QUANTITATIVE EVALUATION OF THE
FIDELITY OF PUBLIC-DOMAIN VEHICLE MODELS
FOR ROADSIDE HARDWARE RESEARCH

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Abstract - In recent years nonlinear finite element analysis has been used as a tool for exploring the effectiveness and performance of roadside safety hardware. A finite element assessment of barrier performance involves detailed models of both the roadside safety hardware and the impacting vehicle. The ability of the combined model to accurately explain or predict the behavior of the barrier in a physical event is a function of the fidelity of both the vehicle and barrier model. Most recent analyses of roadside hardware collisions have used general purpose public-domain vehicle models as a way to develop models quickly without necessarily verifying the fidelity of the vehicle models. This paper assesses the fidelity of several of the most common public-domain vehicle models with respect to their ability to correctly replicate accelerations at the center of gravity in centerline frontal impacts into rigid poles. A variety of quantitative assessment parameters are used to make these comparisons. The purpose of this research was to determine the quantitative parameters that are most useful in assessing the fidelity of vehicle and barrier models.

NOTATION

\[ A, B \] \quad \text{Coefficients of expansion of a signal}

\[ C, C_{\text{max}} \] \quad \text{Calculated signal and maximum calculated signal (e.g., the accelerations from the simulation)}

\[ C \] \quad \text{Comprehensive combined phase (P) and magnitude (M) error factor}

\[ D \] \quad \text{Root mean squared log spectral difference}

\[ \bar{\epsilon}, \bar{\epsilon}' \] \quad \text{Average residual error and relative average residual error}

\[ V_e, V'_e \] \quad \text{Area of the residual error and the relative area of the residual error}

\[ m_i, m_{\text{max}} \] \quad \text{Measured signal and maximum value of the measured signal (e.g., the test accelerations)}

\[ M \] \quad \text{Magnitude error factor}

\[ \Delta M_n, \Delta M'_n \] \quad \text{Difference of the n\textsuperscript{th} moments and relative difference of the n\textsuperscript{th} moments}

\[ n \] \quad \text{Number of paired data points}

\[ P \] \quad \text{Phase error factor}

\[ \Delta R M S'_{\text{log}} \] \quad \text{Relative difference of the log root mean squared signals}

\[ t \] \quad \text{Time}

\[ \Delta t \] \quad \text{Discretized time interval}

\[ T_p \] \quad \text{Paired t statistic}

\[ p(T_p) \] \quad \text{Probability of incorrectly rejecting the null hypothesis (type 1 error) in a t test}

\[ \rho \] \quad \text{Correlation coefficient}

\[ \omega \] \quad \text{Signal frequency}

\[ r(\omega) \] \quad \text{Smoothed power spectra of a signal}

\[ \sigma_e, \sigma'_e \] \quad \text{Standard deviation of residuals and relative standard deviation of the residuals}

INTRODUCTION

Rapid improvements in both computation hardware and software have made the analysis of roadside hardware collisions possible that would have been considered far too complex and computationally expensive just a few years ago. The non-linear finite element program LS-DYNA3D is being used to develop vehicle and roadside hardware models to assess the performance of roadside safety hardware in realistic collision scenarios. [1][1]

Full-scale vehicle crash tests have been performed to evaluate roadside safety hardware for more than 30
years. Examining the acceleration-time history of the vehicle center of gravity has been one of the primary methods of judging the kinematics of the vehicle-barrier interaction in full-scale physical crash tests. Often the only instrumentation used in the physical crash tests are accelerometers mounted at the vehicle center of gravity. When simulating such events using nonlinear finite element analyses a natural first step is to replicate the acceleration-time history of the vehicle center of gravity and compare the time histories of the simulated and physical events. While comparing acceleration histories is a logical first step, other more interesting comparisons could be made if vehicles and barriers were instrumented to collect the data in physical tests. Information about member forces could be collected using strain gauges and accelerations of individual components could also be measured using accelerometers. While the examples in this paper discuss acceleration histories obtained at the center of gravity exclusively, these same quantitative evaluation parameters could also be used for other types of measured time histories like strain histories and rate gyro time histories. The data being compared in this paper reflect the way that the physical tests have been instrumented in the past and not necessarily the best way to instrument physical tests in the future.

