a rigid instrumented pole or wall the calculations are straightforward and should be done. For collisions where there is no instrumentation of the impacted device it will not be possible to determine the strain energy (or work done) experimentally.

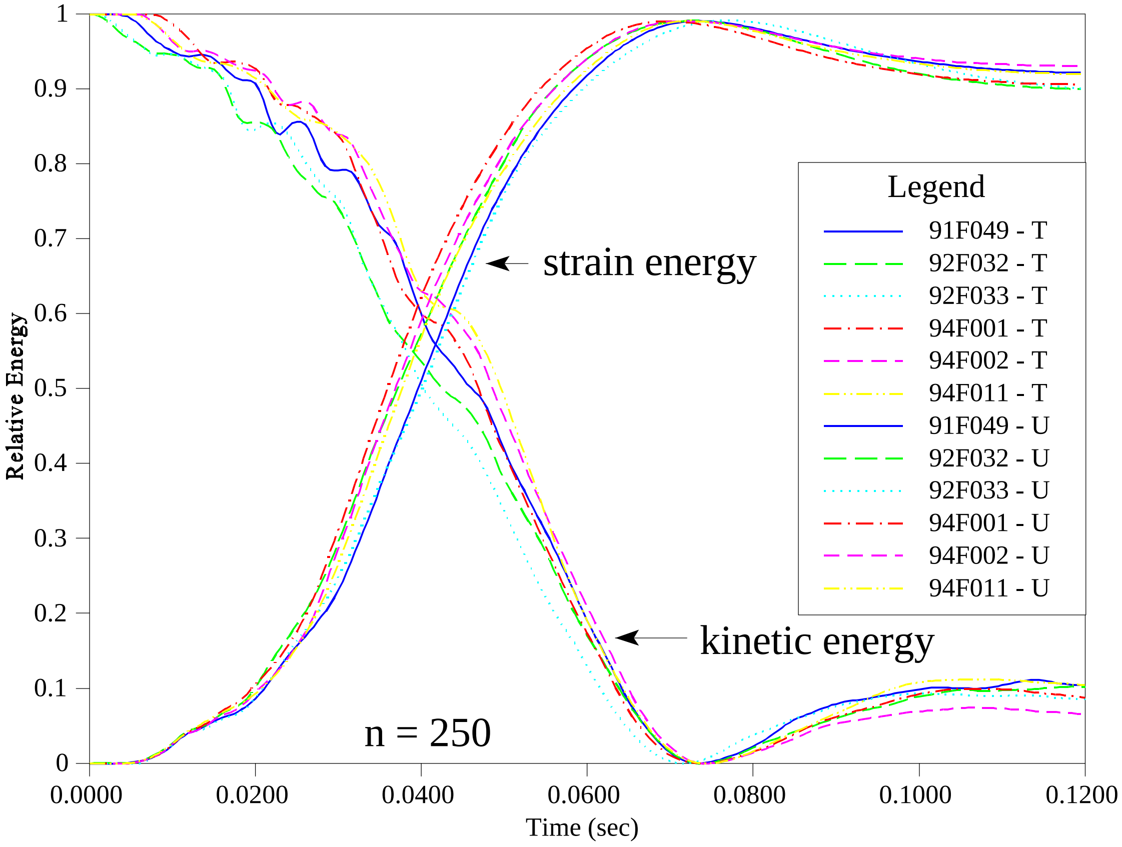

Figure 6. Relative Energy Balance for six identical 32-km/hr rigid pole impacts.

Figure 6 shows an energy balance for the six identical tests. The relative strain energy history is plotted along with the relative kinetic energy history. The relative strain and kinetic energy are found by dividing the actual energy at each time by the initial kinetic energy. This non-dimensionalizes the plot and removes small variations due to slightly different impact speeds. All six tests follow a similar pattern with the kinetic energy at its maximum and the strain energy at a minimum at the time of impact. Throughout the event the total energy, the sum of the strain and kinetic energy, is essentially a constant as should be the case.

