Appendix A

Roadside Safety Verification and Validation Program (RSVVP)

User's Manual

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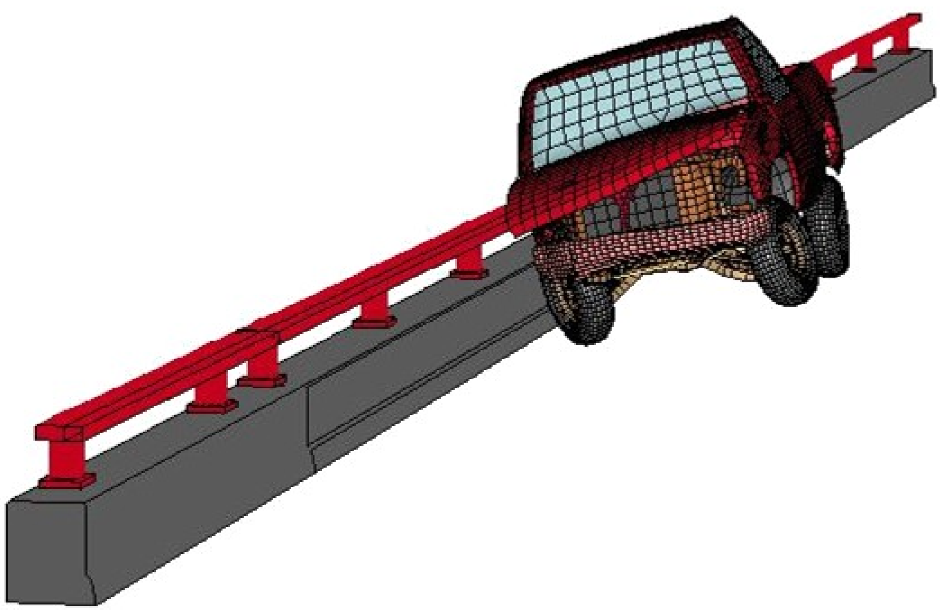

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INTRODUCTION TO RSVVP

The Roadside Safety Verification and Validation Program (RSVVP) quantitatively compares the similarity between two curves, or between multiple pairs of curves, by computing comparison metrics. Comparison metrics are objective, quantitative mathematical measures of the agreement between two curves. The comparison metrics calculated by RSVVP can be used to validate computer simulation results against experimental data, to verify the results of a simulation against the results of another simulation or analytical solution, or to assess the repeatability of a physical experiment. Although RSVVP has been specifically developed to aid in the verification and validation of roadside safety computational models, it can generally be used to provide a quantitative comparison of essentially any pair of curves. The comparison metrics calculated by RSVVP are deterministic, meaning they do not specifically address the probabilistic variation of either experiments or calculations (i.e., the calculation results are the same every time given the same input). For a description of each metric calculated by the RSVVP see the Appendix A1.

In order to ensure the most accurate comparison between the curves, RSVVP allows the user to select among several preprocessing tasks prior to calculating the metrics. The interactive graphical user interface of RSVVP was designed to be as intuitive as possible in order to facilitate the use of the program. Throughout each step of the program, RSVVP provides warnings to alert the user of possible mistakes in their data and to provide general guidance for making proper selection of the various options.

The interpretation of the results obtained using RSVVP is solely the responsibility of the user. The RSVVP program does not presuppose anything about the data; it simply processes the data and calculates the metrics. The user must verify that the data input into the program is appropriate for comparison and that the appropriate options in RSVVP are used for their specific case.

INSTALLATION

SYSTEM REQUIREMENTS

RSVVP has been written and compiled using Matlab®. In order to run the RSVVP program either the full Matlab® (version 2009a or higher) software or the free distributable *MATLAB Component Runtime* (MCR 7.10) software must be installed on the user's system. The minimum hardware requirements to run RSVVP are shown below in Table A1:

Table A1. Minimum hardware requirements for running RSVVP

	32 bit version	**64-bit version**
CPU	Intel® Pentium 4 (and above), Intel Celeron, Intel Xeon, Intel Core, AMD Athlon 64, AMD Opteron, AMD Sempron	Intel® Pentium 4 (and above), Intel Celeron, Intel Xeon, Intel Core, AMD64,
RAM	512 MB	1024 MB
Disk space	510 MB (MATLAB® only)	510 MB (MATLAB® only)

INSTALLATION OF THE MATLAB COMPONENT RUNTIME

The source code for RSVVP was written in Matlab® (version R2007b) and then compiled as an executable file for Windows® XP/Vista in order to create a standalone program that can be run on computers with or without Matlab® installed on them. However, before running RSVVP on a machine without Matlab® it is first necessary to install Matlab® *Component Runtime* (MCR 7.10), which is a free software distributed by Matlab®. MCR provides all the necessary Matlab® functional support to ensure proper execution of the RSVVP software. (Note: the MCR environment only has to be installed once). The latest version of RSVVP and the MCR environment can be downloaded from:
http://civil-ws2.wpi.edu/Documents/Roadsafe/NCHRP22-24/RSVVP/RSVVP_1_7.zip

To install MCR, perform the following steps:

1. Extract the content of the *RSVVP.zip* file in the folder on your PC where you want to install RSVVP (for example: *C:\RSVVP*).
2. Open the folder where you extracted the files and double-click on the *Installer.bat* file.
3. Follow the instructions of the installation wizard. It may take several minutes to complete the installation. This installs the free Matlab® MCR environment that is used in conjunction with RSVVP.
4. Reboot your PC.

At this point RSVVP should be installed on your computer.

STARTING RSVVP

After MCR and RSVVP have been installed, simply double-click the *RSVVP.exe* file located in the installation folder (e.g., *C:\RSVVP*) to start the program. Once started, a series of graphical user interfaces will guide the user through the preprocessing, the evaluation of the comparison metrics and saving the results. The following sections describe the features and use of the program.

EVALUATION METHODS AND DATA ENTRY PROCEDURE

General Discussion

In RSVVP, the baseline curve or reference curve is called the "true curve" as it is assumed to be the correct response, whereas the curve that is to be verified or validated, say from a model or experiment, is called the "test curve." For example, in validating a computer simulation against a full-scale crash test, the time history data from the physical crash test would be input as the "true curve" in RSVVP and the computer simulation time history would be input as the "test curve". Since the comparison metrics assess the degree of similarity between any pair of curves in general, the input curves may represent various physical entities (e.g., acceleration time histories, force-deflection plots, stress-strain plots, etc.). RSVVP does not presuppose anything about the curves being compared so it is the user's responsibility to ensure that the units, for example, are consistent. The only restriction on the input data is that the abscissa values must increase monotonically. Curves representing loading/unloading cycles or, in general, curves which are characterized by more than one data point with the same abscissa value cannot be managed in RSVVP at the moment. As a note of caution: when using RSVVP to compare force-deflection data or stress-strain data, the user must ensure that the abscissa data is monotonically increasing. It may be more appropriate to compare force-time history data and deflection-time history data separately to avoid this problem.

Comparison metrics provide an objective measure of how well two curves match each other and can thus be applied to essentially any monotonically increasing pair of curves. A typical application of the metrics evaluated by RSVVP is the validation of a numerical model by comparing the numerical results with the experimental results. Another application could be to check the repeatability of an experiment by comparing the results obtained from several repetitions of the same experiment. Yet another application is to verify the results of one numerical simulation with the results of another numerical simulation.

Two general types of comparison can be performed in RSVVP:

1. Single Channel - A single pair of curves are compared
2. Multiple Channels- Multiple pairs of curves are compared (i.e., up to three acceleration-time histories and/or three angular rate-time histories).

In the ‘Single Channel’ option, comparison metrics are based on the comparison of a single pair of input curves, while in the ‘Multiple Channel’ option the comparison metrics are computed by either, 1) calculating the metrics for the individual channels (i.e., curve pairs) and then computing composite metrics based on a weighted average of the individual channels, or 2) calculating the resultant of the various channels and then computing the comparison metrics based on the resulting single curve pair. In either case, the ‘Multiple Channel’ option is intended to provide an overall assessment of the multiple data channels by computing a single set of composite metrics.

The *multiple channel* option in RSVVP was created for the specific purpose of comparing numerical simulations of vehicle impact into roadside barriers to the results from a full-scale crash test. An example might be a small sign support test where the longitudinal acceleration has a much greater influence on the results of the impact event than do the lateral or vertical accelerations. The less important channels may not satisfy the criteria because they are essentially recording noise. The longitudinal channel in this example will probably be an order of magnitude greater than some of the other less important channels and the response is essentially completely determined by the one longitudinal channel. The weighting factors used to compute the composite metrics are based on the area under the true curve for that respective channel, and thereby account for the different levels of importance of the various channels.

FORMAT OF INPUT CURVES

The input curve files must be in ASCII format but can have any extension (or no extension) in the file name. The abscissa and ordinate data of the input curves must be tabulated into two columns as shown in Figure A-1. Each line in the input file represents a single data point (e.g., time and corresponding acceleration). If a data file includes a header, RSVVP will automatically detect and skip it. In such case, RSVVP will warn that a header was detected and will ask the user for confirmation of the number of lines to be skipped before staring data entry.

```
Abscissa      Ordinate
0.00000000    0.10000000
0.02000000    0.09900000
0.04000000    0.09800000
0.06000000    0.09700000
0.08000000    0.09600000
0.10000000    0.09500000
0.12000000    0.09400000
0.14000000    0.09300000
..........................................
```

Figure A-1: Format of the test and true curves.

Although no limitation is imposed or assumed for the units of both the abscissa and ordinate columns, the use of some preprocessing features like the SAE filtering option may only make sense for time history data (i.e., the first column represents time). It is the users responsibility to ensure that the units of the input curves are consistent, especially when comparing multiple pairs of curves in the Multichannel mode.

COPY OF THE ORIGINAL INPUT CURVES

A copy of the original input curves is automatically saved into the folder '\Input_curves' in both the main directory of RSVVP and the 'Result_XX' folder. Any file saved into the '\Input_curves' folder located in the main directory is deleted at the beginning of each new run of RSVVP.

LOADING A CONFIGURATION FILE

The user can also load a configuration file from a previous run of RSVVP. This configuration file contains all the necessary information to retrieve the files containing the original input curves and all the selected options for the preprocessing of the curves and the evaluation of the metrics. This configuration file can be loaded into two different ways:

- *Run Completely* mode, or
- *Edit Curves/Preprocessing* mode.

When the *run completely* mode is selected, RSVVP reads the configuration file and automatically evaluates the comparison metrics using the options stored in to the configuration file (e.g. preprocessing, metrics selection time intervals, etc.). This option is a useful tool for providing documentary proof of the values of the comparison metrics obtained during the verification/validation process or to simply enable the user to re-run a previously saved session. Using the *run completely* mode, RSVVP provides the user three options:

1. Reproduce comparison metrics using all the user time intervals from the original run,
2. Reproduce comparison metrics from a portion of the original time intervals (but with the constraint to follow the original sequence of the intervals) or
3. Compute comparison metrics on new user-defined time intervals.

The original configuration file can be updated with the new user defined time intervals at the end of the calculation.

Likewise, in e*dit curves/preprocessing* mode, RSVVP loads the original input curves and automatically preprocesses them according to the options saved in the configuration file. In this mode, however, once the curves have been preprocessed, the user can go back and modify any of the preprocessing options or replace any of the original input curves. This option can be very useful when the analyst wants to assess, for example, how the various pre-processing options affect the values of the comparison metrics.

Procedure for Selecting Evaluation Methods

At the startup of RSVVP, first select a maximum re-sampling rate using the drop-down menu, 'Re-sampling rate limit', as illustrated in Figure A-2. By default, RSVVP limits the rate at which the curves are re-sampled to a maximum of 10 kHz. If a higher limit is desired, the user can choose from the available options in the drop-down menu.

Then choose between 'Single Channel', 'Multiple Channel', or 'Load a Configuration' File options.

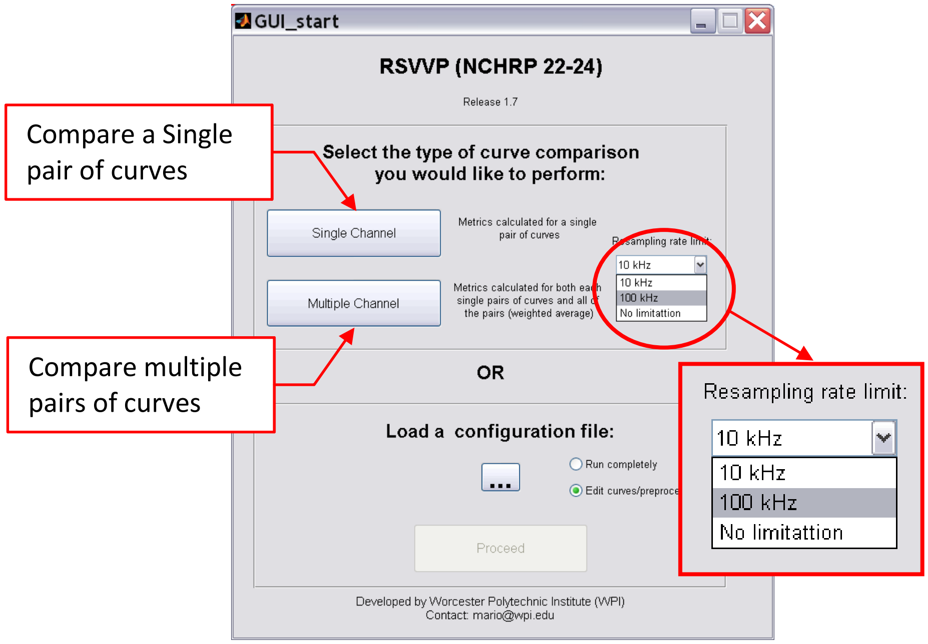


Figure A-2: Selection of the type of comparison and re-sampling limit.

To Load the configuration file, click the button with three dots (i.e. ...). This will open a browse window that can be used to search/select the desired configuration file, as shown in Figure A-3. Once the configuration file has been loaded, the button '*Proceed*' becomes active.

Before proceeding, select the desired mode for running the configuration file (i.e., '*Run completely*' or *'Edit curves/preprocessing')* The default option is to load the configuration file in *Edit* mode; to change to '*Run completely*' mode, select the corresponding radio button

Note: When a configuration file has been loaded in '*run completely*' mode, any selection made by the user to limit the re-sampling rate is overridden by the configuration file. In order to change the re-sampling limit, load the configuration file in 'edit' mode.

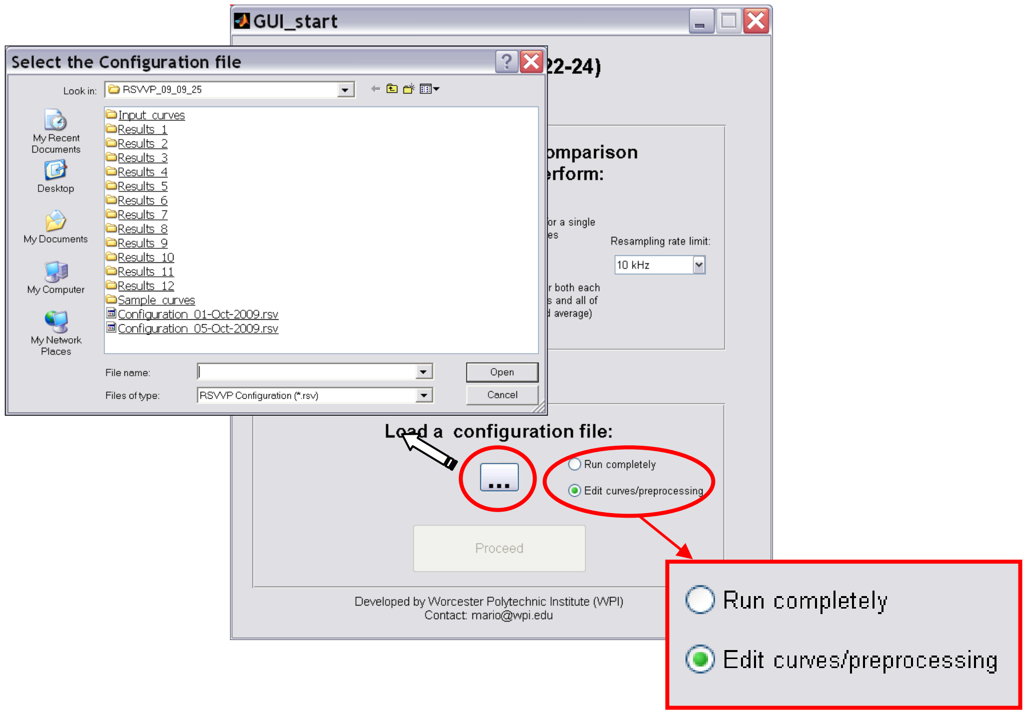


Figure A-3: Selection of the configuration file.

Procedure for Data Entry

After the analysis options have been selected, RSVVP closes the window and opens another graphical user interface that will be used for loading and preprocessing the input curves.

Clicking on the buttons, '*Load True Curve*' and '*Load Test Curve*', opens a browse window that can be used to search/select the corresponding curves, as illustrated in Figure A-4. Recall from the discussion section that the '*True Curve*' is the baseline curve or reference curve and is assumed to be the correct response; the '*Test Curve*' is the data from a model or experiment that is to be verified or validated.

After each input file is loaded, RSVVP will show a preview of the raw curves in the graphics area on the left side of the main window, as shown in Figure A-4.

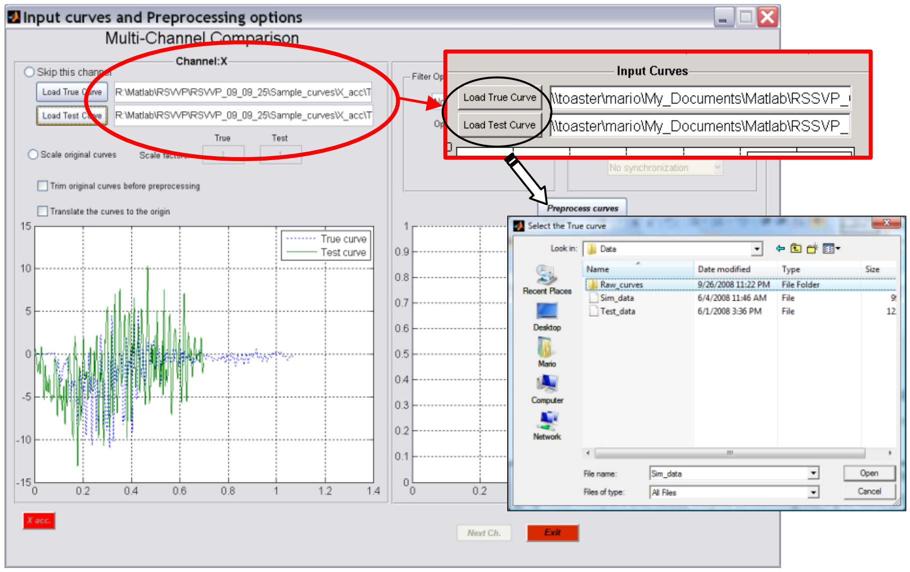


Figure A-2: Input of the test and true curves.

Procedure for Initial Preprocessing

The user is given the option to perform initial adjustments of the data, including scaling, trimming, and translating the curves, prior to applying additional preprocessing options, as shown in Figure A-5. The radio button to scale the input curves and the checkboxes to activate the option to trim and/or translate the curves to the origin can be selected only after both the test and true curves have been input.