The tests used for comparison in this paper were all centerline frontal impacts with rigid poles. This type of impact is perhaps the most symmetric and most repeatable of impact scenarios in roadside safety testing. Most other, more realistic impact scenarios are much more complex and therefore not nearly as repeatable. Since the struck object (e.g., a rigid pole) is for all intents undeformable, the time histories in these events reflect only the response of the vehicle. This is an advantage when assessing the fidelity of the models since it eliminates any uncertainty about the fidelity of the model of the struck object (e.g., some type of traffic barrier). This simple impact scenario establishes the upper bound of quantitative assessment since it is unlikely that better results could be obtained in more complex impact scenarios. Obtaining good comparisons between these simple repeatable physical tests and the simulations will build confidence in the ability of finite element techniques to provide accurate and meaningful answers.

COMPARISON METHODS

Velocity histories are often used to compare impact events rather than acceleration histories. The advantage of using velocity histories is that velocity is related to the kinetic energy remaining in the impacting vehicle. The time integration of the acceleration curve also tends to smooth the response making the comparisons visually more similar. Unfortunately, the time integration of the acceleration response causes errors to accumulate in the velocity history because the error in each acceleration reading is added to the velocity history. In statistical terms, velocity histories derived from acceleration measurements are not statistically independent. Measured accelerations, in contrast, are statistically independent from each other since they are directly observed in the experiment. When an error occurs in an individual acceleration reading it has no affect on subsequent acceleration readings. Whenever quantitative methods of comparison are used the comparisons must use the values that are recorded directly in the experiment. In most full-scale crash tests this corresponds to accelerations obtained from accelerometers, rotational velocities obtained from rate gyros and strains obtained from strain gauges. All of the comparisons discussed in this paper were performed using the primary data collected in the physical experiments, namely accelerations.

The first step in comparing acceleration histories from a physical test to a simulated event is to subjectively evaluate the two responses. Qualitative measures like the shape of the curve, the duration, the number of peaks and other visual characteristics of the time histories are useful points of comparison and often convey
very important information to the analyst. Unfortunately, determining what is a good match and what is a poor match is very difficult using subjective methods; one analyst's good agreement is another's poor agreement. Quantitative methods are useful for calculating comparisons between physical and simulated events that are unambiguous and repeatable. The following sections describe several methods that have been used by a variety of researchers in recent years to compare time histories from physical experiments and finite element simulations. Additional details about each of these methods may be found in the literature cited.

Analysis of the Residuals

The first group of quantitative comparison methods involve an examination of the differences or residuals between the measured accelerations in a physical test \( (a_i) \) and the calculated accelerations from a simulation of the test \( (a_i) \). The residual is the algebraic difference between the experimental value and the simulated value at each time step. If two curves represent the same physical event, the residual differences between the two time histories must be attributable to random experimental error alone. If the residuals of two acceleration time histories can be explained by random experimental error, the distribution of residuals will be normally distributed about a mean residual error of zero. The distribution of the residuals can be examined with a variety of well-known standard statistical techniques that test the assumption that residuals are normally distributed about a mean of zero.

The paired two-tailed \( t \) test has been proposed for comparing two experimental acceleration time histories sampled at the same frequency.[1] For convenience in comparing different types of impacts, the average residual \( \bar{\delta} \) and the standard deviation of residuals \( \sigma_{\delta} \) may be divided by the maximum observed experimental value (e.g., the peak measured acceleration, \( m_{\text{max}} \)) to obtain the relative average residual error, \( \bar{\delta}' \), and the relative standard deviation of the residual errors, \( \sigma_{\delta}' \). The paired \( t \)-statistic is conventionally defined as:

\[
T_p = \frac{\sqrt{n} \bar{\delta}'}{\sigma_{\delta}'}
\]

where \( n \) is the number of paired samples (e.g., the number of acceleration values sampled).[1] When two time histories represent the same physical event, both time histories should be identical such that \( \bar{\delta}' \) and \( \sigma_{\delta}' \) are zero. This is almost never the case in practical situations since experimental error causes small variations between tested responses. If the residual errors are due only to normal random experimental error, then the residuals should be distributed about a mean of zero. The conventional \( T \) statistic provides an effective method for testing the assumption that the observed \( \bar{\delta}' \) is close enough to zero to represent only experimental error. If the observed \( t \) statistic \( (T_p) \) is within the range of critical \( t \) statistics there is no statistically valid reason for rejecting the assumption that the two time histories represent the same event.

\[-t_{\alpha/2,n-1} \leq T_p \leq t_{\alpha/2,n-1}\]

If the computed \( t \) statistic is in the range:
where \( t_{\alpha/2,n-1} \) is the critical two-tail t statistic at the \( \alpha \) confidence level for \( n \) samples, the difference between the two time histories at the \( \alpha \) level can be explained by random experimental error alone.