SIMULATION COMPARISONS

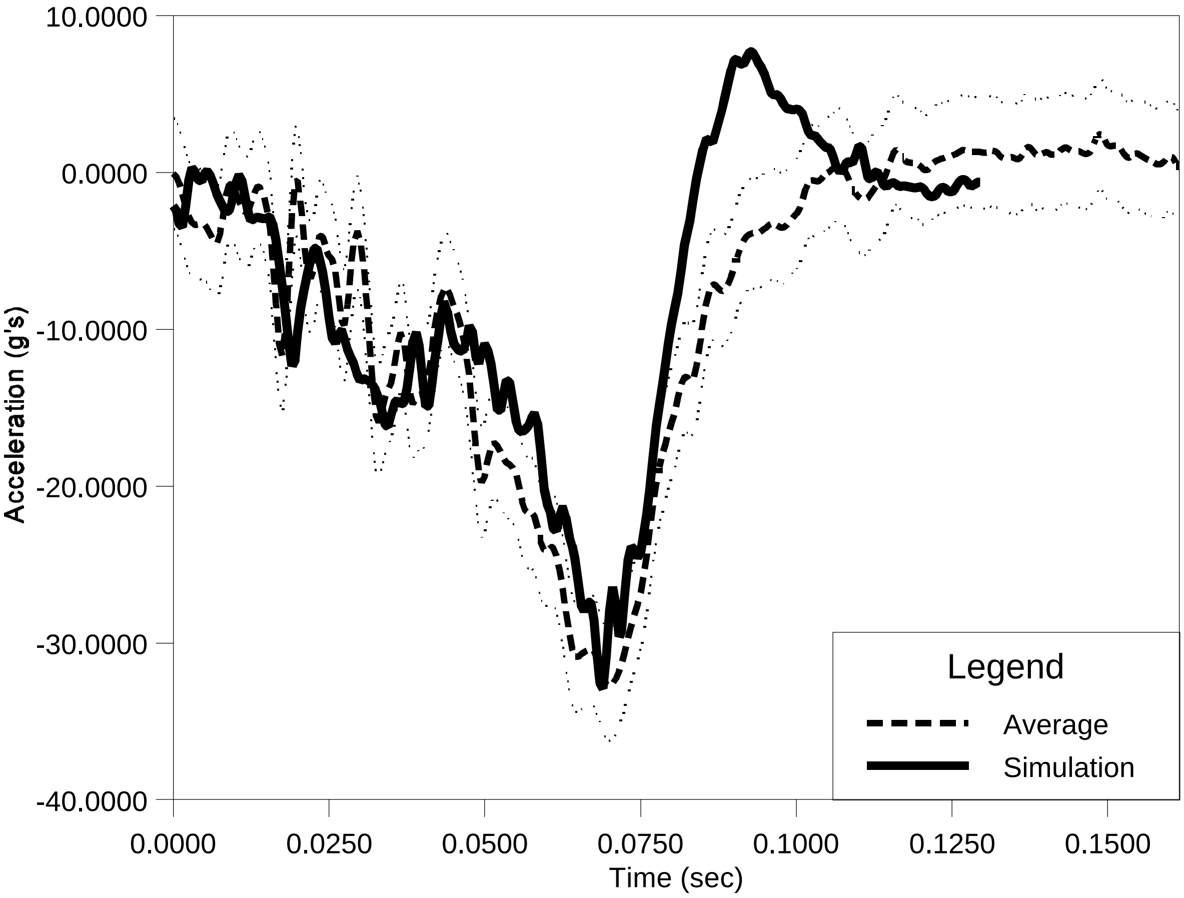

Figure 7. Comparison of a simulation and the average of six tests of 35-km/hr impacts of 1988 Ford Festivas with a rigid instrumented pole.

Table 5. Analysis of variance for a 35-km/hr test and simulation of a 1988 Ford Festiva with a rigid pole.

cut-off time (msec)	70	120
e (g’s)	0.19	1.07
σ_e (g’s)	4.38	4.58
t	0.52	4.18

The small-car rigid-pole impact described in the previous section was also modelled using the DYNA3D nonlinear finite element program.(10) The simulated response is shown with the average response from the six identical tests discussed in the previous section in figure 7. Table 5 shows the values for the analysis of variance of the DYNA3D simulation compared to the average response of the six full-scale crash tests. The two curves follow each other generally but an analysis of the variance would provide a more quantitative assessment of the correlation. The simulation acceleration history seems to follow the test curve better prior to the peak acceleration. The statistics shown in Table 5 also indicate that the correlation is better in the earlier phase of the impact. The t-statistic for the whole event is 4.18, greater than the critical 90-percentile value of 2.58. This suggests that the <u>whole</u> event does not replicate the full-scale tests. An analysis of just the first 70 msec of the event (the time up to the peak acceleration) indicates that the simulation and full-scale tests cannot be distinguisted from each other, at least as far as the t-statistic is concerned. This analysis of the variance suggests that the model does a good job at predicting the response of the full-scale tests up until the peak loading occurs.

Table 6. Analysis of variance for a 56-km/hr test and simulation of a 1988 Taurus rigid wall impact.

e (g’s)	-3.71
σ_e (g’s)	24.78
t	-0.02

Figure 8 shows an example of another simulation compared to a full-scale crash test. This test involves a 1988 Ford Taurus impacting a rigid wall at 57 km/hr, the typical FMVSS 208 test conditions.(11) (12) As shown in figure 8, the two acceleration histories correspond quite closely to each other so they appear, subjectively, to represent the same event. If the time histories residuals are examined as discussed above the results shown in figure 8 are obtained. The standard deviations of the residuals are about 17 percent of the peak acceleration and the average residual is about two percent of the peak acceleration. The t-statistic indicates that there is no statistically valid reason for not considering these two time histories equivalent. The model, therefore, is as good a predictor as running another test at the same impact conditions.