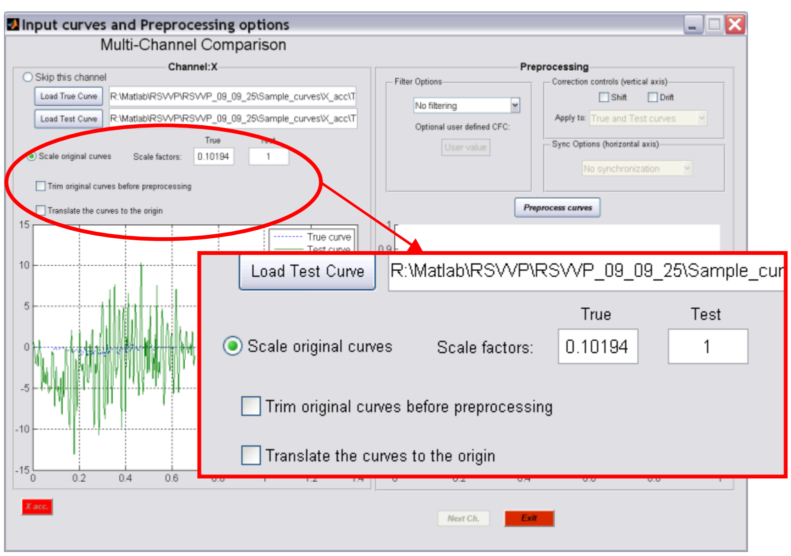


Figure A-5: Checkboxes for the manual trim and the translation of the raw curves.

Curve scaling

The '*scale*' option allows the user to scale the original time histories using user-defined scale factors. The true and test curves can be scaled by separate scale factors. This option may be used, for example, to invert the sign of time histories or to convert units (e.g., accelerations can be converted from m/s^2 to g's).

To scale either the true curve or test curve or both, check the radio button '*Scale original curves*' shown in Figure A-5. Input the scale factor for the true and/or test curves into the respective fields '*True*' and '*Test*' located beside the radio button. Each time a new scale factor is defined for either the true or the test curve (or the scaling option is deselected), the graphs are automatically updated.

Curve trimming

The '*trim*' option allows the user to trim the beginning and/or the end of the raw data *before* preprocessing the curves. This option can be used, for example, to remove the pre- and post-impact data from the curves to ensure that the comparison evaluation is applied only to the impact portion of the data. The '*trim*' option can also be used, for example, to trim the input data at a point where the true and test curves start diverging to allow for better synchronization of the curves in the preprocessing phase. Although it is possible to specify a *user defined time interval* over which to evaluate the comparison metrics (see section *Time Interval*), it is advisable to trim the input curves when they have a 'null head' or 'null tail' in order to improve data synchronization during the preprocessing operations.

To trim the original data, check the box '*Trim original curves before preprocessing*'. This action will open the pop-up window shown in Figure A-6. The '*trim*' option is applied to the true and test curves independently. The fields 'Lower limit' and 'Upper limit' show the boundary values for the curve selected using the radio buttons for either the test or true curve. Only one curve at a time can be selected in order to allow for independent trimming of each of the two curves. The curve selection is performed using the radio buttons located at the bottom left of the window. A straight and dotted line respectively indicates the lower and upper limit in the graph area. Both the lines move according to the value input in the user fields (blue and green color are used for the true and test curves, respectively). By default, both the test and true curves are shown in the graph area; however, RSVVP provides an option to only show the curve being trimmed, which is useful when the curves cannot easily be distinguished.

If the raw data curves are characterized by a high level of noise, the *trim window* also provides an option for the user to filter the curves before performing the trim operation. The user can select the desired CFC value from the drop-down menu located in the '*Filter option*' box. While it is not recommended, if the user wants to use filter specifications different from the standard SAE J211 filters, user defined filters parameters can be specified.

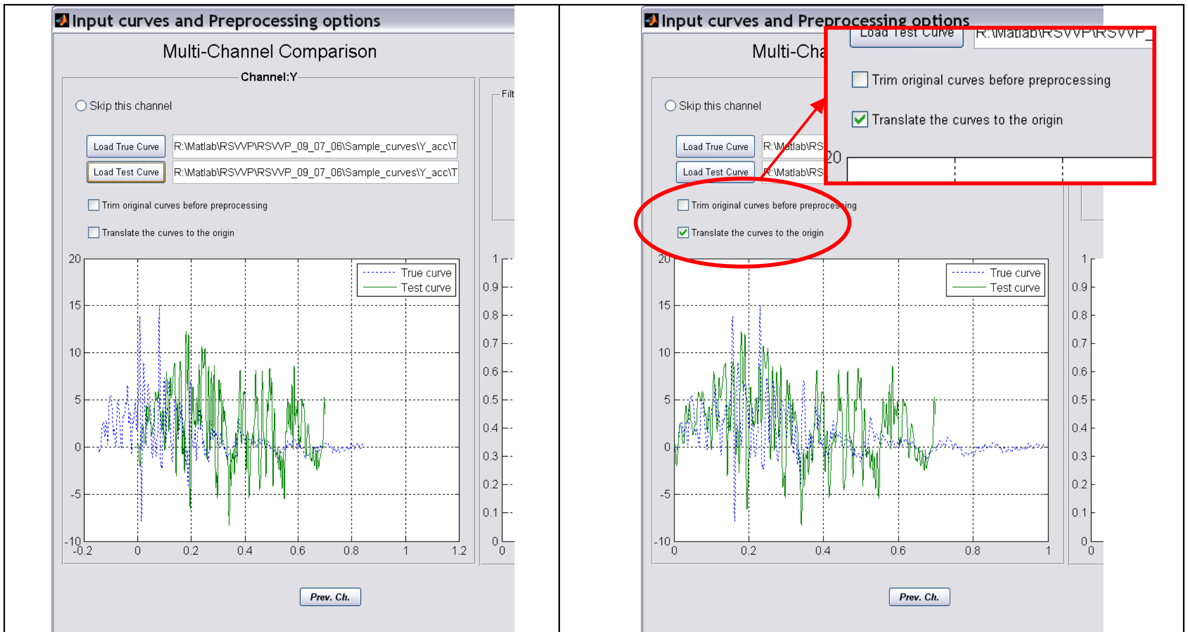
<u>Note:</u> If data is filtered during the trimming process, the user will not be allowed to change the filtering option during subsequent preprocessing operations. If a different filtering option is desired, it will be necessary to return to the 'trimming' box to make any change in the choice of filtering.

Figure A-6: Window for trimming input curves.

<u>Curve translation</u>

The '*translate*' option allows the user to shift the input curves along the abscissa. This may be used, for example, to ensure that the beginning of the abscissa vector starts at zero (e.g., if time histories are input, the time vector can be shifted to start at time zero). This option works for either positive or negative value.

If the '*trim*' option has been used, then the curves are automatically translated to the origin so there is no need to perform the '*curve translation*' procedure. In fact, the checkbox to translate the original raw curves is not active when the '*trim*' option has been selected. This option is useful whenever one or both the original input curves are shifted with respect to the origin. A typical application is shown in Figure A-7.



Original input true and test curve	True and test curves after the translation to the origin

Figure A-7: Shift of one of the two input curves to the origin.

<u>*Note*</u>*:* If the option to scale the original curves is changed or if the scaling factors are changed, RSVVP will automatically update the graph of the original input curves as well as the graph of the preprocessed curves.

<u>*Note*</u>*:* If the 'trim' option or the 'translate' option is changed, or if an input curve is changed, then all the preprocessing operations applied to the curves are reset by RSVVP.

<u>*Note*</u>*:* The *copies* of the original input curves (automatically saved by RSVVP) do not include any of these initial preprocessing results.

PREPROCESSING

RSVVP is now ready to perform some basic and <u>necessary</u> pre-processing operations on the input curves, as well as some <u>optional</u> preprocessing operations that can be selected by the user based on qualitative visual assessment of the original data. In order to calculate the comparison metrics, all the curves must all have the same sampling rate and the same number of data points. Because these operations are necessary for subsequent calculations, they are performed automatically by RSVVP and do not permit user control. When the '*multiple channel*' option has been selected, RSVVP trims each individual channel of data based on the shortest curve in each curve pair; then, after all the data has been input and preprocessed, the curves are further trimmed to the length of the shortest channel.

If the original sampling rate of one of the curves is larger than the '*re-sampling rate limit*', the data will be re-sampled to the chosen limit value (see Figure A-2). Note that higher sampling rates result in more data points and will therefore increase computation time. When the '*multiple channel*' option has been selected, the sampling rate determined for the first pair of curves is used for all subsequent data pairs.

In order to proceed to the next step (i.e., metrics selection) it is necessary to press the '*Preprocess curves'* button even if no optional preprocessing options have been selected.

RSVVP provides three optional pre-processing operations, including:

- Filtering,
- Shift/drift control and
- Synchronization.

Each of these three preprocessing operations is <u>optional</u> and can be <u>selected independently</u> from each other. After selecting the desired preprocessing options, press the '*Preprocess curves'* button located immediately below the *Preprocessing box* to preview results. If the results are not satisfactory, any of the previous options can be changed until satisfactory results are obtained.

<u>Note:</u> When the '*multiple channel*' option has been selected, the synchronization option will not be active in the preprocessing window. For multiple channels, the option for data synchronization, as well as other preprocessing operations, will be made available in an additional/secondary preprocessing step.

FILTERING

RSVVP gives the user the option of filtering the two input curves. This option can be very useful when the original input curves are noisy (e.g., noise created by the transducer during the acquisition process of experimental curves or undesired high-frequency vibrations). In order to obtain a value of the comparison metrics that is as reliable as possible, it is very important to remove noise from both the test and true curves. While noise derives from different sources in physical experiments and numerical simulations, the true and test curves should be filtered using the same filter to ensure that differences in the metric evaluation are not based on the difference in frequency content in the true and test signals.

The filter options in RSVVP are compliant with the SAE J211/1 specification. It is recommended that raw data be used whenever possible in the evaluation to avoid inconsistent processing of the two curves. It is also important that both the test and true curves are filtered in the same way to avoid errors due to different filtering techniques. Although there is no general limitation to the type of units used for the input to RSVVP, the SAE filtering option presumes that the curves are time histories with time values expressed in units of seconds. In a future release of RSVVP, the option to use different units for the time vector of the time histories will be implemented.

The user can select between the following SAE J211 Channel Frequency Class (CFC) filters: 60, 180, 600 and 1000. Table shows the specifications of each CFC value as defined by SAE J211/1.

Table 2: Specifications for typical CFC values.

CFC value	3 dB limit frequency [Hz]	Stop damping [dB]
60	100	-30
180	300	-30
600	1000	-40
1000	1650	-40

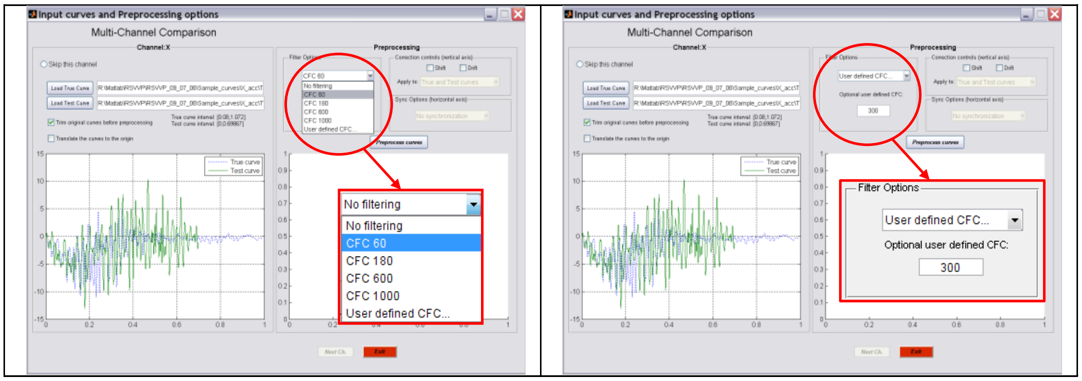
While it is not recommended, if the user wants to use filter specifications different from the standard SAE J211 filters, user defined filters parameters can be specified.

Procedure for Filtering Data

By default RSVVP does NOT filter the input curves. To apply the filter option, click on the drop-down menu in the 'Filter Options' box (Figure A-8a) and select the desired CFC value

If it is necessary to specify a CFC value that is not listed in the menu, select the option '*User defined CFC…*' at the end of the list and input the desired CFC parameters in the 'Optional user defined CFC' field located right below (Figure A-8b).

Note: This field is active only if the 'User defined CFC' option is selected from the drop-down menu.



(a) (b)

Figure A-8: Filter Options' box - (a) drop down menu and (b) 'Optional user defined CFC' field.

Note: If the original curves have already been filtered during the optional trimming process, the 'Filter Options' box will show the filtering option chosen at that time without allowing the user to make any change. If a different filtering option is desired, it is necessary to go back to the trimming box to make any change to the previous choice.

SHIFT/DRIFT CONTROLS

Another preprocessing option supported by RSVVP is the possibility to correct any initial shift and/or drift in the curves. Experimental data sometimes contain shift and/or drift effects due to the change of temperature immediately before or during the test. The shift effect is an initial vertical shift of the curve due an increase of the temperature after the measurement gauges have been zeroed while the drift effect is a linear drift of experimental curve typical of the increase of the temperature during the test. The shift and drift controls of RSVVP correct the above mentioned effects and, therefore, can be very useful in case one or both the two input curves have been recorded from experimental tests and present either or both these data acquisition problems. As either the initial shift or drift of the test and/or the true curve are caused by an incorrect acquisition of the experimental data, these pre-processing options are important for an accurate evaluation of the comparison metrics. In generally, curves resulting from numerical solution should not need to use these options since shift and drift are features of sensor characteristics in physical tests. The use of the shift and drift options is, therefore, not recommended for curves resulting from computer simulations.

Procedure for Applying Shift and Drift

Both the *shift* and *drift* controls can be activated independently from each other by checking the respective boxes. Once one or both of them have been checked, the user has the choice to apply the selected control/s to the true curve, the test curve or both the true and test curves (Figure A-9). By default these controls are inactive.

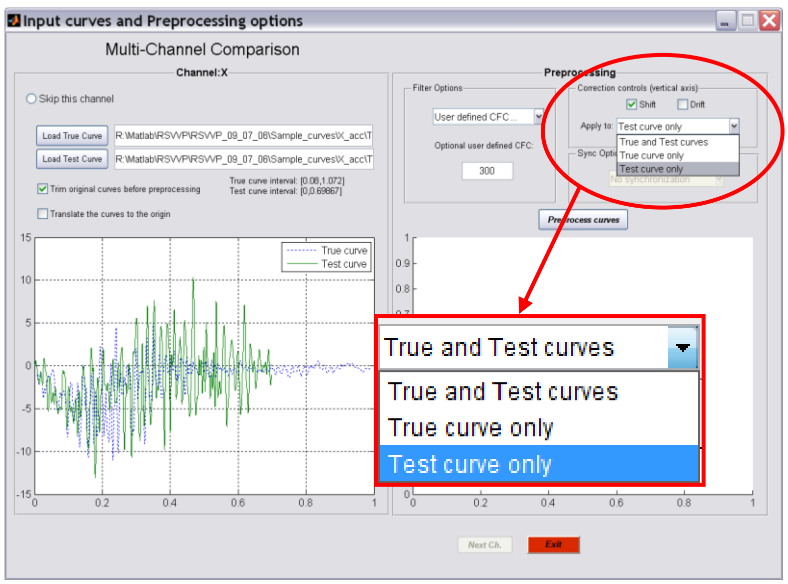


Figure A-9: Shift and Drift controls.

CURVE SYNCHRONIZATION (SINGLE-CHANNEL MODE)

RSVVP allows the user to optionally synchronize the two input curves before evaluating the comparison metrics. This option can be very useful if the original test and true curves have not been acquired starting at exactly the same instant (e.g., the test and true curve represent respectively a numerical simulation and an experimental test of the same crash test but the instant at which data collection was started is not the same). The synchronization of the two input curves is very important as any initial shift in the time of acquisition between the test and true curves could seriously affect the final value of the comparison metrics. For example, two identical input curves with an initial phase difference due to a different starting point in the acquisition process would probably lead to poor results of some of the comparison metrics.

Two different synchronization options are available in RSVVP: (1) the absolute area between the two curves (i.e., the area of the residuals) and (2) the squared error between the two curves. Both options are based on the minimization of a target function. Although these two methods are similar, they sometimes give slightly different results. Selecting one of these methods will result in the most probable pairing point for the two curves. Once the original curves have been preprocessed, the user is given the option to further refine the synchronization of the data.

Procedure for Applying Synchronization

By default RSVVP does NOT synchronize the input curves. To apply the synchronization option, click on the drop-down menu in the 'Sync Options' box, shown in Figure A-10, and select one of the two available synchronization methods: (1) Minimum absolute area of residuals or (2) Least Square error. As previously noted: when the '*multiple channel*' option has been selected, the option for data synchronization, as well as other preprocessing operations, will be made available in an additional/secondary preprocessing step.

Once the curves have been preprocessed by pressing the '*Preprocess curves*' button, a pop-up window will ask the user to verify that the synchronization is satisfactory. If the '*No*' button is selected, another pop-up window with a slider will appear, as illustrated in Figure A-11. Moving the slider changes the initial starting point of the minimization algorithm on which the synchronization process is based.

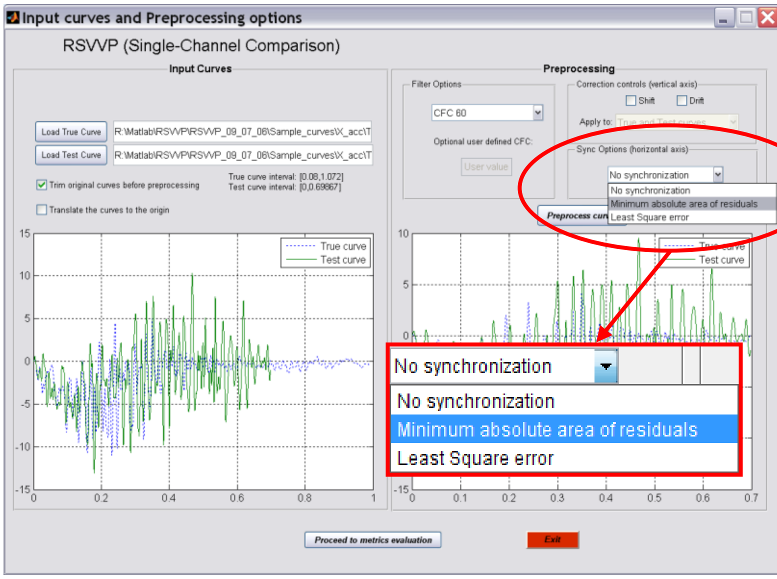


Figure A-10: Drop down menu of the 'Sync Options' box.

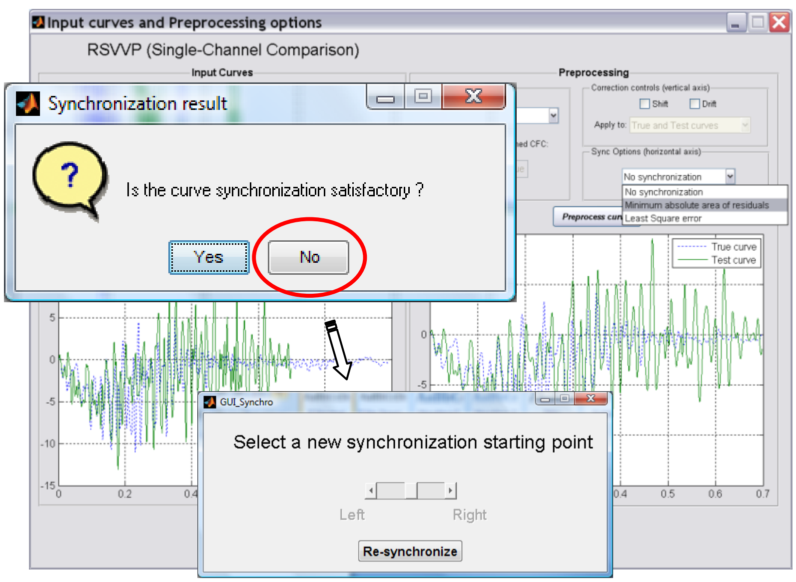


Figure A-11: Option for selecting new starting point for synchronization.