Still another approach based on an examination of the residuals is to calculate area between the two signals. The area between the signals, is given by (in this and all subsequent equations, the measured and calculated accelerations are presumed to be in engineering units rather than g's):

\[
V_e = \left[ \sum_{i=1}^{n} (m_i - c_i)^2 \right]^{1/2} \Delta t
\]

and calculated accelerations are presumed to be in engineering units rather than g's).

The area under an acceleration curve has units of velocity so the area between the acceleration curves will also have units of velocity. The method of least squares states that the comparison with the smallest area between the two signals is the best predictor of the response since it minimizes the residuals (i.e., error). The area of the residual can be divided by the initial impact velocity to obtain a non-dimensional measure of the amount of residual error between two time history responses, \( V_e' \). Smaller values of the \( V_e' \) indicate smaller residual errors between the physical test and the simulated event. If the measured and calculated responses are identical, \( V_e' \) will be zero.

NARD Validation Method

The NARD Validation Manual published by Federal Highway Administration (FHWA) in 1988 lists comparison criteria for time domain and frequency domain analysis.[1] The time domain parameters for comparison of simulation and full scale crash tests are: (1) the relative absolute difference of moments of the two signals, (2) the root mean square (RMS) log measure of the difference between the two signals and, (3) the measure of correlation between the signals. Frequency domain methods have rarely been used since crash events are usually short duration transient events where spectral methods are not easily applied.

Moments are mathematical characteristics of a shape (e.g., moments of inertia) and can be defined by the following general expression:

\[
M_j = \sum_{i=1}^{n} t_i m_i
\]

The lower order moments have some physical meaning. For example, the 0th order moment (e.g., \( j = 0 \)) when divided by the number of samples is the average acceleration. The 1st order moment (e.g., \( j = 1 \)) divided by the 0th order moment locates the time at the centroid of the time history. Moments of order greater than one have little physical meaning when comparing time histories and are simply mathematical characteristics of the shapes. The more moments (e.g., characteristics) that two shapes have in common
the more likely, in a general sense, they are to represent the same shape. If enough characteristics of the measured acceleration history shape match the characteristics of the calculated acceleration history the shapes should be similar. The \( n^{th} \) moment difference of a measured \((m_i)\) and calculated \((c_i)\) signal normalized by the \( n^{th} \) moment of the calculated signal is given by:

The NARD procedure recommends that the \( 0^{th} \) through \( 5^{th} \) relative differences of the moments be calculated. The NARD Validation Manual arbitrarily considers the measured and calculated moments to be similar if the absolute difference between \( M_n(m) \) and \( M_n(c) \) is less than 0.2.

The mean of a signal is simply the algebraic sum of the values divided by the number of values. Similarly, the mean squared is the algebraic sum of the square of the values divided by the number of values. If the square root of the mean squared is taken the root mean square (RMS) is obtained as shown below:

The RMS is the average value of the signal without respect to its sign. The RMS of two signals can be compared by taking the difference of the two RMS and dividing by the average of the two RMS as follows:

Like moments, the RMS is simply a characteristic of a particular shape, in this case the average value of the accelerations without respect to the sign.

The NARD Validation Manual gives the logarithmic form of the RMS difference as:

Statistical correlation measures the dependence between two signals. Correlation does not mean, however, that the signals are identical but only that one can be linearly transformed into the other. The correlation coefficient is, therefore, a measure of the relative phasing of the two signals. The correlation coefficient of two signals is given by:
The three frequency domain criteria given in the NARD Validation Manual for the comparison of transformed signals \( F(\omega) \) and \( G(\omega) \) are: relative absolute difference of amplitude of two signals, pointwise absolute difference of amplitudes of two signals and, RMS log spectral difference between two signals. The time domain signal is transformed into its corresponding frequency domain signal using a Fourier transformation. Any time domain signal can be expressed in the form:

\[
f(t) = \sum_{n=-\infty}^{\infty} A_n \cos(n\omega t) + B_n \sin(n\omega t)
\]

\[
\Delta M^r_j = \sum_{t=1}^{n} t^j \sum_{i=1}^{n} t^i c_i
\]

\[
\sum_{i=1}^{n} t^i c_i
\]

If \( A_m \) and \( B_m \) are coefficients of \( m \) and \( A_c \) and \( B_c \) are coefficients of \( c \), then, if the point-wise absolute differences:

\[
|A_m - A_c|; |B_m - B_c|
\]

differences:

\[
\sqrt{A_m^2 + B_m^2} - \sqrt{A_c^2 + B_c^2}
\]

and the relative absolute difference:

are less than 20 percent, then the signals are considered to be close to one another.