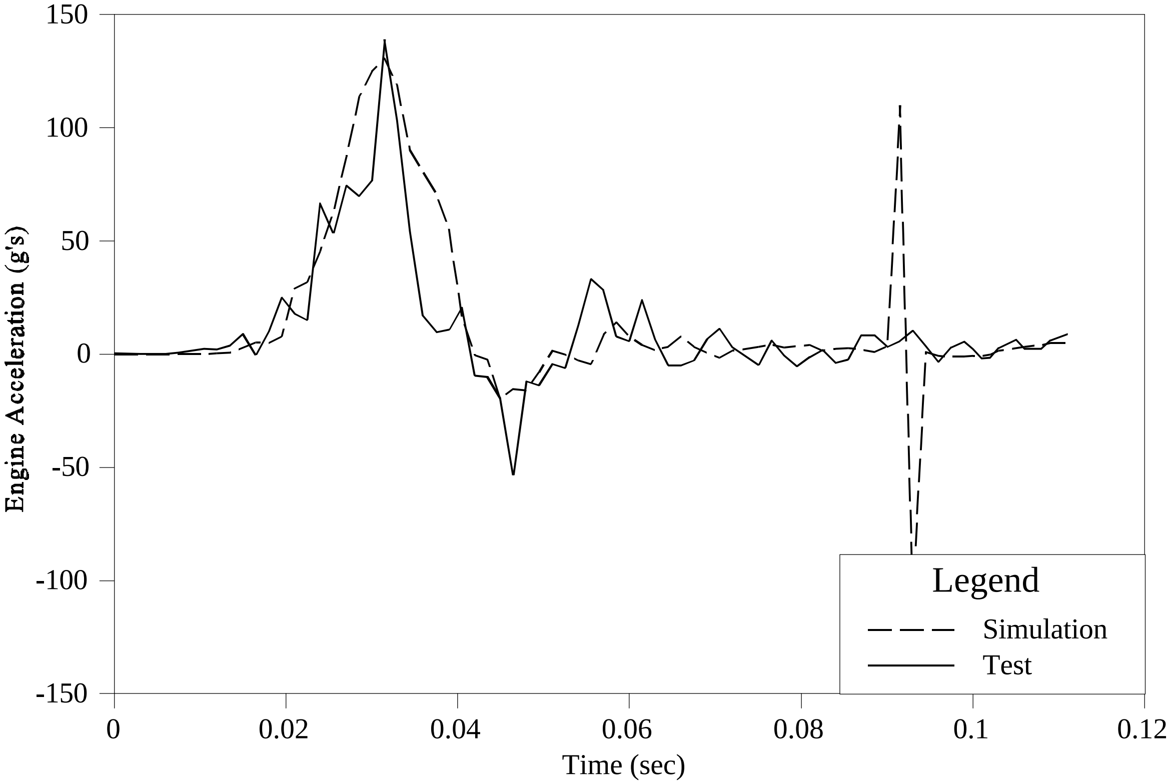

Figure 8. Comparison of a simulation and test of a 57-km/hr frontal impact of a 1988 Taurus with a rigid wall.

CONCLUSIONS

The technique described in the previous sections is certainly not the only method that can be used to compare crash test and simulation data. The particular choice of what measure of validation to use is not nearly as important as a commitment to using some type of quantifiable and objective measure.

The full-scale crash tests used in this work represent some of the <u>most</u> repeatable of crash test scenarios. The critical values recommended herein may prove to be too restrictive for some roadside hardware collision scenarios. On the other hand, these results should be useful for examining typical NHTSA compliance tests like FMVSS 208 which also feature highly repeatable crash test scenarios. Only additional experience with typical roadside hardware simulations and crash tests will provide the answers for how well crash tests and simulations can be correlated. The suggestions in this document are intended to provide a quantifiable technique for making such comparisons.

A simulation should be judged an adequate representation of a full-scale crash test when the following conditions are met:

- The average residual of the test curve compared to the simulation curve should ideally be zero. For practical purposes, if the average is less than 5 percent of the peak acceleration it should be considered to be close enough to zero.
- The standard deviation of the residuals should be less than about 20 percent of the peak acceleration.
- A t statistic should be calculated between the test and simulation curve. The calculated t statistics should be less than 3.

Using more quantifiable validation criteria will assist analysts in making more objective decisions about the quality of finite element models and their ability to predict impact events. As demonstrated in this paper, there is some degree of variability between nearly identical tests and even between different accelerometers measuring the impact event. Finite element analysis should produce results that fall within the normally expected values for tests if a series of tests were performed.

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