Procedure for defining input for Multiple Channels

For the *multiple channel* option, selecting the '*Next Ch.*' button located at the bottom of the screen advances the input selection to the next channel (note: the name of the current channel appears at the top of the window). If data is not available for a particular channel, the radio button, '*Skip this channel*,' (located at the top of the window) may be used to skip any of the six available channels.

In the multichannel mode, six tabs are located at the bottom, left corner of the GUI window, as shown in Figure A-12. The tab corresponding to the current channel's input/preprocessing page is highlighted in red. If the user wants to return to a previous channel, for instance, to change the input files or to modify preprocessing options, the user can simply select the corresponding tab and RSVVP will display the selected channel's input/preprocessing page.

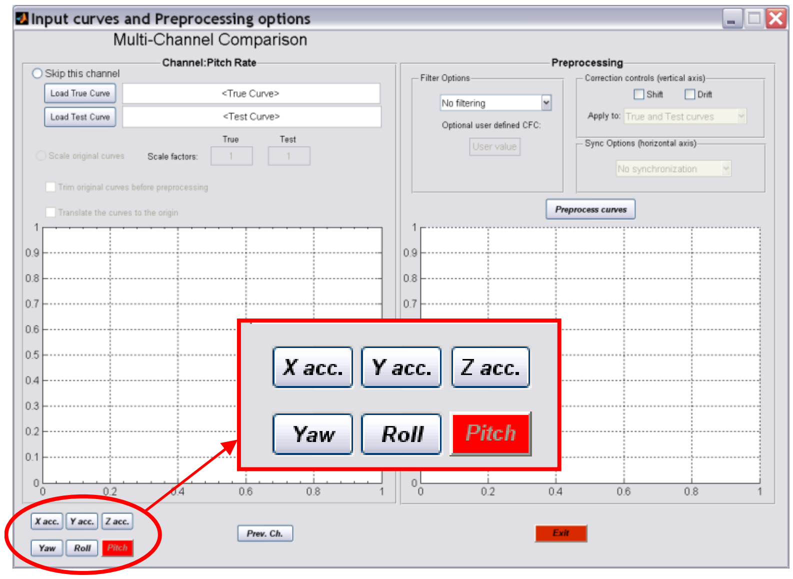


Figure A-*12*: Tabs linked to the input/preprocessing page for each channel

Procedure for Performing Additional Preprocessing in Multiple-Channel Mode

RSVVP provides two methods for evaluating the multiple channels of data: 1) weighting factors method and 2) resultant method. The *weighting factors* method calculates the metrics for the individual channels (i.e., curve pairs) and then computes composite metrics based on a weighted average of the individual channels. The 'resultant' method, on the other hand, calculates the resultant of the various channels and then computes the comparison metrics based on the resulting single curve pair. In either case, the 'Multiple Channel' option is intended to provide an overall assessment of the multiple data channels by computing a single set of composite metrics.

After the preprocessing has been completed for each data channel, press the button '*Proceed to curves synchro.*' This opens a second window that will be used to select the *Evaluation Method* and synchronize the curves.

Note: If the last channel is skipped, RSVVP will automatically proceed to this second GUI.

In the *Evaluation method* box, select the desired method for the evaluation of the multiple data channels using the dropdown menu, as illustrated in Figure A-13. The default method is to use 'Weighting Factors.' If this method is selected, the graph on the left side of the window will show the curves for the first available channel. To switch to the resultant method, click on the drop down menu and select '*Resultant*'. Once the method has been changed, the button '*Update*' becomes red (refer to Figure A-13). Press this button in order to update to the new selected method. The graph will now show the resultant of the first three channels.

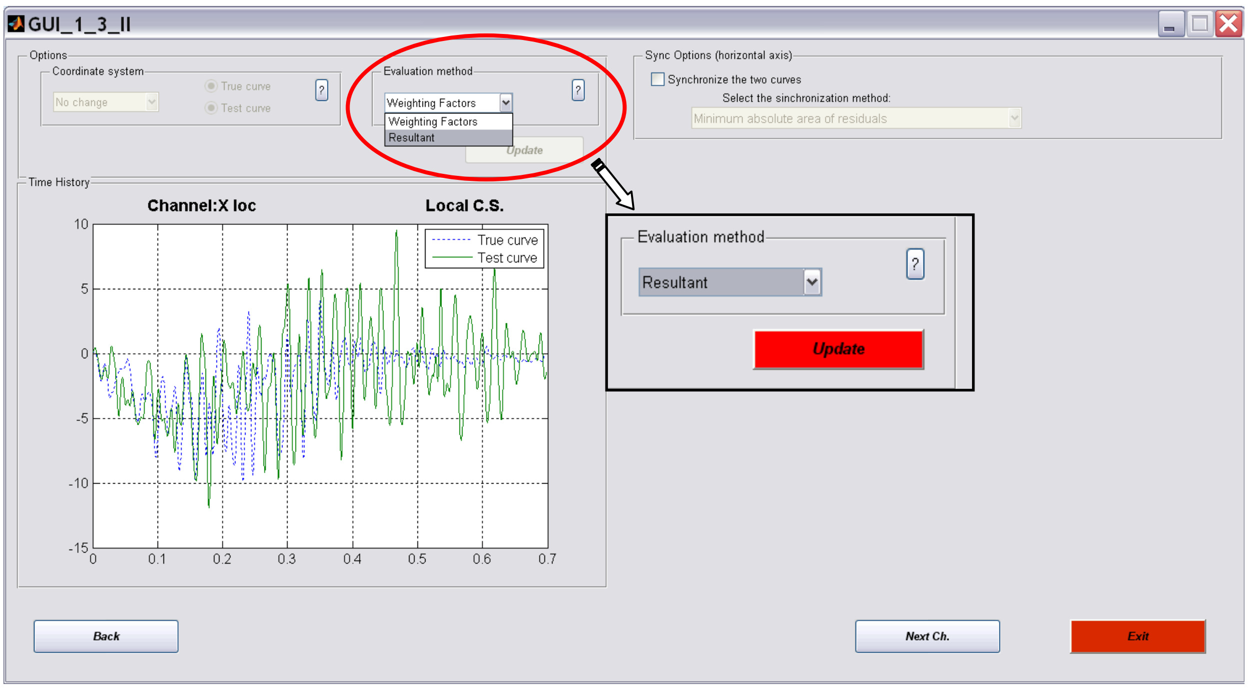


Figure A-13: Selection of the method for the computation of the multichannel metrics.

After the evaluation method has been selected, RSVVP is now ready to synchronize the curves. To begin the synchronization process, select the checkbox '*Synchronize the two curves*' located in the *Synch options* box on the left side of the GUI, as shown in Figure A-14 (Note: Synchronization starts automatically). Synchronization of the curves is optional, and leaving the checkbox unselected will allow the user to skip this operation.

As in the single channel mode, two different synchronization methods are available: (1) minimum area of residuals and (2) least square error. Both options are based on the minimization of a target function. Although these two methods are similar, they sometimes give slightly different results. Selecting one of these methods will result in the most probable pairing point for the two curves. However, if the user is not satisfied with the synchronization, he has the option of changing the initial starting point used in the minimization algorithms.

To proceed to the next channel, press the button, '*Next Ch.*'

Note: If the *resultant method* has been selected, pressing the '*Next Ch.*' button then displays the resultant curves computed from the second group of channels (i.e., the angular rate channels).

Note: Each time the evaluation method is changed, it is necessary to select the '*Update*' button to make the change effective.

Note: Changing the evaluation method resets all curve synchronizations.

When the last channel/resultant has been reached, the button '*Proceed to metrics selection*' will become active. Pressing it will advance RSVVP to the next phase of the program.

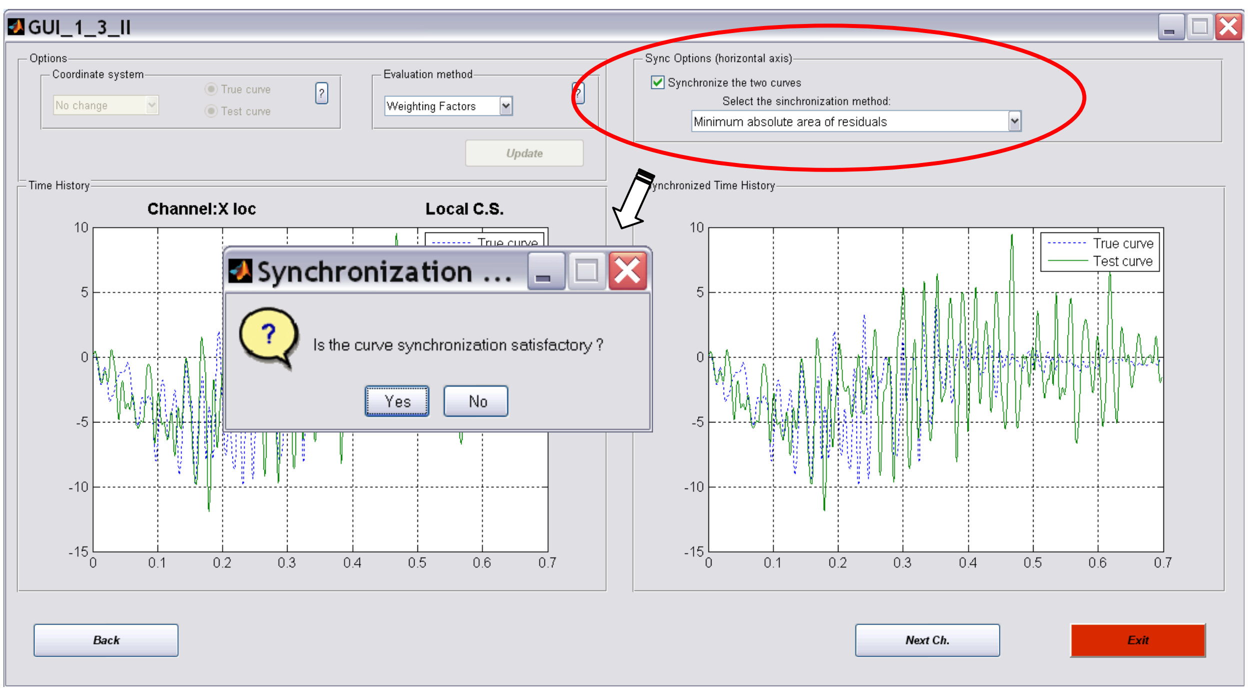


Figure A-3: Synchronization of the channel/resultant.

METRICS SELECTION

METRICS SELECTION

The metrics computed in RSVVP provide mathematical measures that quantify the level of agreement between the shapes of two curves (e.g., time-history data obtained from numerical simulations and full-scale tests). There are currently fourteen metrics available in RSVVP for computing quantitative comparison measures; all are deterministic shape-comparison metrics and are classified into three main categories:

1. **Magnitude Phase Composite (MPC) metrics**
    a) Geers
    b) Geers CSA
    c) Sprague & Geers
    d) Russell
    e) Knowles & Gear
2. **Single Value Metrics**
    f) Whang's inequality
    g) Theil's inequality
    h) Zilliacus error
    i) RSS error
    j) Weighted Integrated Factor
    k) Regression coefficient
    l) Correlation Coefficient
    m) Correlation Coefficient (NARD)
3. **Analysis of Variance (ANOVA)**
    n) Ray

A description of each metric is provided in Appendix A1.

The MPC metrics treat the magnitude and phase of the curves separately and combine them into a single value comprehensive metric. The single-value metrics give a single numerical value that represents the agreement between two curves. The ANOVA metric is a statistical assessment of whether the variance between two curves can be attributed to random error.

The recommended metrics that have been suggested by the NCHRP 22-24 project team for comparing time-history traces from full-scale crash tests and/or simulations of crash tests are the Sprague & Geers metrics and the ANOVA metrics. The Sprague & Geers metrics assess the magnitude and phase of two curves while the ANOVA examines the differences of residual errors between them. Of the fourteen different metrics available in RSVVP, the Sprague-Geers

MPC metrics were found to be the most useful metrics for assessing the similarity of magnitude and phase between curves and the ANOVA metrics were found to be the best for examining the characteristics of the residual errors. For more details regarding the definitions of these metrics refer to Appendix A1.

Procedure for Metrics selection

Select the desired *Metric profile* from the drop down menu at the top of the metrics window, as illustrated in Figure A-15. There are three metrics profiles available:

1. NCHRP 22-24 (default),
2. All metrics, and
3. User selected metrics.

The '*NCHRP 22-24'* profile is the default profile and it is suggested that this profile be used when validating numerical simulations against full-scale crash tests (e.g., NCHRP Report 350 crash tests).

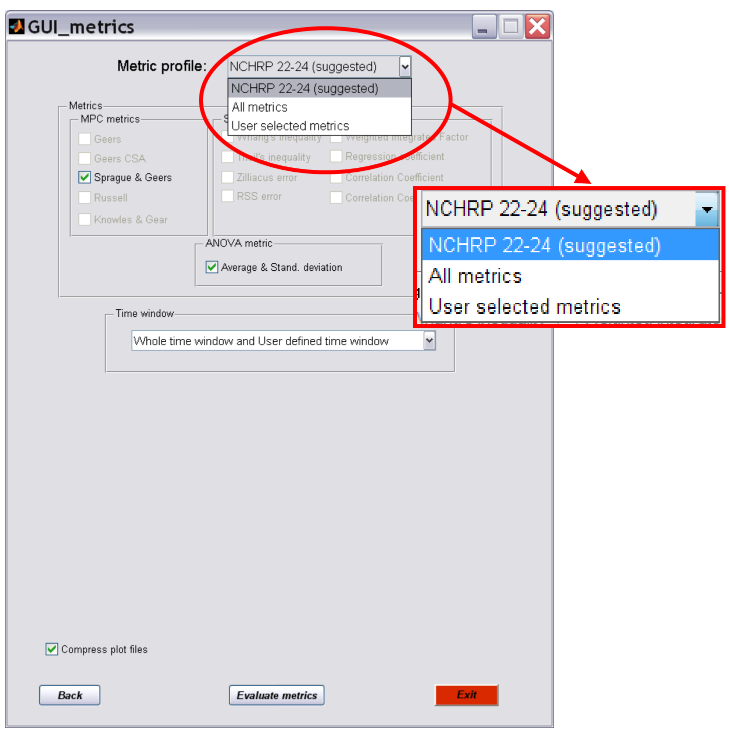


Figure A-4: Select the metric profile from the drop-down menu.

The second profile '*All metrics*' automatically selects all fourteen different comparison metrics that are available in RSVVP.   If the '*User selected metrics*' profile has been selected, the checkbox beside each available metric will become active and allow the user to select any number of the available metrics by selecting the corresponding checkboxes, as shown in Figure A-16.

Figure A-5: Example of a metrics selection using the '*User selected metrics*' profile.

TIME INTERVAL

In RSVVP, metrics can be evaluated over the complete length of the curve (e.g., whole time interval) and/or over one or more user defined time intervals.

Procedure for Selecting Time Window

From the drop-down menu in the *Time window* box shown in Figure A-17, select from one of the three available options:

1) *Whole time window and User defined time window*,
2) *Whole time window only* and
3) *User defined time window only*.

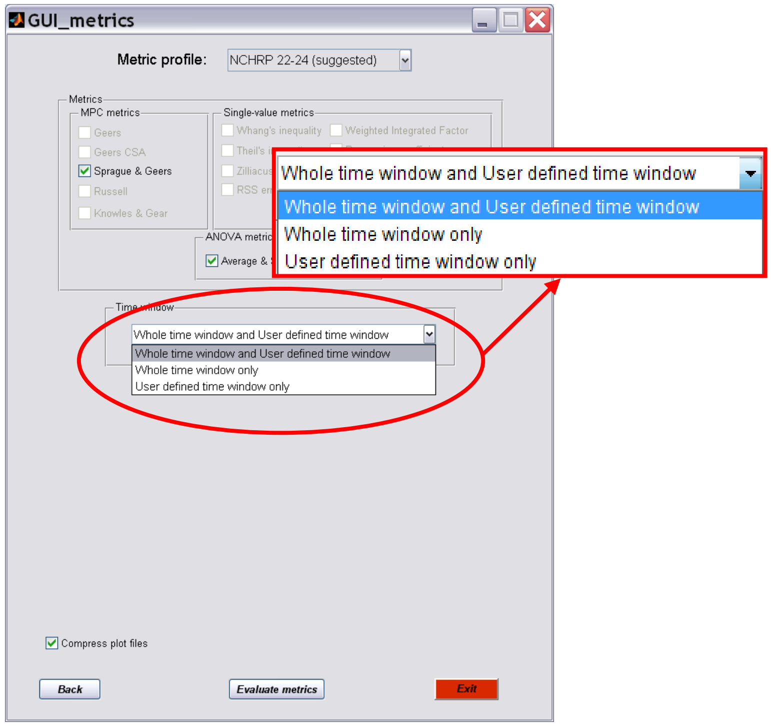


Figure A-6: Time window(s) selection.

If the "Whole time window" option is selected, the metrics are computed using all the available data (i.e., the complete length of the curves). If the "User defined time window" option is selected, the metrics will be computed for one or more arbitrary user defined intervals of data.

By default RSVVP evaluates the selected metrics on both the *whole time interval* and *user selected time interval(s)*. If this option is selected, RSVVP will first compute the comparison metrics over the '*Whole Time interval,*' then, after displaying the results, it will prompt the user to define an arbitrary '*User Defined Time interval*' over which to calculate the metrics.

Procedure for Compression of Image Files

During the computation of the metrics, RSVVP creates several graphs and saves them as bitmap images (*.bmp*). Since the cumulated size of these entire image files may exceed several megabytes, the default option in RSVVP is to compress them in *.zip* format. RSVVP provides an option for overriding file the file compression by unchecking the box '*Compress plot files*' at the bottom of the window, as shown in Figure A-18.

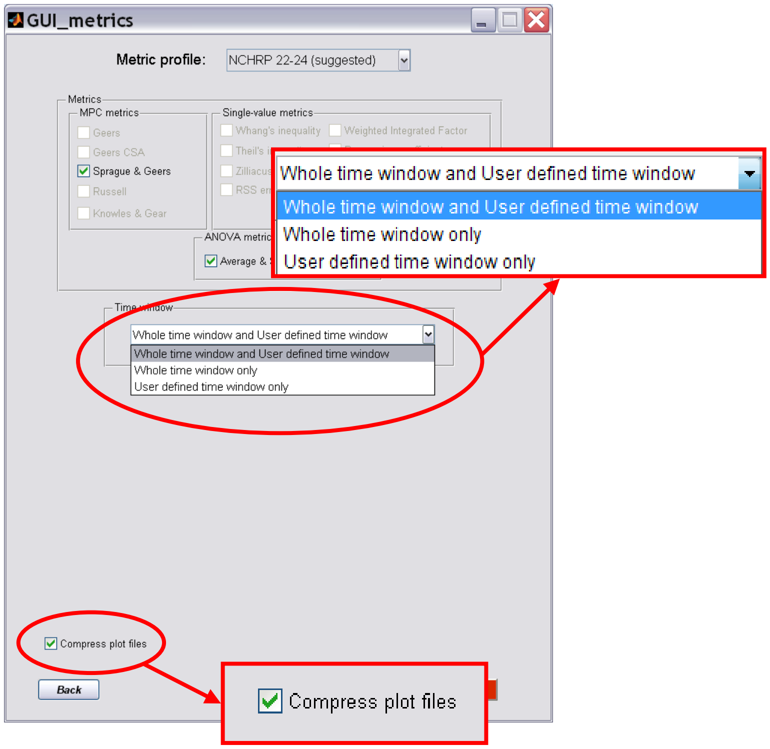


Figure A-7: Option to compress/uncompress the image files created by RSVVP.