The RMS log spectral distance in units of decibels (db) is given by:
\[ D = \frac{1}{2\pi} \int_{-\pi}^{\pi} \left| \ln \left( \frac{r_m(\omega)}{r_c(\omega)} \right) \right|^2 d\omega \]

The smaller the RMS log spectral distance between the signals is, the closer the signals are. A distance of 20 db or less indicates that the difference between the signals is not more than 20 percent. The smoothed power spectra of \( m \) and \( c \) are given by:

\[ C_m(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} m_t \ast m_{t+\tau} \, dt \]

where

**Magnitude-Phase Method**

Geers proposed three parameters for comparing an experimental time history to a calculated time histories.[1] This method, like the analysis of residuals method, is a paired data analysis method that requires both the physical and simulated time histories to be sampled at the same interval. The magnitude error-factor is given by:

\[ C_c(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} c_t \ast c_{t+\tau} \, dt \]
A comparison of Equations 5 and 8 shows that the magnitude error factor is simply one subtracted from the ratio between the measured and calculated root RMS signals.

\[ M = \left( \frac{\sum_{i=1}^{n} c_i^2}{\sum_{i=1}^{n} m_i^2} \right)^{1/2} - 1 \]

A comparison of Equations 9 and 7 shows that the phase error factor is simply one minus the square root of the correlation coefficient.

\[ P = 1 - \sqrt{1 - \rho} = 1 - \sqrt{\frac{\sum_{i=1}^{n} c_i m_i}{\sqrt{\sum_{i=1}^{n} c_i^2 \sum_{i=1}^{n} m_i^2}}} \]

The phase error-factor is given by:
A comparison of Equations 9 and 7 shows that the phase error factor is simply one minus the square root of the correlation coefficient.

\[ C = \sqrt{M^2 + P^2} \]

The comprehensive error factor combines both the magnitude and phase measure and is given by:
The quantitative comparison parameters described above represent the common values used to compare two time histories. All of them will be used in the following sections to assess the fidelity of public-domain vehicle models.

**IDENTIFYING THE IMPACT POINT**

Identifying the precise location of the impact point in a time history can often be a difficult practical matter. When two time histories are compared, finding the impact point is particularly important. One method for finding the most likely pairing point is using the method of least squares. The residuals are calculated, squared and summed using the analyst's best guess for the pairing point to calculate \( c_{\text{avg}} \). The most probable pairing point is the point that minimizes \( c_{\text{avg}} \) since this point would result in the least possible amount of error. The best pairing point can be easily found using a computer program that calculates \( c_{\text{avg}} \) for a number of possible pairing points. When the quantitative values discussed in the previous section are plotted with respect to the time shift, the optimal values were obtained at the most likely pairing point (e.g., the minimum value \( c_{\text{avg}} \)). The variation of the correlation coefficient, the standard deviation of the residuals, and the normalized form of the average sum of the squared residuals (\( c_{\text{avg}} \)) as the test data is shifted in time are shown in Figure 1. It can be seen from the figure that the maximum correlation occurs
at the same point as the normalized average residual square (e_{avg}) is also minimized. In the following analysis, all time histories curves were paired using this technique to ensure that the optimal statistics were obtained.

**COMPARISONS OF PUBLIC-DOMAIN VEHICLE MODELS STRIKING A RIGID POLE**

Fortunately, there are a number of centerline frontal rigid-pole full-scale crash tests that can be used to assess the fidelity of public-domain vehicle models. Many of these tests were performed specifically to be used in validating the vehicle models. The following sections will describe comparisons of rigid pole impacts with (1) a 1982 Honda Civic, (2) a generic 820-kg small passenger car, (3) a frontal impact bogie and (4) a C-2500 Chevrolet pickup truck. Noteably absent from this list is the 1988 Ford Taurus. A finite element model of this vehicle does exist but there are no frontal rigid pole impact available to compare the results of the simulations to so this model is not addressed in this paper. The frontal rigid pole tests are a good choice for comparing the fidelity of vehicle models
since all the energy must be deformed either through deformation or the kinematics of the vehicle. If the comparisons were made to collisions with deformable objects any errors could be due to the model of the object struck as well as the vehicle model.