METRICS EVALUATION

Once the desired metrics have been selected, and the time intervals over which the metrics will be calculated have been defined by the user, RSVVP begins the metrics calculation process. In the multichannel mode, RSVVP first calculates the value of the metric for each individual channel (or channel resultants if the *resultant method* was selected) and then computes single metric value based on a weighted average of the results. For details regarding the weighting scheme refer to Appendix A2.

Procedure for Metrics Evaluation

To start the metrics evaluation, press the '*Evaluate metrics*' button located at the bottom of the window, as shown in Figure A-19. Note: It is possible to go back to the main graphical interface to change any of the selected input curves and /or modify any of the preprocessing options by clicking the 'Back' button.

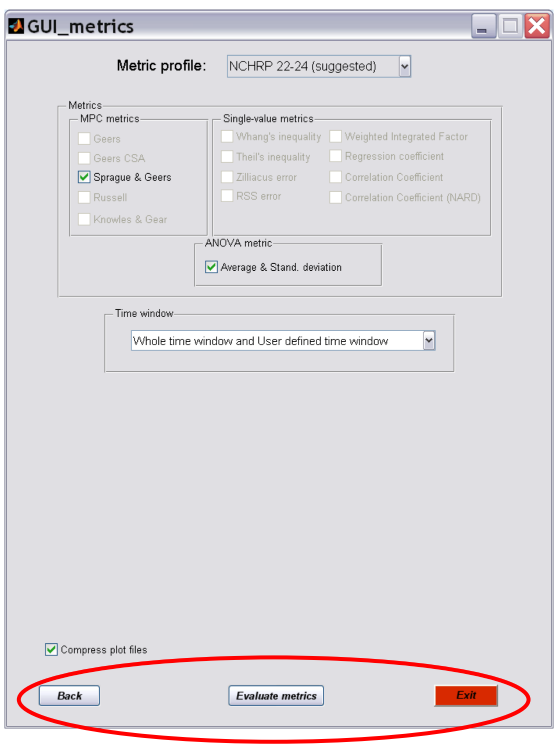


Figure A-8: Press the '*Evaluate metrics*' button to begin the metrics calculations.

Before the metrics are evaluated, a pop-up window appears, as shown in Figure A-20, asking the user to indicate a location and file name for saving the configuration file. The configuration file contains all the information that has been input in RSVVP, including all the preprocessing options as well as the metrics selection. Thus, the configuration file contains all the information necessary to repeat the analysis. By default, the location of the configuration file is in the "working" directory and the name of the configuration file is 'Configuration_Day-Month-Year.rsv', where Day, Month and Year correspond to the data that the file is being created.

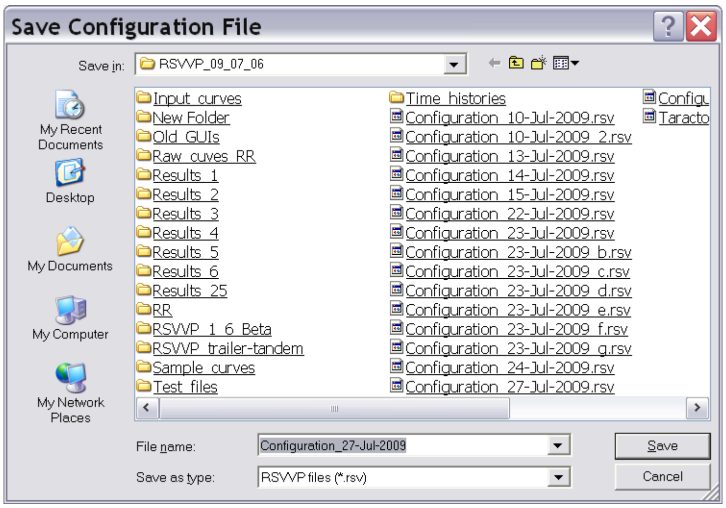


Figure A-9: Pop-up window for saving the configuration file.

Note: A copy of the configuration file is also saved in the subfolder .../Results_x that is created by RSVVP at the end of the run (see section *Output of Results* for more details about the result folder).

Note: The configuration file can be used, for example: (i) to quickly re-input a set of curves and configurations and then modify any of the previously selected options or (ii) to *exactly* repeat a previous run.

Procedure for Defining the Whole-Time Window

No action is needed to define the time interval for the '*Whole time window*' option (i.e., options 1 and 2 from the *time interval* box) as RSVVP will automatically consider the maximum time interval possible for the data.

Procedure for Defining User-Defined-Time Window(s)

If a '*User defined time window*' was selected (i.e., options 1 and 3 from the *time interval* box), RSVVP will prompt the user to select the upper and lower boundaries of the local time interval on which the comparison metrics will be evaluated. RSVVP shows a window with a graph of the test and true curves and two blank fields at the bottom which are used to define respectively the time value of the lower and upper boundary, as shown in Figure A-21. Fill in the desired values and press the '*Evaluate metrics*' button to start the evaluation of the metrics on the defined interval.

Figure A-10: Defining data range in the user defined time window.

When the limits are input into the fields, the upper and lower limits are shown as vertical lines in the graph. For multichannel input, a drop-down menu located at the bottom of the window allows the user to select the desired channel to use for defining the limits.

Note 1: The selected upper and lower boundaries do not change when a new channel is plotted as they share the same interval for each channel in the multi-channel option.

It is possible to evaluate the metrics on as many user defined time windows as desired; after the results of the user defined time window have been shown, RSVVP will prompt the user for a new *User Defined* time window. The results obtained for each time interval will be saved separately.

SCREEN OUTPUT

For each of the time intervals on which the comparison metrics were evaluated, RSVVP shows various screen outputs to present the results:

- Graph of the true curve and test curve,
- Graphs of the time-integration of the curves,
- Values of the comparison metrics,
- Graph of residual time history,
- Graph of the residual histogram and
- Graph of the residual cumulative distribution.

Note: Comparison metrics are always computed using the curves shown in the graph of the true and test curves. The time-integrated curves are shown only to provide additional interpretation of the curves. For example, if acceleration data is being compared, it is often quite noisy and difficult to visually interpret. The time-integration of acceleration, however, yields a velocity-time history plot that is much easier for the user to interpret.

Figure A-11 and Figure A-12 show the typical output screen for the *NCHRP 22-24 profile* and the other two metric selection profiles, respectively (i.e., 'All metrics' or 'User defined' profiles). If the *NCHRP 22-24 profile* was selected, only the Sprague and Geers and ANOVA metrics are shown. The word 'Passed' and a green square beside the value of each metric indicate that the metric value meets the NCHRP 22-24 acceptance criterion for that specific metric; the word 'Not passed' and a red square indicate that the value does not meet the suggested acceptance criterion.

When either of the other two metrics profiles is selected, the results of all fourteen metrics are shown in the window and the word N/A appears beside any metrics that were not calculated (i.e., metrics not checked by the user in the '*User defined*' profile). In these cases, no acceptance criteria have been defined and the user must use their own judgment regarding acceptable values. Also, only the graph of the true curve and test curve is shown.

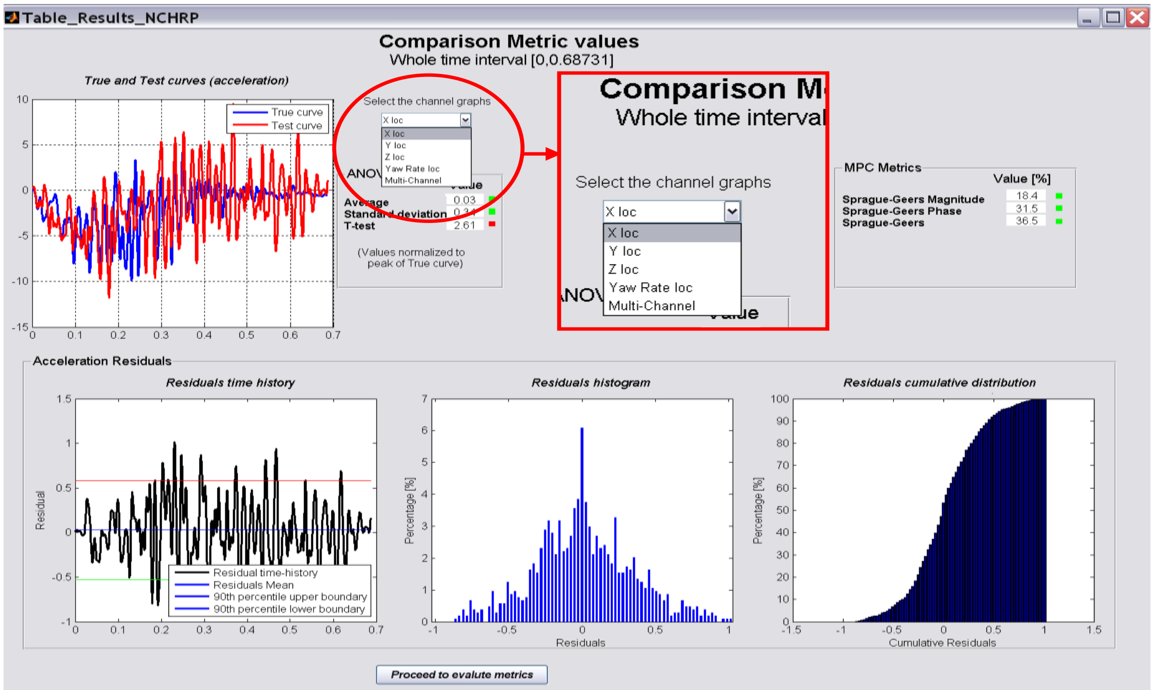


Figure A-11: Screen output for the NCHRP 22-24 profile

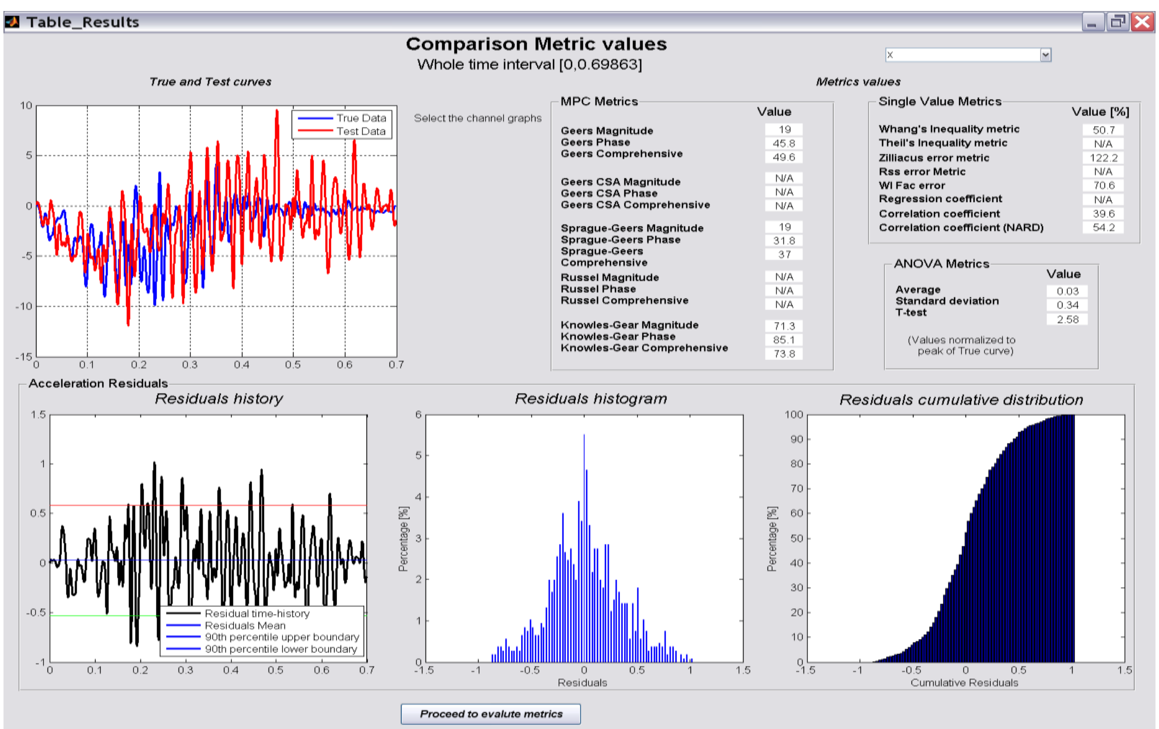


Figure A-12: Screen output for the '*All metrics*' or '*User defined*' profiles

For multichannel input, if the *weighting factors method* has been selected, the user can view the results for any of the individual channels or the multi-channel weighted results by selecting the desired option from the drop-down menu beside the time-history graph. When the *Multi-channel* results is selected from the drop-down menu, a histogram graph of the weighting factors used to compute the metric values in the multichannel mode is plotted. This gives an immediate understanding of the weight of each input channel with respect to the others in the evaluation of the multichannel metrics.

Note: It may be necessary to wait a few seconds before the metric values and the graphs are updated to a new selected channel.

The next step in RSVVP depends on whether or not the option for *User time intervals* was selected in the Metrics Selection GUI. If so, the user has the option to: (1) proceed to the evaluation of a new interval and/or (2) to save the results and quit the program. Select the button corresponding to the desired action. If the option '*whole and user defined time interval'* was selected, RSVVP requires the user to go through the process of defining at least one user-defined time interval before they will have the option to save the results and quit RSVVP.

OUTPUT OF RESULTS

During the curve preprocessing and evaluation of the metrics, RSVVP generates several types of output, which are saved in the output-folder location defined by the user. If no output-folder was selected, RSVVP automatically saves the results in a folder called '\Results_X', where X is an incremental numbering (i.e., 1, 2, etc). The folder '*\Results_X'* is created in the folder where RSVVP was executed. At the beginning of the run, RSVVP checks to see if there is a previous sequence of folders named "\Results_X", and creates a new Results folder with the suffix corresponding to the next number in the sequence. For example, if there is already a previous folder named ...\Results_3, the new output folder will be named *...\Results_4*).

Procedure for Exiting and Saving Results

Pressing the button 'Save results and Exit' will open a browse window, as shown in Figure A-24, for the user to select where to save the results.

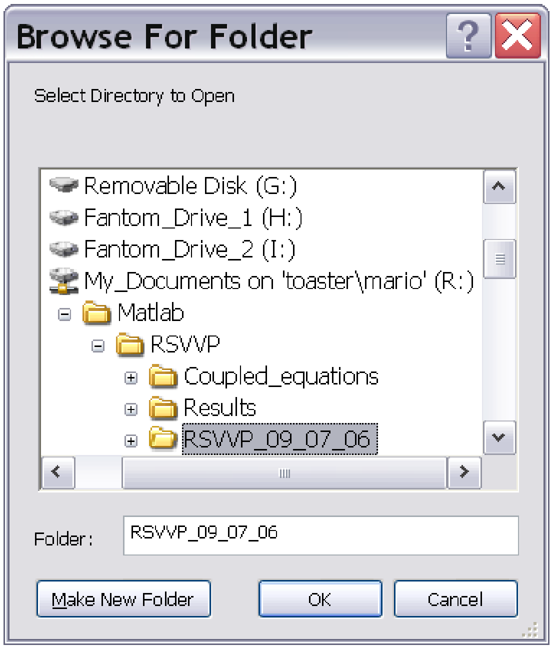


Figure A-13: Pop-up browse window for selecting output folder for RSVVP results.

The user has the option of creating a new folder by selecting the tab 'Make New Folder' in the browse window. If no selection has been made or if the cancel button has been pressed, RSVVP will automatically create a folder named 'Results_X' in the current directory.

Note: The process of saving of the results may take a few minutes. During this period, RSVVP displays the message shown in Figure A-25.

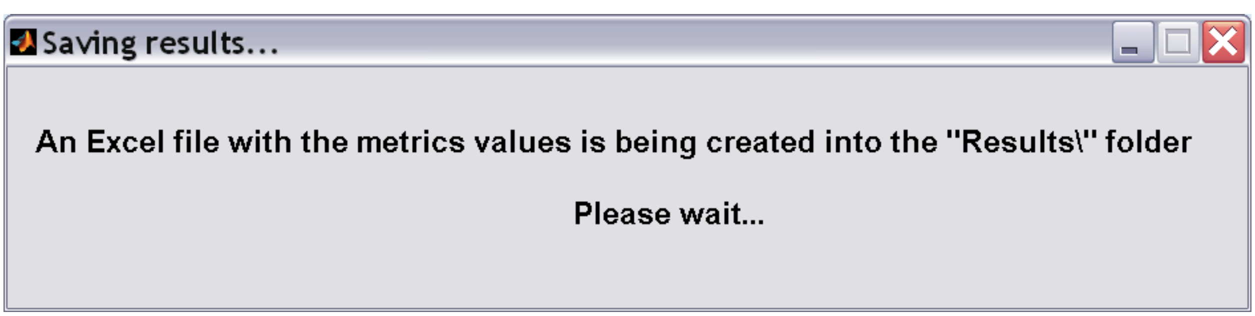


Figure A-14: Message shown while RSVVP creates results folder.

TABLE OF RESULTS (EXCEL® WORKSHEET)

The results of the comparison metrics are saved in the Excel file '*Comparison Metrics.xls'*. This spreadsheet contains the results for all the comparison metrics computed for the *whole time interval* and all *user defined time* intervals, as shown in Figure A-26. The time interval used in each evaluation is indicated in the heading of each column.

	Whole time interval [0,0.5474]	User time interval #1 [0.08005,0.19995]	User time interval #2 [0.12005,0.21995]
MPC Metrics	**Value [%]**	**Value [%]**	**Value [%]**
Geers Magnitude	7.1	4.7	10.5
Geers Phase	23.9	22.1	21.4
Geers Comprehensive	24.9	22.6	23.8
Geers CSA Magnitude	N/A	N/A	N/A
Geers CSA Phase	N/A	N/A	N/A
Geers CSA Comprehensive	N/A	N/A	N/A
Sprague-Geers Magnitude	N/A	N/A	N/A
Sprague-Geers Phase	N/A	N/A	N/A
Sprague-Geers Comprehensive	N/A	N/A	N/A
Russell Magnitude	5.6	3.8	7.9
Russell Phase	22.5	21.6	21.2
Russell Comprehensive	20.5	19.4	20.1
Knowles-Gear Magnitude	58	101.1	1573.2
Knowles-Gear Phase	1.8	0	0
Knowles-Gear Comprehensive	53	92.3	1436.2
Single Value Metrics	**Value [%]**	**Value [%]**	**Value [%]**
Whang's inequality metric	38.5	36.5	38.1
Theil's inequality metric	N/A	N/A	N/A
Zilliacus error metric	76.8	76.5	85.9
RSS error metric metric	N/A	N/A	N/A
WIFac_Error	N/A	N/A	N/A
Regression Coefficient	66.7	49.9	65.2
Correlation Coefficient	N/A	N/A	N/A
Correlation Coefficient(NARD)	76.1	77.9	78.6
ANOVA Metrics	**Value**	**Value**	**Value**
Average	0.01	0.04	0.05
Std	0.15	0.25	0.16
T-test	7.21	7.39	14.43
T/T_c	2.81	2.88	5.63

Figure A-15: Excel table containing the metrics results for the various time intervals.

A summary of the input files and preprocessing options for each channel is written at the end of the Excel file, as shown in Figure A-27. If RSVVP is run in multichannel mode using the *weighting factors* method, the weighting factors and the metrics values calculated for each separate channel are provided in the Excel file on separate sheets, as indicated in Figure A-27.

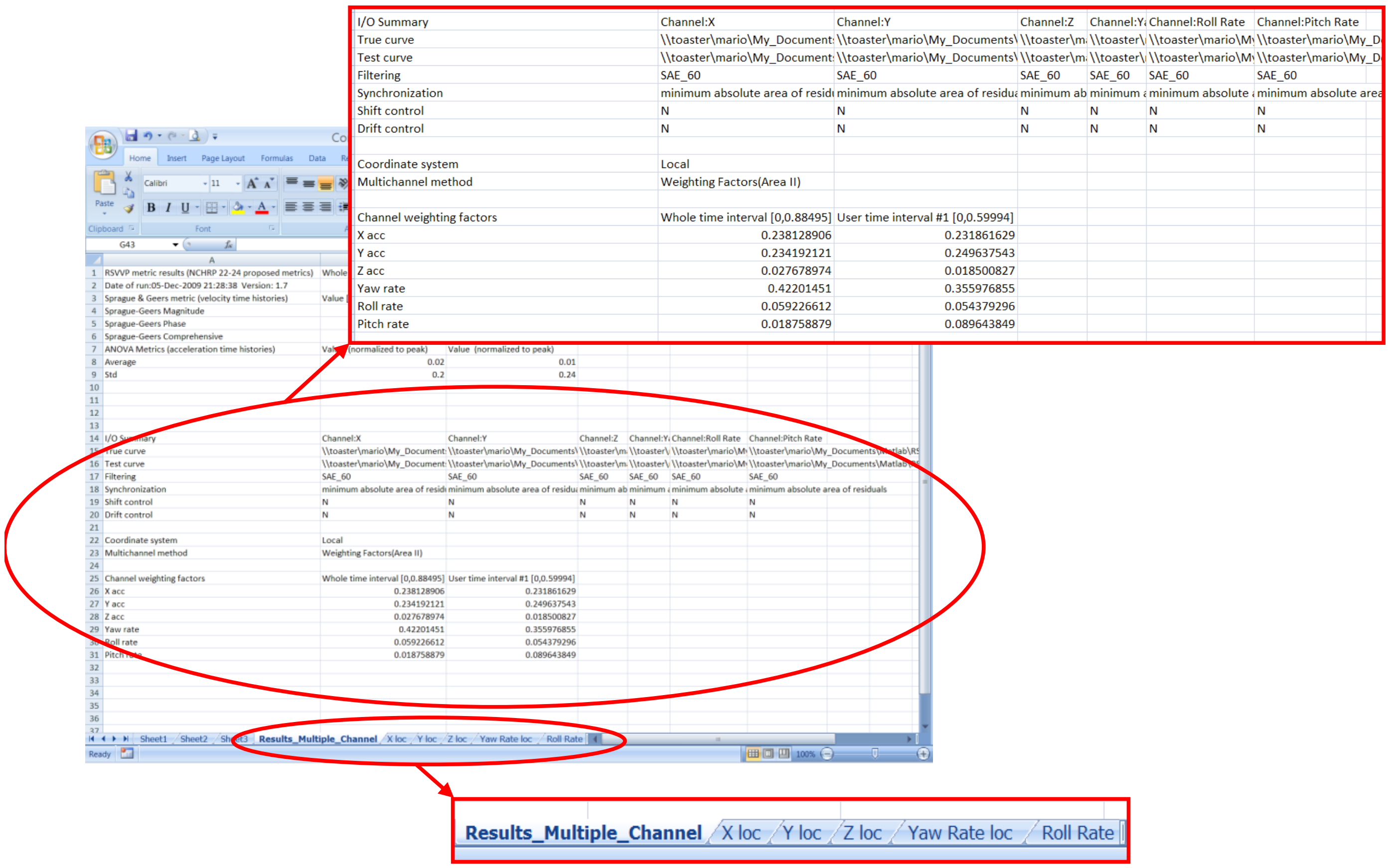


Figure A-16: Summary of preprocessing options and separate sheets for each input channel in the Excel file.

GRAPHS

RSVVP creates several graphs during the evaluation of the metrics and saves them as *bitmap* image files. For each time interval evaluated in RSVVP, the following graphs are created in the folder *…/Results/Time-histories/*:

a) Time histories of the true and test curves,
b) Time histories of the metrics and
c) Residuals time histories, histogram and cumulative distribution.

For multichannel input, the time histories of the metrics represent the weighted average of the time histories of the metrics from each channel. Similarly, the residuals time history, histogram and distribution are plotted using the weighted average from the residual histories of each channel. The graphs are saved in separate directories corresponding to each time interval.

TIME HISTORIES RESULTS

time-history data generated by RSVVP is saved in a convenient format (ASCII or Excel) so that the user has ready access to the data. For example, the user may want to conduct additional post processing of the data, or to simply recreate the graphs produced by RSVVP so that they can be reformatted for inclusion in a report.

RSVVP generates time history files for the following:

a) Original input curves
b) Preprocessed curves
c) Calculated metrics

Each of the original input curves is saved as an ASCII file in the subfolder .../results_X/Input_curves. Likewise, the preprocessed curves used in the metrics calculations are saved ASCII files in the subfolder …/Results/Preprocessed_curves. The time histories of the metrics are saved in Excel format; a separate metrics-time history file is created for each time interval evaluated (e.g., Metrics_histories_whole.xlsx).

EXAMPLES

Two examples are presented in the following sections in order to illustrate the step-by-step procedure for using RSVVP. In Example 1, an acceleration-time history from a full-scale crash test is compared to that of another "essentially" identical full-scale crash test using the *single channel* option in RSVVP. In Example 2, data from multiple data channels (including three acceleration channels and three rotational rate channels) from a numerical simulation are compared to those from a full-scale crash test using the *multiple channels* option.

EXAMPLE 1: SINGLE-CHANNEL COMPARISON

In this example, RSVVP is used to compare the longitudinal acceleration-time history between two full-scale crash tests. The tests involved a small car impacting a rigid longitudinal barrier at 100 km/hr at a 25-degree impact angle. Both tests were performed using new vehicles of the same make and model and the *same* longitudinal barrier. The acceleration-time history data was collected from the center-of-gravity of the vehicle in each case.

Although, theoretically, the results from two essentially identical crash tests should be the same, in practice, results from supposedly identical tests will always show some variations due to random differences in material make-up and experimental procedure. In fact, in complex experiments such as full-scale crash tests, it is practically impossible to *completely* control parameters such as the initial impact speed, impact angle, point of impact, or especially the behavior of the vehicle's mechanical components. As such, perfect agreement between experiments is rarely achieved; however, the agreement should be within an acceptable range of expected differences that are typical of such experiments (e.g., tolerances determined from experience).

The steps of the evaluation process in this example will include 1) data entry, 2) preprocessing, 3) selection of comparison metrics, 4) calculation of the metrics and 5) interpretation of the results based on recommended acceptance criteria for these types of full-scale crash tests.

Analysis Type

The first step is to select the type of curve comparison that will be performed. In this example, only a single pair of curves is being compared, so the option '*single channel*' is selected in the GUI window, as shown in Figure A-17.

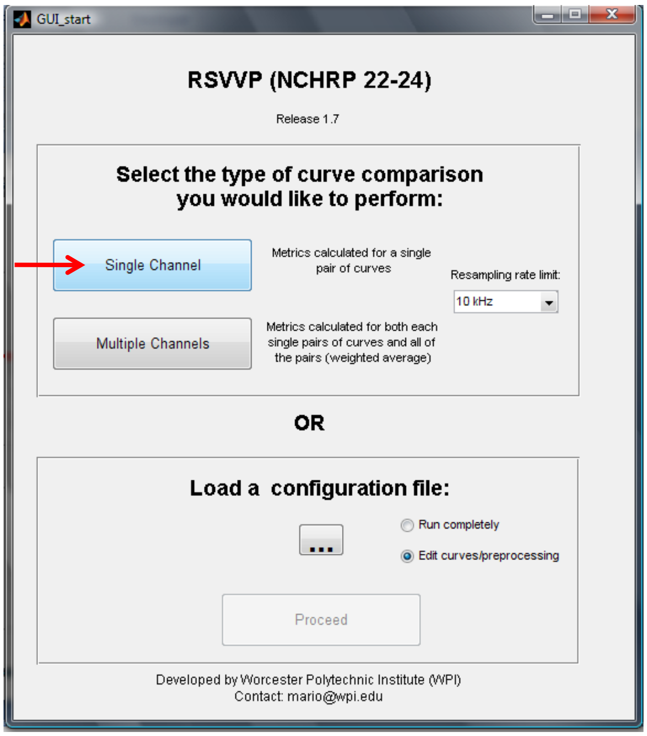


Figure A-17: The *Single Channel* option is selected in the GUI window

Data Entry and Preprocessing

The next step is to load the two acceleration time histories (i.e., curve 1 and 2) into RSVVP. Note that when comparing results from a numerical computation to those from a physical experiment, the experimental data will *always* be considered the *true curve* and the numerical data will be the *test curve*. In this case, however, both curves are from physical experiments, thus the choice of *true curve* and *test curve* is irrelevant. In this example, curve 1 is arbitrarily designated as the *true curve*, as shown in Figure A-18.

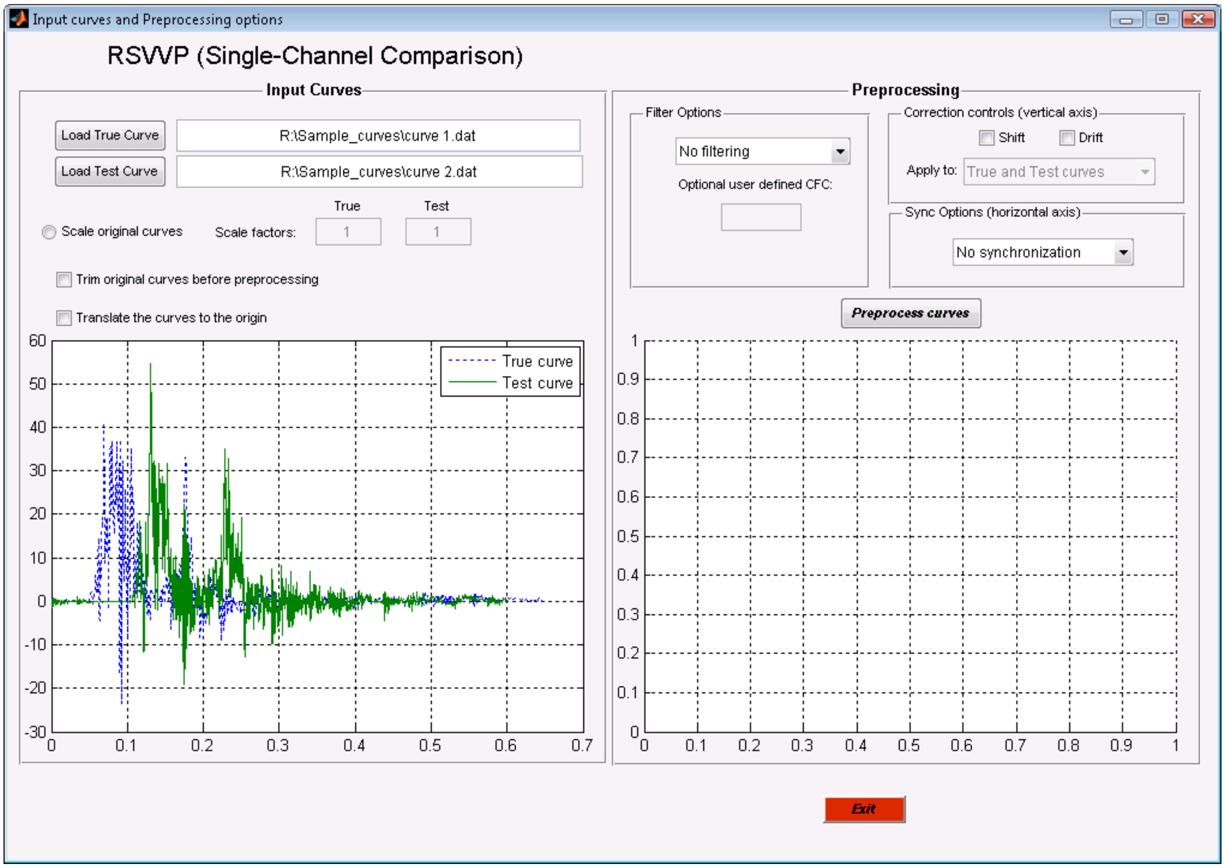


Figure A-18: GUI-preview of original input data loaded into RSVVP.

The various preprocessing operations are applied incrementally in this example in order to demonstrate how each operation contributes to the general improvement of the input curves. Note, however, that these preprocessing operations can be applied simultaneously.

From the graph shown in the GUI window (Figure A-18), it is obvious that both curves include some pre- and post-impact data. That is, the curves have an initial "flat" section at the beginning (pre-impact data) and a relatively flat section at the end starting at approximately 0.4 seconds (post impact data). To trim the heads and tails of the curves, select the checkbox beside the option '*trim original curves before preprocessing*', as shown in Figure A-19. Note: this option opens a pop-up window (not shown) that permits the user to perform the trim operation.

The tails of the two curves were trimmed starting at 0.4 seconds, and the results are shown in the graphics display in the GUI window in Figure A-19. In this example, only the tail of the each curve is trimmed in order to demonstrate the effectiveness of the *synchronization* option, which will be used in a later step. Note: It is typically desirable to also trim the head of the curves to eliminate any pre-impact data from the curve comparison.

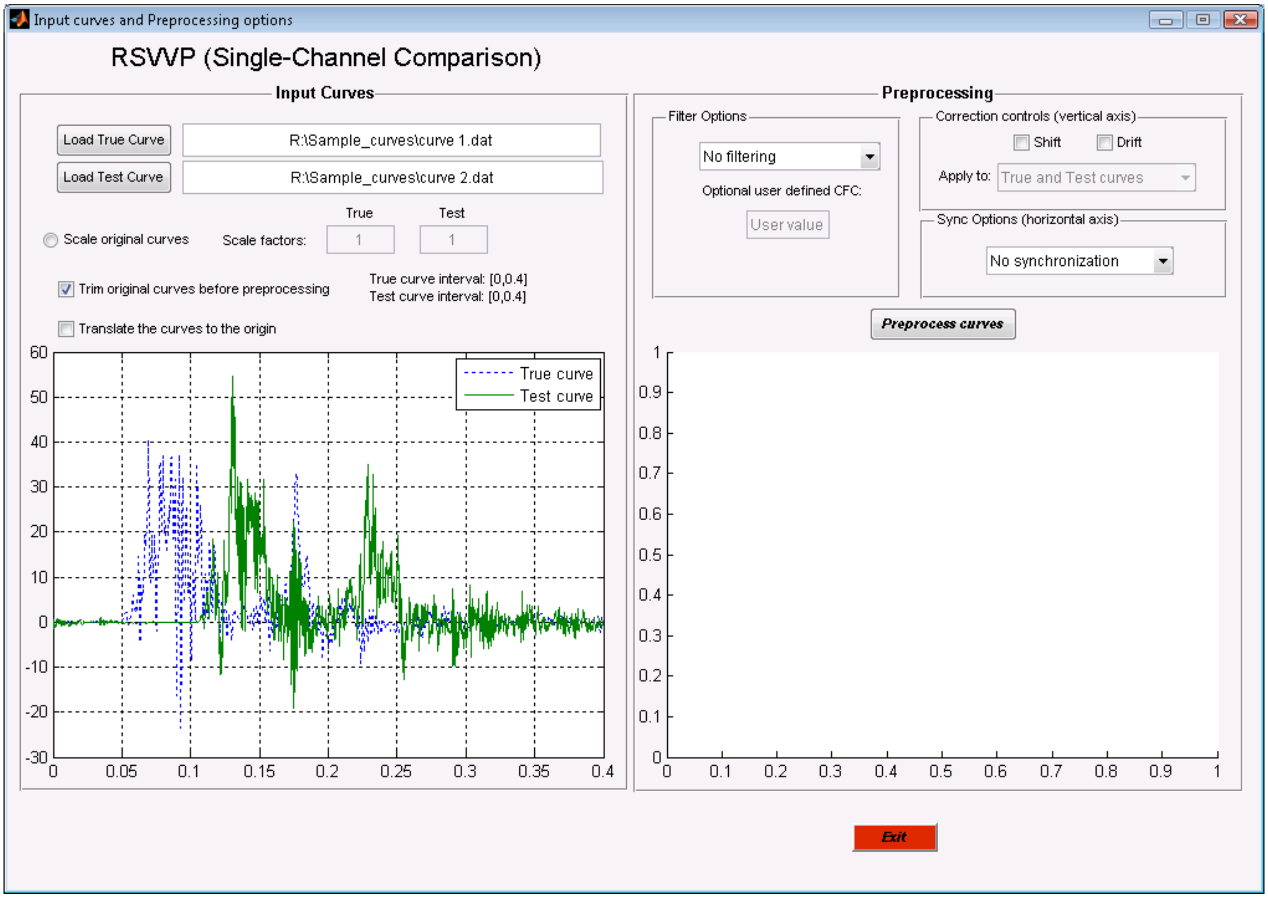


Figure A-19: Input curves after the manual trimming operation.

The input curves are characterized by a certain level of high frequency vibrations (as is typical of most acceleration data), which are not generally important in overall response of the vehicle, and should be filtered before computing the comparison metrics. In this example, the CFC 60 filter is selected and the results of the filtering operation are shown in the graph on the right side of the GUI-window in figure A-20.