**1982 Honda Civic**

The Honda Civic model was developed by Easi Engineering for the FHWA for use in simulating roadside hardware collisions. The model, shown in Figure 2, is a frontal impact, low resolution model of approximately 5000 elements and is available as a DYNA3D input deck or as an Ingrid input file.[1] To reduce the noise (vibrations) in the accelerometer readings at the center of gravity, the vehicle components behind the firewall were made rigid. The vehicle acceleration time history was collected from the response of this rigid portion of the model. The acceleration time history obtained from an LS-DYNA3D analysis was compared to several full scale crash tests of 1982 Honda Civics.[1] The vehicle struck the rigid pole at a velocity of 32 km/hr. The frequency of data collection was 2000 Hz in both the physical test and the simulation resulting in over 300 paired acceleration data points. The time histories are shown in Figure 3 and the comparison parameters are listed in Table 1.

As shown in Figure 3, there is a considerable area enclosed between the measured and calculated curves. The change in velocity represented by the area between the two curves is almost 5 percent of the initial impact velocity. The relative mean residual error is -6.29 percent of the peak measured acceleration indicating that on average the calculated response is smaller than the measured response as illustrated by Figure 3. The relative standard deviation of the residual error is almost 20 percent of the peak acceleration indicating that there are some substantial differences between the magnitude peaks of the two curves. As a result of the relatively large standard deviation and the non-zero relative mean residual, the T statistic is -4.97. A T-statistic of this magnitude (T statistics are not even tabulated about a value of ±3.4) suggests that the probability of these two curves representing the same event is less than 0.0002. The analysis of the variance terms indicate there are some important differences between the measured and calculated responses that cannot be explained by normal experimental error.

The NARD Validation Manual parameters are also shown in Table 1. The relative 0th moment (\(M_0\)) 18 percent of the calculated 0th moment. This indicates that the average acceleration of the measured response is 18 percent larger than the calculated response. The relative 1st moment (\(M_1\)) is a measure of the relative change in velocity. The measured response had a change in velocity that was 22 percent greater than the calculated response. The higher order moments (\(M_2\) through \(M_f\)) are also all around 20 percent but their physical significance is not apparent. The relative difference of the root mean squares (\(dRMS\)) indicates that the average unsigned acceleration is larger in the measured response than in the calculated response as can be confirmed by Figure 3. The two curves have similar phasing with the notable exception of a large negative peak in the measured response that is not replicated in the calculated response. The overall good phasing is represented by a high positive value (0.92) of the correlation coefficient, \(\rho\). With the
exception of the correlation coefficient, the NARD Validation Manual parameters also indicate that there are substantial differences between the measured and calculated responses.

Geer's magnitude-phase factors are also tabulated in Table 1. The phase factor, $P$, is also a measure of the relative phasing between the measured and calculated responses. The value of 4 percent, being close to zero, indicates good overall phase agreement. The magnitude factor, $M$, is a relatively high value of 22 percent indicating large differences between the measured and calculated peaks. The poor magnitude result is reflected in the correspondingly poor value for the combined factor, $C$. Gerr's parameters, therefore, also indicate that there are substantial differences between the measured and calculated responses.

**Report 350 820C vehicle**

The FHWA sponsored the development this low resolution, frontal impact model based on a 1989 Ford Festiva.[1] The 820c, shown in Figure 4, has about 4000 elements and is available as a DYNA3D input deck or a Trugrid input file. The floor was separated from the inner fenders and made rigid to aid in collecting center-of-gravity data. The occupant masses and accelerometer mass were also made rigid and merged with the floor. The material type of the car body was changed from an elastic to elastic-plastic material. The vehicle was impacted at the front center with a rigid pole at 32 km/hr. The data was collected at a frequency of 2000 Hz resulting
in 240 paired acceleration points. The acceleration time history of a simulation and six full-scale tests

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are shown in Figure 5 and the comparison values are shown in Table 2.

The acceleration data obtained from the simulation was compared with the six full scale frontal impact crash tests of Ford Festiva (820C vehicle) and is shown in Figure 5.[1][1] This test series provides an
unusual opportunity to examine the variability of the various parameters. As shown in Figure 5, there is good visual agreement between all the measured and calculated responses after approximately 30 msec but the first 30 msec of the calculated response are much smaller than any of the measured responses. The relative mean residual error between the calculated response and all six of the measured events is between -3.32 and -4.42 percent of the peak measured acceleration. The negative values of the relative mean residual confirm the visual observation that the calculated response is less than the measured responses. The relative standard deviation of the residual error is between 14 and 19 percent of the peak acceleration indicating that there are some substantial differences between the magnitude peaks of the two curves as can be confirmed visually in Figure 5. As a result of the relatively large standard deviation and the non-zero relative mean residual, the T statistics vary between almost three and almost 4.5. T-statistics of this magnitude suggest that the probability of the measured responses representing the same event as the calculated response is not better than 0.0052. The change in velocity represented by the area between the measured responses and the calculated response is approximately five percent of the initial impact velocity for all the measured events. All the variance measures shown in Table 2 show a great deal of consistency from test to test. The analysis of the variance terms, then, indicate there are some important differences between the measured and calculated responses that cannot be explained by normal experimental error.