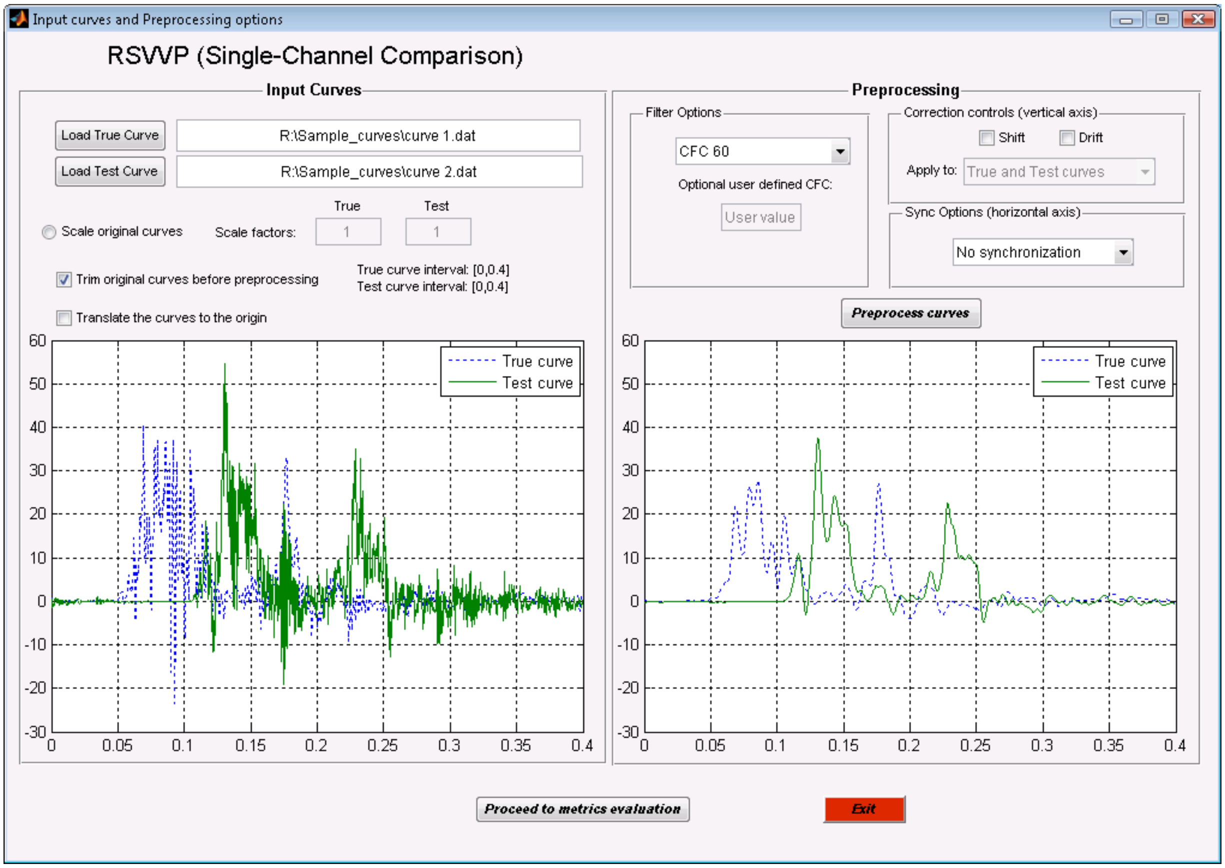
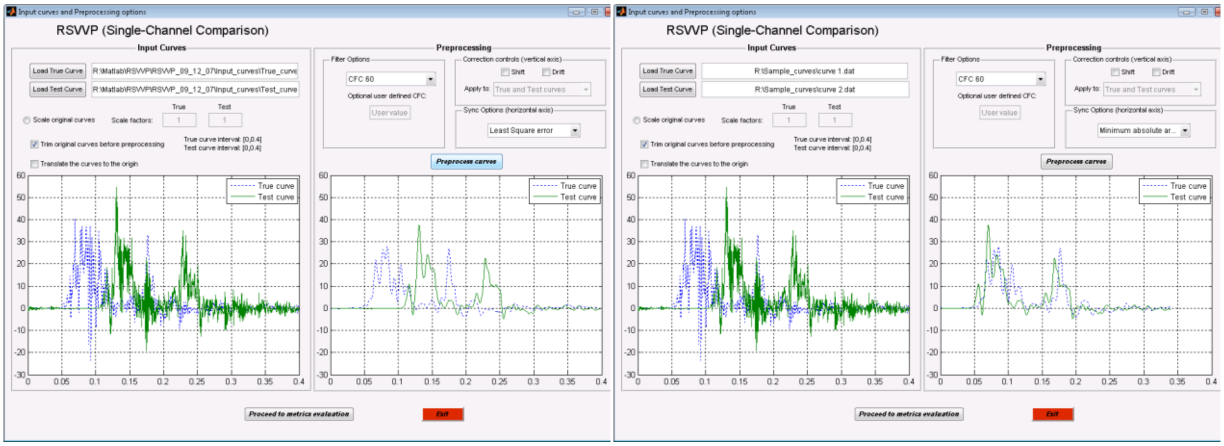


Figure A-20: Original and filtered acceleration time histories.

It is apparent from the graphs in Figure A-20 that the two curves are not synchronized with each other, as each curve demonstrates a different start-time at which the acceleration data started recording.

There are two methods available in RSVVP for performing the synchronization operation: one based on the '*Least squares*' and the other based on '*Minimum area of residuals*'. The results from both methods are shown in Figure A-21. Both of these methods typically give good results, especially if the pre- and post-impact data is trimmed appropriately. In this case, however, the method of '*Minimum area of residuals*' provides the best results.

Note: RSVVP shows a warning message if no filtering and/or synchronization options were selected.



(a) ***(b)***

Figure A-21: Data synchronization results using (a) the *Least squares* method and (b) the *Minimum Area of Residuals* method.

After the test and true curves have been preprocessed, the next step is the selection of the metrics and time intervals.

Metric selection and evaluation

There are three *metrics profiles* available in RSVVP: 1) *NCHRP 22-24*, 2) *All Metrics* and 3) *User Selected Metrics*. In this example, the *NCHRP 22-24* metrics profile is selected, which is the recommended profile for comparing full-scale crash test data. This profile calculates Sprague-Geers MPC metrics and the ANOVA metrics and provides an interpretation of the data based on recommended acceptance criteria.

The option '*Whole time window and user-defined time window*' was selected from the drop-down list in the *Time Window* box. For this option, RSVVP first computes the metrics based on all the available data from the preprocessed curves (i.e., complete length of curves) and then computes the metrics on a select interval of the data defined by the user.

The metric evaluation is initiated by pushing the '*Evaluate metrics*' button shown in Figure A-22.

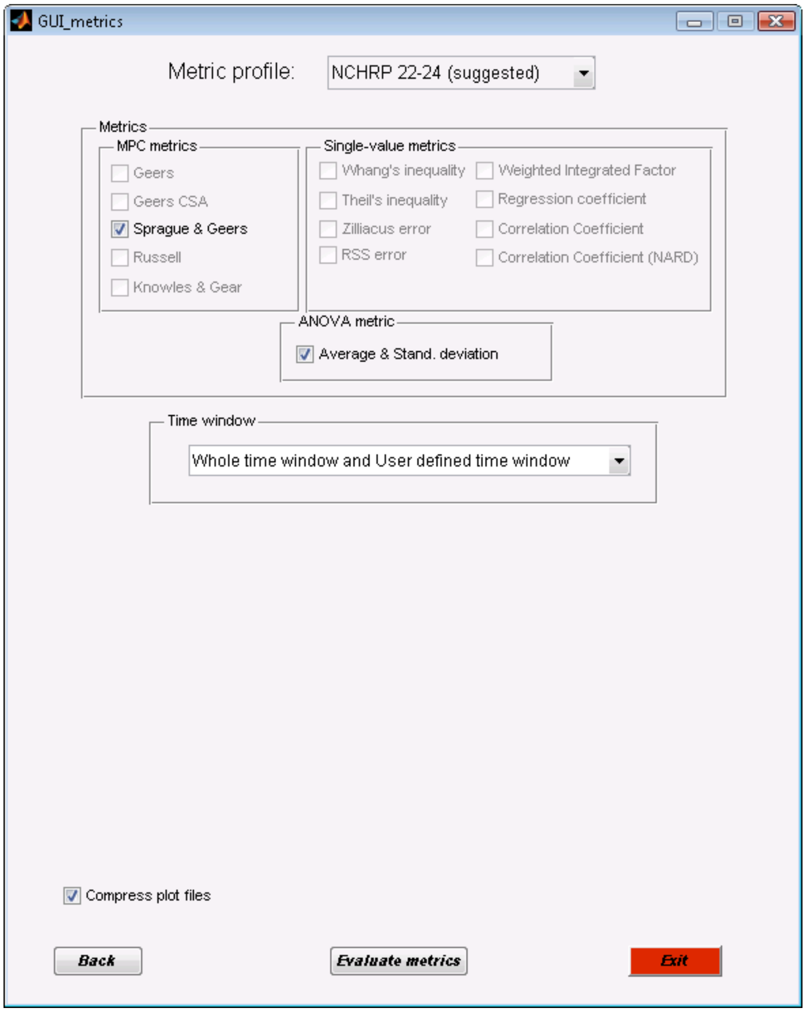


Figure A- 22: Selection of the metrics profile and time interval.

During the calculations of the metrics, various graphs appear and disappear on the computer screen. Screen-captures of these graphs are taken during this process and the files are saved in the output directory defined by the user. When the metrics calculations are completed, the results are displayed in the GUI-window shown Figure A-23. Note that beside each metric value RSVVP indicates whether or not the result meets the recommended acceptance criteria.

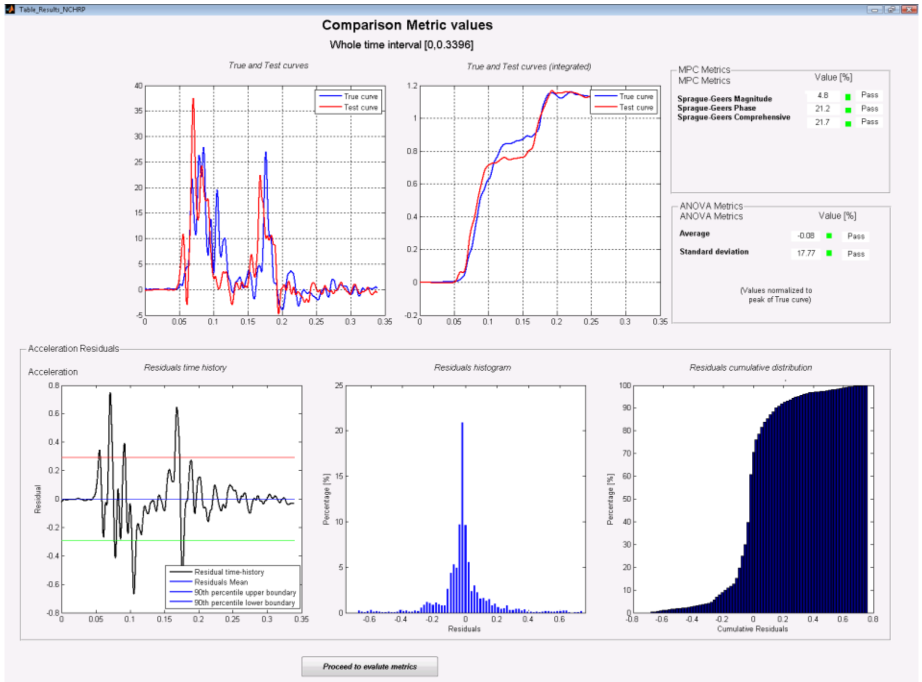


Figure A-23: GUI-window displaying results from *whole time interval* metrics calculations

Clicking the '*Proceed to evaluate metrics*' button, opens a GUI-window, as shown in Figure A-24, that will allow the user to define *upper* and *lower* boundaries for a new time interval over which to calculate the metrics. The interval selected for this example is 0.05 seconds to 0.15 seconds.

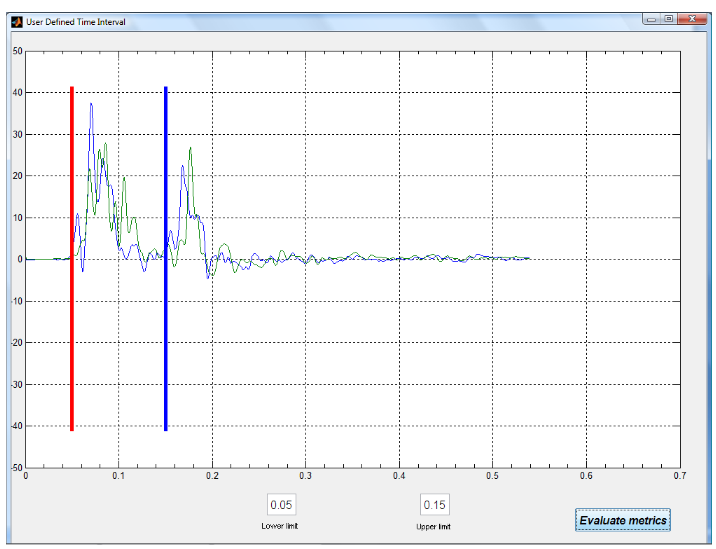
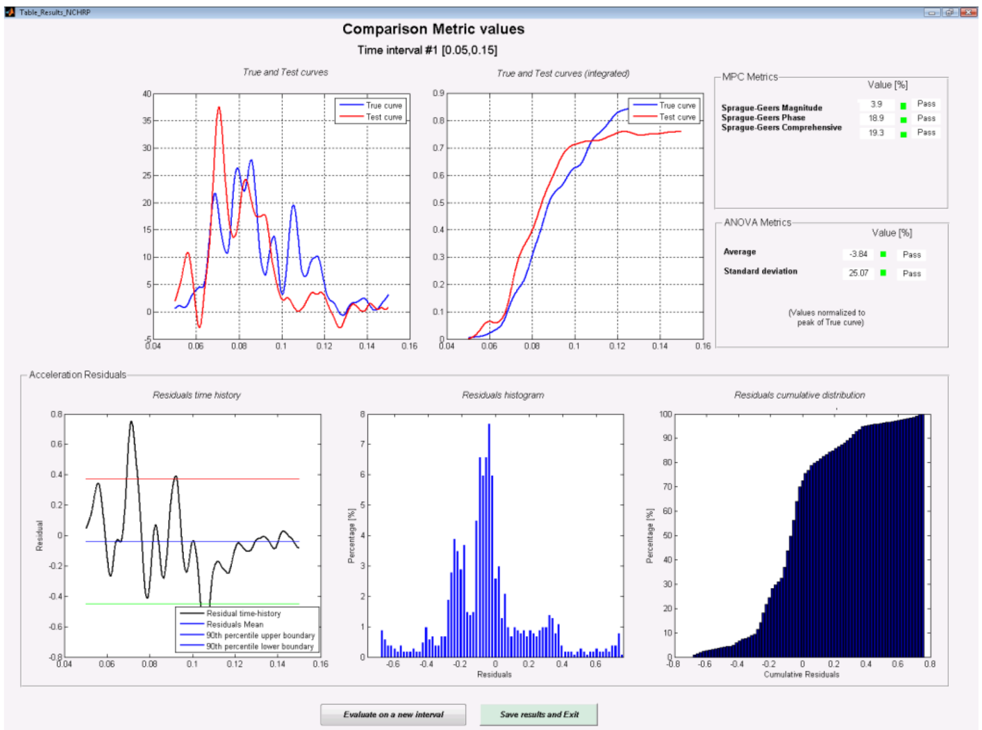


Figure A-24: GUI window for setting *user defined time interval*.

Once the user time window has been defined, the button '*Evaluate metrics*' is pressed to start the calculations of the metrics based on the data within the user defined interval. As before, various graphs appear and disappear on the computer screen, as RSVVP captures and saves the data. The results of the metrics calculations for the user defined window are shown in the GUI-window shown in Figure A-25.



FigureA-25: Metrics results for user-defined *time interval* [0.05 sec , 0.15 sec]

At this point we have the option to save results and exit or to evaluate metrics on another time interval. For this example, we will select the '*Evaluate on a new interval*' button and define another time interval over which to compute the metrics following the same procedure used in defining the first time interval. In this case, the time interval 0.15 seconds to 0.20 seconds is defined, as shown in Figure A-26; the resulting metrics calculations are shown in Figure A-27. Note: The preceding procedure can be repeated indefinitely to compute comparison metrics for as many user-defined time intervals as desired.

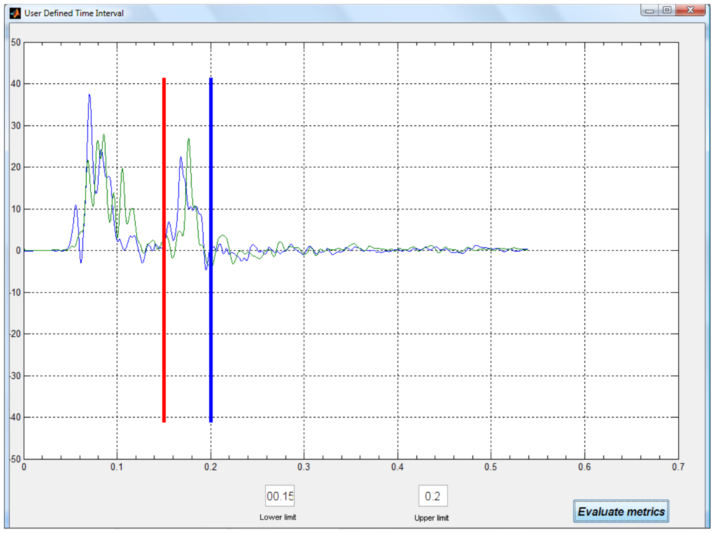


Figure A-26: Time interval 0.15 seconds to 0.20 seconds defined using GUI window

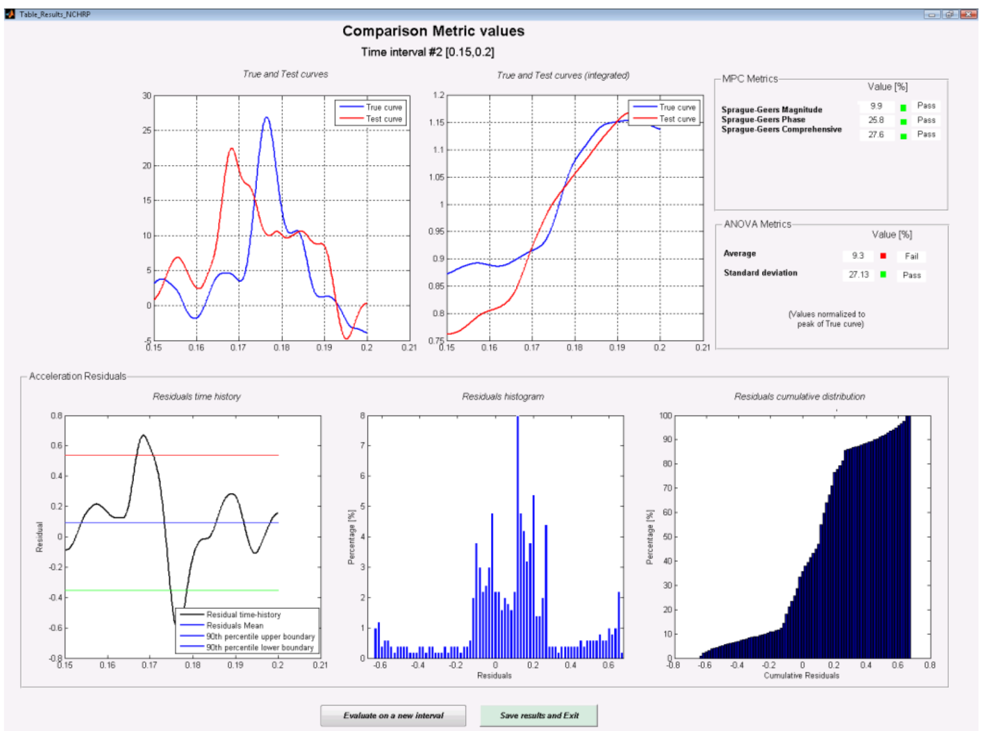


Figure A-27: Metrics computed for time interval [0.15 sec, 0.20 sec]

Save Results

To save results and exit, simply press the button '*Save results and Exit*'. RSVVP creates a folder called *Results*\ in the 'working' directory and creates subfolders for each time interval evaluated during the metrics calculations. For this example, three different subfolders were created:

- Whole_time_Interval,
- User_defined_interval_1_[0.05 , 0.15] and
- User_defined_interval_2_[0.15005 , 0.19995].

Also, an Excel file named *Comparison Metrics.xls* is created that contains a summary of the metrics values for each interval.

Table A-3 summarizes the results of the comparison metrics for each of the three time intervals (i.e., whole time and two user defined time intervals). The values of the metrics computed using the whole time interval of data are all within the recommended acceptance criteria for these types of data, which indicates that they are similar enough to be considered "*equivalent"*. The metric values computed for the data between 0.5 seconds and 0.15 seconds also indicate that the two curves are effectively "equivalent." The metric values calculated for the data between 0.15 seconds and 0.20 seconds, however, yield mixed results. For this section of the curves, the values for Sprague & Geers indicate that they are more or less "Equivalent," while the ANOVA metrics indicate that the differences between the curves are at least not likely to be attributable to random experimental errors. This result should not be surprising, since any differences that occur during the crash event are cumulative and will continuously alter the response of the vehicle. Thus, the similarity of the curves should be expected to diminish as the test progresses, especially towards the end of the test.

Table A-3: Summary of the metrics values for each of the time intervals evaluated.

Calculated Metric	Whole Time Interval [0, 0.3396]	User Time Interval [0.05, 0.15]	User Time Interval [0.15, 0.20]
Sprague & Geers Magnitude	4.8% [pass]	3.9% [pass]	9.9% [pass]
Sprague & Geers Phase	21.2% [pass]	18.9% [pass]	25.8% [pass]
Sprague & Geers Comprehensive	21.7% [pass]	19.3% [pass]	27.6% [pass]
ANOVA Average Residual Error	-.08% [pass]	-3.84% [pass]	9.3% [fail]
ANOVA Standard Deviation of Residual Errors	17.77% [pass]	25.07% [pass]	27.13% [pass]

EXAMPLE 2: MULTIPLE-CHANNEL COMPARISON

In this second example, the *multiple channel option* in RSVVP is used to compare the results from a finite element analysis to the results of a full-scale crash test. Six data channels are compared: three acceleration channels and three rotational rate channels.

Although each of these channels could be compared independently using the *single channel* option in RSVVP, the *multiple channel option* provides an additional analysis feature. That is, in addition to computing the metrics for each individual channel, the program also computes a *single set of metrics* that provide a comprehensive assessment of the combined data. The basic concept of this comprehensive assessment is to calculate a *weight factor* for each channel that is representative of its importance with respect to the other channels. Once the weighting factors have been evaluated, the multi-channel comprehensive metrics are calculated from a weighted average of the individual channel metrics.

Analysis Type

The first step is to select the type of curve comparison that will be performed. In this example, six pairs of curves are being compared, so the option '*multiple channel*' is selected in the GUI window, as shown in Figure A-28.

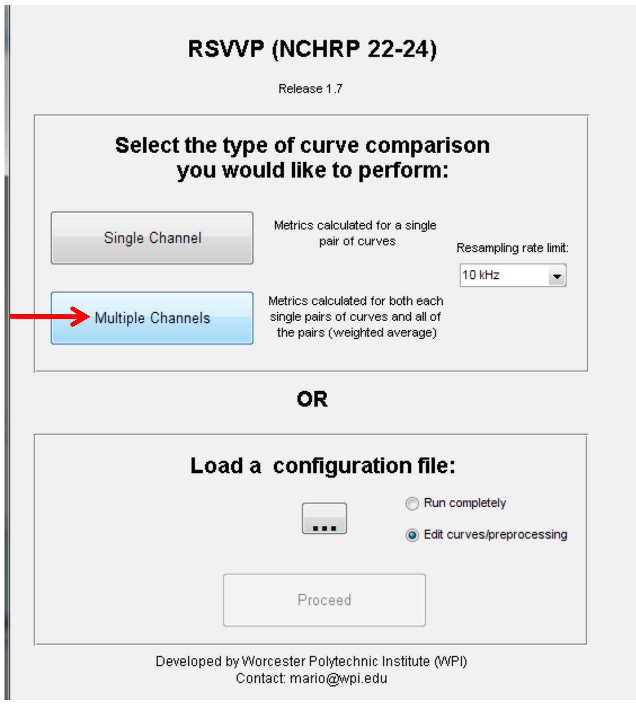


Figure A-28: The *Multiple Channel* option is selected in the GUI window

Data Entry and Preprocessing

The data entry for the *multiple channel* option is accomplished by loading and preprocessing each pair of data channels one at a time, using the same basic procedure described in Example 1. In fact, the GUI for the *multiple channel* option is the same basic GUI used in the *single channel* option. Since each pair of curves are processed independently, it is possible to select different preprocessing options for each channel. In this example, however, the same preprocessing options are used for each of the six pairs of data. In particular, all curves were trimmed using the '*trim original curves before preprocessing*' option (i.e., lower limit = 0.0 and upper limit = 0.9 seconds), and filtered using SAE 60 filter. Figure A-29 shows the original and preprocessed curve pairs for each of the acceleration and rotational rate channels.

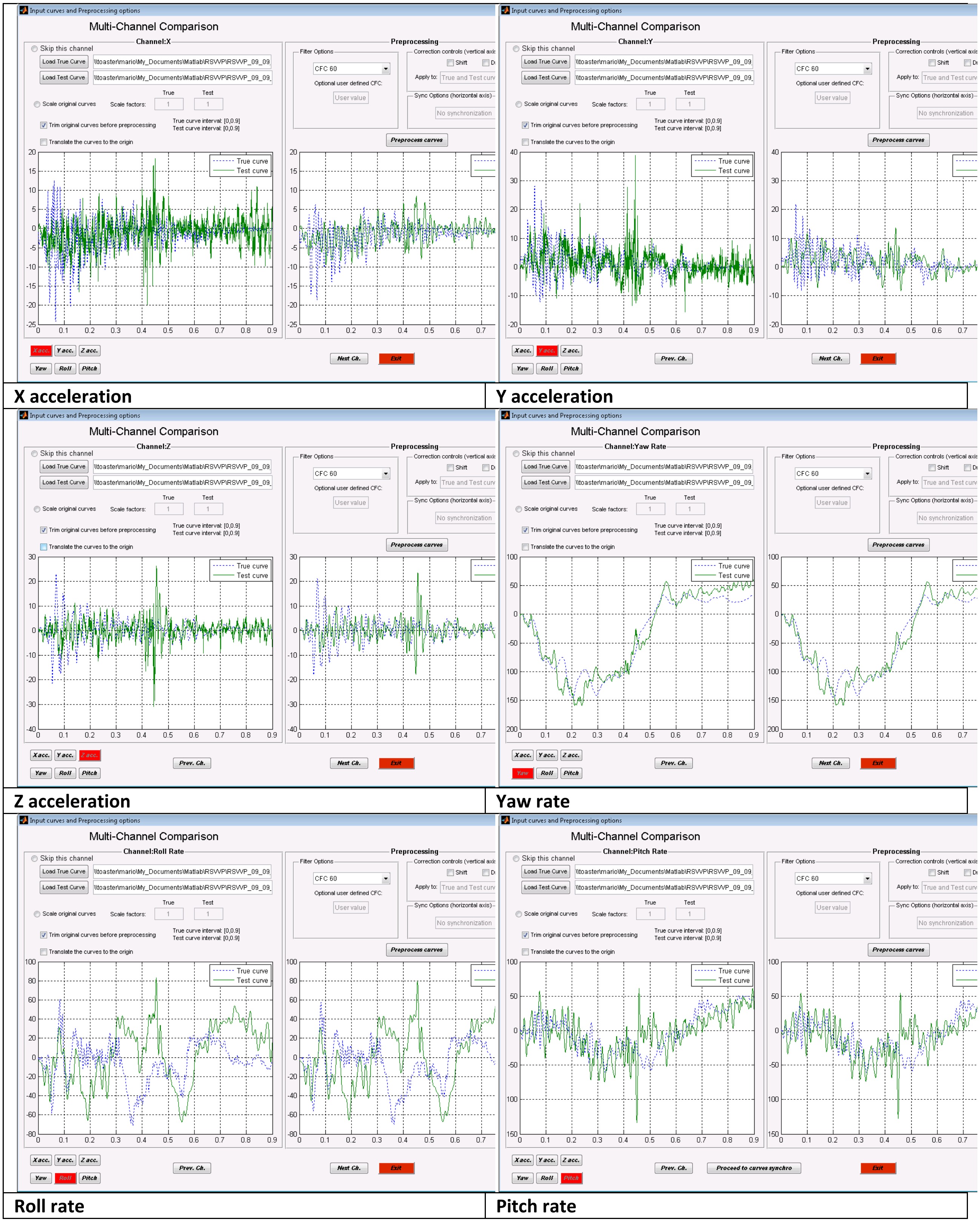


Figure A-29: Original and preprocessed curve pairs for each data channel

Note that, in the multi-channel case, the synchronization is performed in an intermediate step, after all the channels have been input. Once all the curve pairs have been entered into RSVVP and preprocessed, the '*Proceed to curves syncho*' option at the bottom of the GUI window will open a new GUI for synchronizing the curves. The default evaluation method, '*Weighting Factors,*' will be used in this example (see Appendix A2 for more details regarding the Weighting Factor method). The default synchronization method, '*Minimum absolute area of residuals,*' is then used to synchronize each of the curve pairs. The results of the synchronization operation are shown in Figure A-30.

Figure A-30: Synchronization results

Metric selection and evaluation

After the synchronization process is completed, RSVVP automatically opens another GUI for selecting the desired metrics. For this example, the NCHRP 22-24 metrics profile (i.e., ANOVA metrics and the Sprague & Geers MPC metrics) was selected from the *Metrics Box* and the option *Whole time window only*' was selected from the drop-down men in the *Time Window Box*.

The metrics calculations are initiated by pressing the '*Evaluate metrics*' button at the bottom of the GUI window. RSVVP then calculates the metrics for each individual channel, computes a weight factor for each channel based on a pseudo momentum approach (see Appendix A2), and computes the multi-channel comprehensive metrics from a weighted average of the individual channels. During the calculations of the metrics, various graphs appear and disappear on the computer screen. Screen-captures of these graphs are taken during this process and the files are saved in the output directory defined by the user. When the metrics calculations are completed, RSVVP displays the results of the first channel on the screen. Note that beside each metric value RSVVP indicates whether or not the result meets the recommended acceptance criteria. To view the results for the other five channels or to view the weighted average results, use the drop-down menu at the left of the *True and Test curves* graph to select the corresponding option. Note that when the *weighted average of the results* is selected from the drop-down menu, RSVVP displays a bar graph of the weight factors for each channel. Figures A-31 through A-36 show the results obtained for each channel, and Figure A-37 shows the weighted average results.

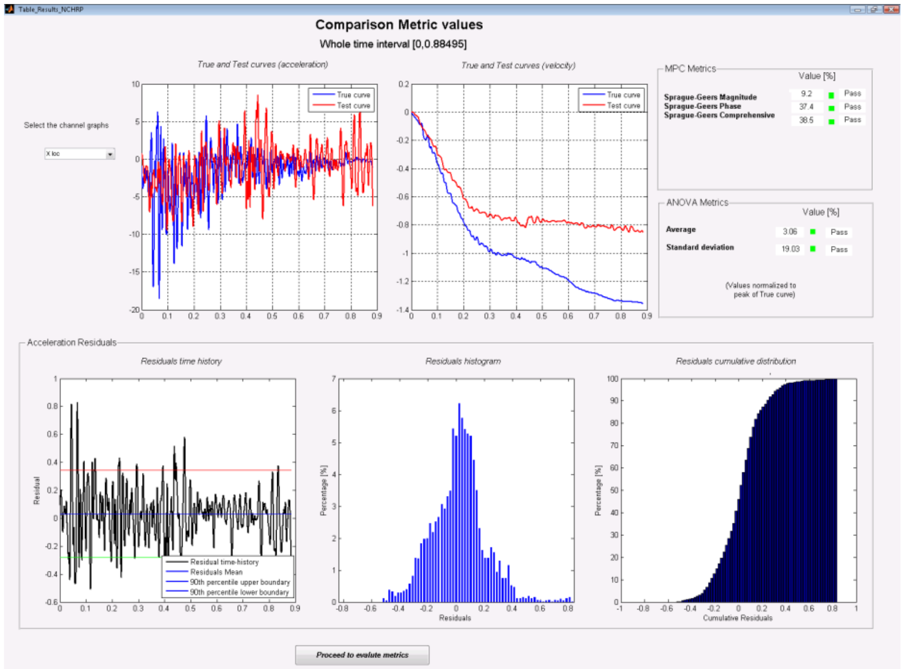


Figure A-31: Screen output of the results for the X channel.

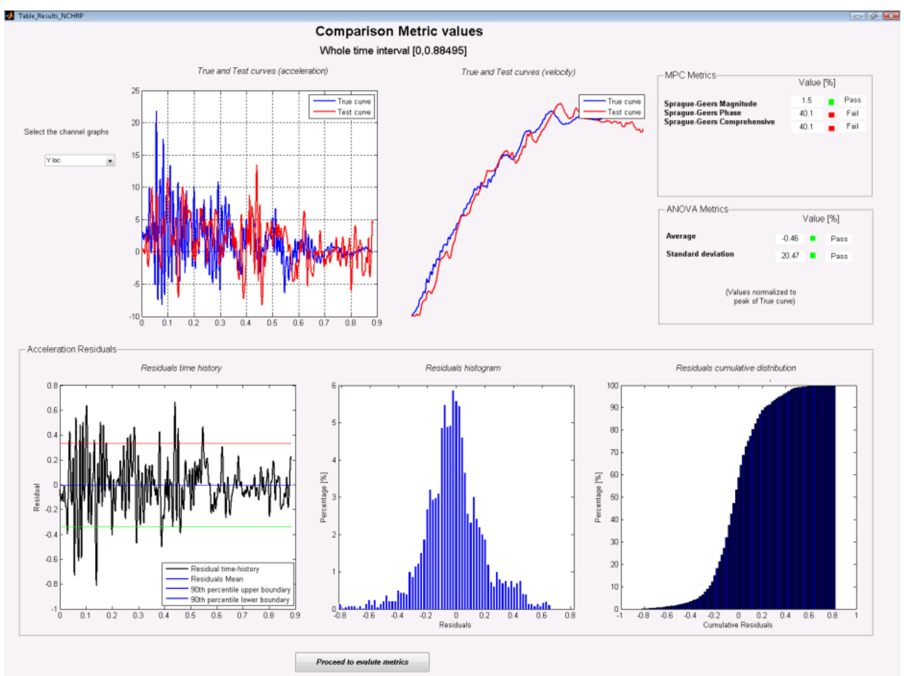


Figure A-32: Screen output of the results for the Y channel.

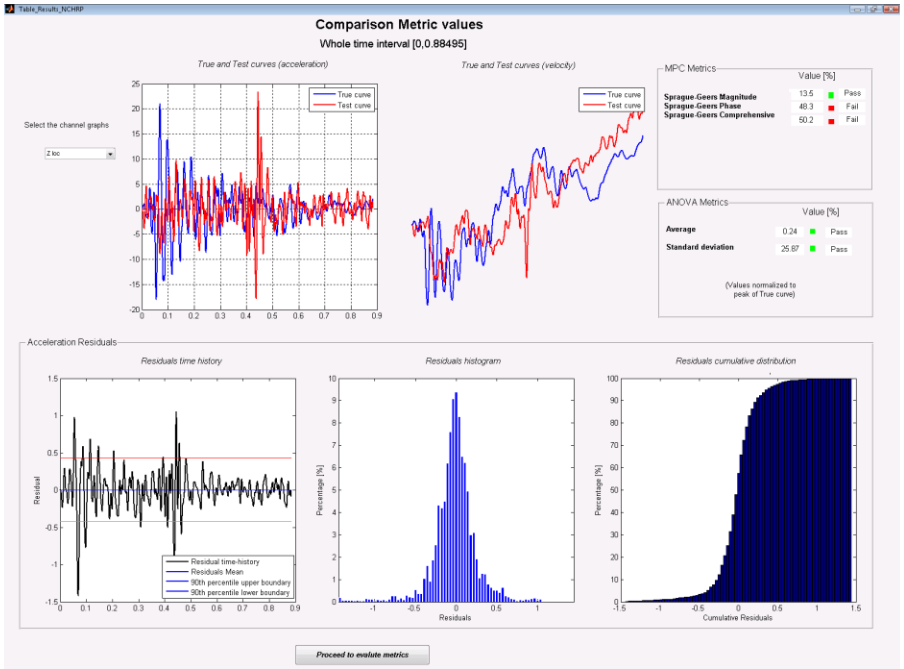


Figure A-33: Screen output of the results for the Z channel.

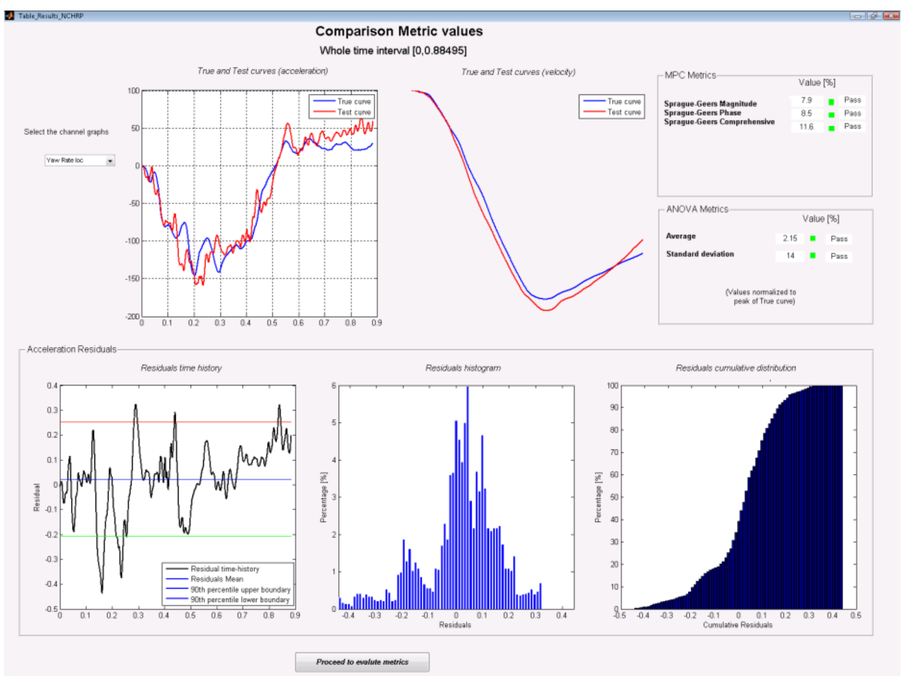


Figure A-34: Screen output of the results for the Yaw channel.

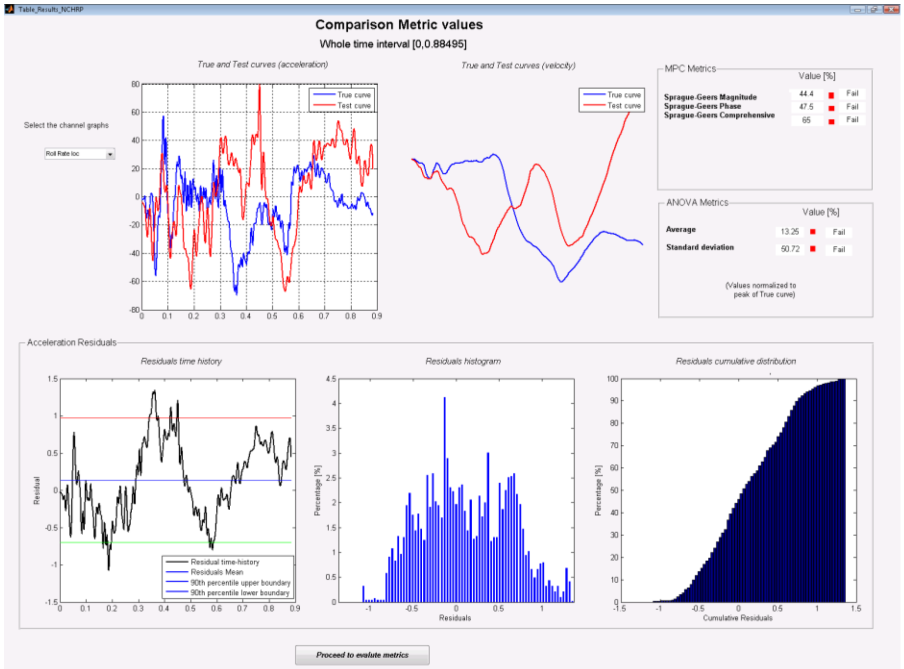


Figure A-35: Screen output of the results for the Roll channel.