The NARD Validation Manual parameters are also shown in Table 2. The relative 0th moment \( (M_0') \) is between 11 and 14 percent indicating that the average acceleration of the measured response is generally about 12 percent larger than the calculated response. The relative 1st moment \( (M_1') \) indicates that the relative change in velocity is within five percent of the measured values. Both the 0th and the 1st order moments are very consistent from test to test. The higher order moments \( (M_2' \text{ through } M_5') \) vary dramatically from and are not consistent from test to test. This indicates that the higher order moments may not be particularly useful in quantifying a comparison between a measured and calculated response. The relative difference of the root mean squares \( (\Delta RMS') \) indicates that the average unsigned acceleration is a little more than 70 percent larger in the measured response than in the calculated response as can be confirmed by Figure 3. \( \Delta RMS' \) is also very consistent from test to test. The overall good phasing is represented by a high positive value (0.92) of the correlation coefficient, \( \rho \). The 0th and 1st order moments, \( \Delta RMS' \) and \( \rho \) indicate relatively good agreement. With the exception of the higher order moments which are of uncertain physical significance, the NARD Validation Manual parameters indicate that the measured responses are suitably similar to the calculated response.

Geer's magnitude-phase factors are also tabulated in Table 2. Both the phase and magnitude factors are generally less than five percent indicating good relative agreement between the peaks as well as the phasing. Geer's parameters indicate that there is good agreement between the measured and calculated responses.
Frontal impact bogie vehicle

The bogie vehicle was developed in the late 1980's as a surrogate for actual production automobiles.[1] The simulation model of the bogie is composed of approximately 1500 elements and is available as an LS-DYNA3D input deck. The nose of the bogie model is made of crushable honey comb material. The material type for the 3rd stage was made the same as that of the 1st stage as is indicated on the construction drawings of the bogie. The back of the bogie was changed to a rigid material to ensure that good center of gravity data could be obtained. The bogie vehicle was impacted into a rigid pole at 32 km/hr and acceleration data was collected at 2000 Hz resulting in 280 paired acceleration points. The acceleration history of the bogie model was compared to the time histories obtained from four crash tests; two tests conducted using the FOIL version of the bogie and two tests using the ENSCO version of the bogie.[1] All the tests struck an instrumented rigid pole at a velocity of 32 km/hr. The time histories are shown in Figure 7 and the comparison parameters given in Table 3.

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NARD Validation

| $\Delta M_0$ | 16 % | 17 % | 18 % | 19 % |
| $\Delta M_1$ | 20 % | 24 % | 24 % | 23 % |
| $\Delta M_2$ | 22 % | 28 % | 28 % | 25 % |
| $\Delta M_3$ | 23 % | 31 % | 31 % | 27 % |
| $\Delta M_4$ | 24 % | 33 % | 34 % | 30 % |
| $\Delta M_5$ | 25 % | 35 % | 37 % | 33 % |
| $\Delta RMS_{\log}$ | 1.21 % | 1.22 % | 1.24 % | 1.24 % |
| $\rho$ | 0.97 | 0.96 | 0.95 | 0.96 |
| $\Delta AB_{rel}$ | 0.18 | 0.19 | 0.21 | 0.22 |
| $D$ | 0.010 | 0.023 | 0.031 | 0.017 |

Magnitude-Phase

| $M$ | -18 % | -20 % | -20 % | -19 % |
| $P$ | 1 % | 2 % | 2 % | 2 % |
| $C$ | 18 % | 20 % | 21 % | 20 % |

The $M$, $P$ and $C$ statistics are less than 0.2 for the bogie simulation with the exception of one value of $C$ which was just over 0.20. All the analysis of variance measures were close to the critical values with several just on the unacceptable side of the range. With the exception of the zeroth moment, which is simply the average acceleration, all the other moment measures were greater than 0.2. The correlation coefficient was much greater than the recommended value of 0.80.

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