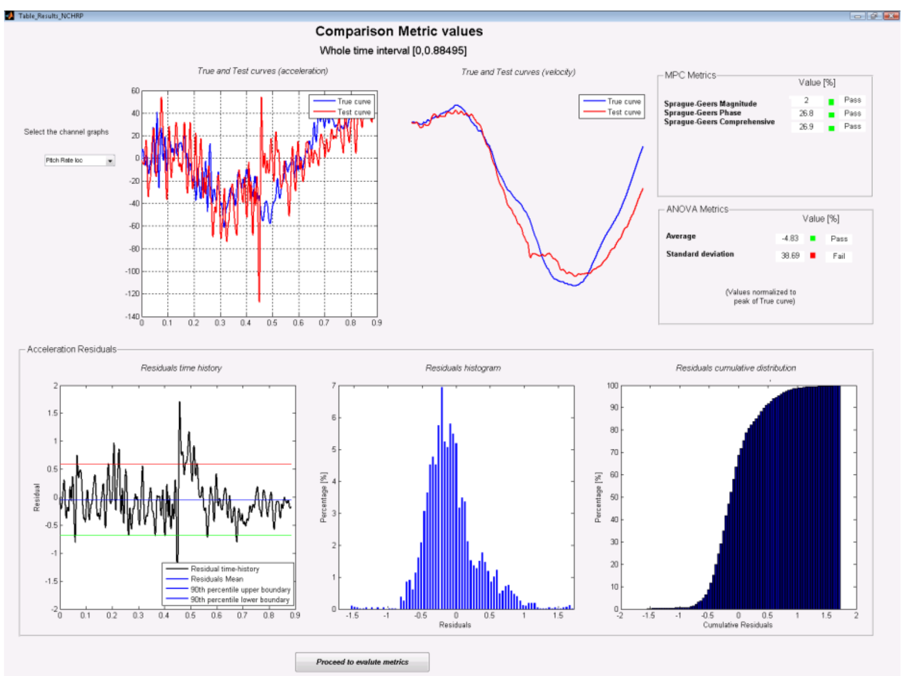


Figure A-36: Screen output of the results for the Pitch channel.

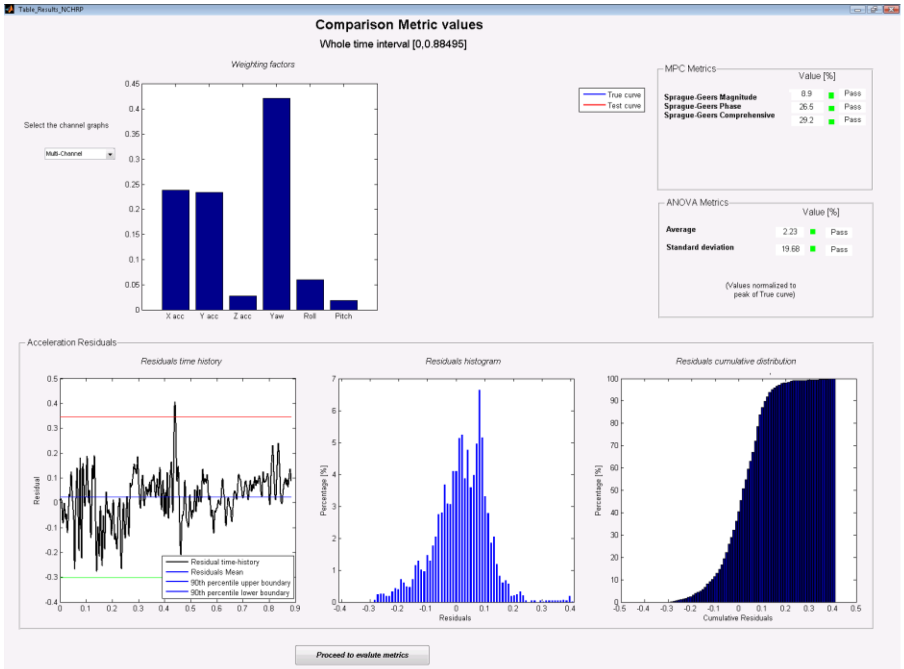


Figure A-37: Screen output of the results for the weighted average.

Table A-4 shows a summary of the comparison metrics computed for each data channel and the weighted average. The values that exceed the NCHRP 22-24 recommended acceptance criterion for that metric are displayed with a red background in the table.

The comparison of the roll-channel shows that the simulation results were not similar to those measured in the test. The magnitudes of the z-channel accelerations in the numerical simulation are consistent with the test data, but they are out of phase with each other. The pitch-channel data from the simulation was of similar magnitude and phase, but failed to meet the criterion for the standard deviation of residual errors. Thus, based on the comparison metrics for the individual channels, the numerical model cannot be deemed valid.

Taking into consideration the weighted contribution of each channel to the overall response of the vehicle in the test event, however, yields a set of comprehensive metrics which indicate that, in fact, the simulation and test are in agreement. The weighting factors for each channel are shown in Figure A-37, which indicate that the response of the vehicle was dominated by the x-acceleration, y-acceleration and yaw-rate. It should not be surprising that the numerical simulation and the test were not in agreement with respect to the z-, roll-, and pitch-channels; Since there is such low energy involved in these channels, compared to the other channels, the agreement would not be expected to be in any better had we been comparing two identical full-scale crash tests.

Table A-4: Summary of the calculated metrics for the multi-channel data

Data Channel	Sprague & Geers		ANOVA	
	(M)	(P)	(average)	(std)
x	9 %	37 %	3 %	19 %
y	2 %	40 %	0 %	2 %
z	14 %	48 %	0 %	26 %
Yaw	8 %	9 %	2 %	14 %
Roll	44 %	48%	13 %	51 %
Pitch	2 %	27 %	-5 %	39 %
Weighted Average	9 %	27 %	0 %	2 %

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APPENDIX A1: Comparison Metrics in RSVVP

A brief description of the metrics evaluated by RSVVP is presented in this section. All fourteen metrics available in RSVVP are deterministic shape-comparison metrics. Details about the mathematical formulation of each metric can be found in the cited literature. Conceptually, the metrics evaluated can be classified into three main categories: (i) magnitude-phase-composite (MPC) metrics, (ii) single-value metrics and (iii) analysis of variance (ANOVA) metrics.

MPC METRICS

MPC metrics treat the curve magnitude and phase separately using two different metrics (i.e., M and P, respectively). The M and P metrics are then combined into a single value comprehensive metric, C. The following MPC metrics are included in RSVVP: (a) Geers (original formulation and two variants), (b) Russell and (c) Knowles and Gear. [3-8] Table A1-1Table A1-1 shows the analytical definition of each metric. In this and the following sections, the terms m_i and c_i refer to the measured and computed quantities, respectively, with the "i" subscribe indicating a specific instant in time.

In all MPC metrics the phase component (P) should be insensitive to magnitude differences but sensitive to differences in phasing or timing between the two time histories. Similarly, the magnitude component (M) should be sensitive to differences in magnitude but relatively insensitive to differences in phase. These characteristics of MPC metrics allow the analyst to identify the aspects of the curves that do not agree. For each component of the MPC metrics, zero indicates that the two curves are identical. Each of the MPC metrics differs slightly in its mathematical formulation. The different variations of the MPC metrics are primarily distinguished in the way the phase metric is computed, how it is scaled with respect to the magnitude metric and how it deals with synchronizing the phase. In particular, the Sprague and Geers metric [5] uses the same phase component as the Russell metric [6]. Also, the magnitude component of the Russell metric is peculiar as it is based on a base-10 logarithm and it is the only MPC metric that is symmetric (i.e., the order of the two curves is irrelevant). The Knowles and Gear metric [7,8] is the most recent variation of MPC-type metrics. Unlike the previously discussed MPC metrics, it is based on a point-to-point comparison. In fact, this metric requires that the two compared curves are first synchronized in time based on the so called Time of Arrival (TOA), which represents the time at which a curve reaches a certain percentage of the peak value. In RSVVP the percentage of the peak value used to evaluate the TOA was 5%, which is the typical value found in literature. Once the curves have been synchronized using the TOA, it is possible to evaluate the magnitude metric. Also, in order to avoid creating a gap between time histories characterized by a large magnitude and those characterized by a smaller one, the magnitude component M has to be normalized using the normalization factor QS.

Table A1-1: Definition of MPC metrics.

	Magnitude	***Phase***	***Comprehensive***
Integral comparison metrics			
Geers	$M_G = \sqrt{\frac{\sum c_i^2}{\sum m_i^2}} - 1$	$P_G = 1 - \frac{\sum c_i m_i}{\sqrt{\sum c_i^2 \sum m_i^2}}$	$\sqrt{M_G^2 + P_G^2}$
Geers CSA	$M_G = \sqrt{\frac{\sum c_i^2}{\sum m_i^2}} - 1$	$P_{CSA} = 1 - \frac{\lvert\sum c_i m_i\rvert}{\sqrt{\sum c_i^2 \sum m_i^2}}$	$sign\left(\sum c_i m_i\right)\sqrt{M_{CSA}^2 + P_{CSA}^2}$
Sprague & Geers	$M_G = \sqrt{\frac{\sum c_i^2}{\sum m_i^2}} - 1$	$P_{SG} = \frac{1}{\pi} cos^{-1} \frac{\sum c_i m_i}{\sqrt{\sum c_i^2 \sum m_i^2}}$	$\sqrt{M_{SG}^2 + P_{SG}^2}$
Russell	$M_R = sign(m) \cdot Log_{10}(1 + \lvert m\rvert)$ *where* $m = \frac{(\sum c_i^2 - \sum m_i^2)}{\sqrt{\sum c_i^2 \sum m_i^2}}$	$P_R = \frac{1}{\pi} cos^{-1} \frac{\sum c_i m_i}{\sqrt{\sum c_i^2 \sum m_i^2}}$	$\sqrt{\frac{\pi}{4}(M_R^2 + P_R^2)}$
Point-to-point comparison metrics			
Knowles & Gear	$M_{KG} = \sqrt{\frac{\sum \left(\frac{\lvert m_i\rvert}{m_{max}}\right)^p (\tilde{c}_i - m_i)^2}{\sum \left(\frac{\lvert m_i\rvert}{m_{max}}\right)^p (m_i)^2}}$ *where* $\tilde{c} = c(t - \tau)$ (*with* $\tau = TOA_c - TOA_m$)	$P_{KG} = \frac{\lvert TOA_c - TOA_m\rvert}{TOA_m}$	$\sqrt{\frac{10M_{KG}^2 + 2P_{KG}^2}{12}}$

SINGLE-VALUE METRICS

Single-value metrics give a single numerical value that represents the agreement between the two curves. Seven single-value metrics were considered in this work: (1) the correlation coefficient metric, (2) the NARD correlation coefficient metric (NARD), (3) Zilliacus error metric, (4) RSS error metric, (5) Theil's inequality metric, (6) Whang's inequality metric and (7) the regression coefficient metric. [9-12] The first two metrics are based on integral comparisons while the others are based on a point-to-point comparisons. The definition of each metric is shown in Table A1-2.

Table A1-2: Definition of single-value metrics.

Integral comparison metrics			
Correlation Coefficient	$\frac{n\sum c_i m_i - \sum c_i \sum m_i}{\sqrt{n\sum c_i^2 - (\sum c_i)^2}\sqrt{n\sum m_i^2 - (\sum m_i)^2}}$	***Correlation Coefficient (NARD)***	$\frac{\sum c_i m_i}{\sqrt{\sum c_i^2}\sqrt{\sum m_i^2}}$
Weighted Integrated Factor		$\sqrt{\frac{\sum \max\left(m_i^2, c_i^2\right)\cdot\left(1-\frac{\max(0, m_i\cdot c_i)}{\max\left(m_i^2,c_i^2\right)}\right)^2}{\sum\max\left(m_i^2,c_i^2\right)}}$	
Point-to-point comparison metrics			
Zilliacus error	$\frac{\sum\lvert c_i - m_i\rvert}{\sum\lvert m_i\rvert}$	***RSS error***	$\frac{\sqrt{\sum(c_i-m_i)^2}}{\sqrt{\sum m_i^2}}$
Theil's inequality	$\frac{\sqrt{\sum(c_i-m_i)^2}}{\sqrt{\sum c_i^2}+\sqrt{\sum m_i^2}}$	***Whang's inequality***	$\frac{\sum\lvert c_i-m_i\rvert}{\sum\lvert c_i\rvert+\sum\lvert m_i\rvert}$
Regression coefficient	$\sqrt{1-\frac{(n-1)\sum(c_i-m_i)^2}{n\sum(m_i-\overline{m})^2}}$		

ANOVA METRICS

ANOVA metrics are based on the assumption that two curves do, in fact, represent the same event such that any differences between the curves must be attributable only to random experimental error. The analysis of variance (i.e., ANOVA) is a standard statistical test that assesses whether the variance between two curves can be attributed to random error.[1,2] When two time histories represent the same physical event, both should be identical such that the mean residual error, $\bar{e}$, and the standard deviation of the residual errors, σ, are both zero. Of course, this is never the case in practical situations (e.g., experimental errors cause small variations between tested responses even in identical tests). Ray proposed a method where the residual error and its standard deviation are normalized with respect to the peak value of the true curve and came to the following acceptance criteria based on six repeated frontal full-scale crash tests [1]:

- The average residual error normalized by the peak response (i.e., $\bar{e}^r$) should be less than five percent.

$$\bar{e}^r = \frac{\sum (c_i - m_i)/m_{max}}{n} < 0.05 \cdot m_{max}$$

- The standard deviation of the normalized residuals (i.e., σ) should be less than 35 percent.

$$\sigma = \sqrt{\frac{\sum \left(e_i^r - \bar{e}^r\right)^2}{n-1}} < 0.35 \cdot m_{max}$$

APPENDIX A2: Multi-Channel Weight Factors

The multi-channel mode in RSVVP was created for the specific purpose of comparing numerical simulations of vehicle impact into roadside barriers to the results from a full-scale crash test. The data that are typically collected in such tests include (at a minimum) three acceleration channels (i.e., longitudinal, transverse and vertical directions) and three rotational rate channels (i.e., roll, pitch and yaw angular rates). These data are collected at the center of gravity of the vehicle and are used to measure vehicle response (e.g., stability) and are also used to estimate occupant risk factors (e.g., occupant impact velocity and occupant ride-down acceleration). It is desired to have as much time history data as possible available from the physical experiment for use in validating the numerical model; however, it is more often the case that only the six aforementioned channels of data are collected in the full-scale tests. As such, all these data should be used in the validation process.

Sometimes, however, there may be one or two relatively unimportant channels that do not result in good quantitative comparisons. An example might be a small sign support test where the longitudinal acceleration has a much greater influence on the results of the impact event than do the lateral or vertical accelerations. The less important channels may not satisfy the criteria because they are essentially recording noise. The longitudinal channel in this example will probably be an order of magnitude greater than some of the other less important channels, and the response would essentially be determined by a single channel, i.e., the longitudinal channel.

In such case, the analyst may want to ignore any of the channels that appear to be less meaningful to the outcome of the crash event, or at least to rank those channels with less importance. The issue then is how to make the decision *objective*, since it is not likely that everyone will have the same opinion on how to rank each channel.

The RSVVP program calculates a *weight* for each channel that corresponds to the importance that each channel had in the overall response in the physical test. The methods available in RSVVP for computing these *weight factors* include:

1. Inertial Method – weighted momentum approach and

2. Area Method (default) – pseudo momentum approach
3. Kinetic Energy Approach – (not available in current version of RSVVP)

The *Inertial method* determines the *weight* for each channel by computing the linear and rotational momentum of the six channels of data. The weight factors correspond to the proportion of the momentum in each channel. This method provides the most accurate weight value for each channel but requires that the mass of the vehicle and the three angular inertial properties be input into RSVVP. In many cases, however, the exact inertial properties for the test vehicle are not known.

The *Area method*, on the other hand, calculates a *weight* for each channel based on a *pseudo* momentum approach using the area under the curves. In this method, the inertial properties of the vehicle are not used in the calculations and therefore the weight values will not be an exact representation of the momentum change associated with each channel. The *Area Met*hod has been shown, however, to provide values *similar* to those computed using the *Inertial Method* for cases involving vehicle impact into longitudinal roadside barriers (e.g., concrete median barrier).

AREA METHOD WEIGHT FACTORS

In this section, a brief description of how the weighting factors are calculated in RSVVP for the Area Method is presented. Note: The weight factors are calculated in all cases using the data from the *true curve* input.

Using the Area Method, RSVVP computes weight factors for each individual channel based on a 'pseudo' momentum approach. The basic concept of this weighting scheme is to calculate a local index for each channel that is representative of its importance (or weight) with respect to the other channels. Once these indexes have been computed, the weighting factors are calculated by simply dividing the index calculated for each channel by the sum of all the channels indexes. Thus the total sum of the weight factors equals unity.

Because the units differ between linear and rotational momentum, each of these two groups of channels will be treated separately. The weighting factors for each channel are calculated using the following procedure:

- Evaluation of the area of the *True curve* for each acceleration channel, a_i , and rotational channel, v_i.
- Evaluation of the sum of the acceleration areas, a_{Sum}, and rotational areas, v_{Sum}.
- Evaluation of the local weight of each acceleration channel, $lw_i^{(a)} = \frac{a_i}{a_{Sum}}$, and rotational channel $lw_i^{(v)} = \frac{v_i}{v_{Sum}}$
- Evaluation of the channel weight factors,

$$w_i^{(a)} = \frac{\mathrm{lw}_i^{(a)}}{\sum \mathrm{lw}_i^{(a)} + \sum \mathrm{lw}_i^{(v)}}$$

$$w_i^{(v)} = \frac{\mathrm{lw}_i^{(v)}}{\sum \mathrm{lw}_i^{(a)} + \sum \mathrm{lw}_i^{(v)}}$$

Once the weighting factors have been evaluated, the multi-channel metrics are calculated using a weighted average of the individual channel metrics. Note that the combination of the time histories is performed for each of the metrics selected at the beginning of the run by the user.

Table A2-1 shows the acceptance criteria proposed for the verification and validation of finite element models in roadside safety using the NCHRP 22-24 metrics profile.

Table A1: Acceptance criteria suggested for the NCHRP 22-24 metrics profile.

Sprague & Geers metrics		**ANOVA metrics**	
Magnitude (M)	≤ 40	***Mean***	≤ 0.05
Phase (P)	≤ 40	***Standard deviation***	≤ 0.35
Composite (C)	≤ 40		

Apart from the value of the comparison metrics, it is important that the graphs of the cumulative distribution and histogram of the residual errors have the following typical characteristics of a normal distribution:

- The histogram should have a normal or bell shaped distribution and the
- Cumulative distribution should have an "S" shape

If the histogram and the cumulative distribution do have these shape characteristics, the residuals between the two curves are most likely due to some systematic error which should be identified and corrected.