Chapter 5

TRAKVU Validation

This chapter describes the method used to validate TRAKVU and its track generation capabilities, and also presents the results of the validation. A comparison of the track data is presented first, followed by a comparison of dynamic responses. The actual dynamic response of a rail vehicle is compared with the dynamic response from a NUCARS simulation using track data created by TRAKVU. The dynamic response from a NUCARS simulation using measured track data is then compared to the dynamic response of a NUCARS simulation using track data created by TRAKVU.

5.1 Validation Process

The validation of TRAKVU consisted of two parts. First, a direct comparison of the track data, which includes a direct comparison between a section of track created by TRAKVU and a section of actual track with the same class, was conducted. A statistical analysis and frequency analysis were performed on both tracks. The results were then compared to determine how well TRAKVU recreated the characteristics of the actual track.

The second part of the validation involved a comparison of the NUCARS dynamic response due to TRAKVU, with:

1. Actual field measurements
2. NUCARS results with measured track data.

5.2 Track Data Validation

This section describes the comparison between the TRAKVU-generated track parameters and actual measurements made on TTCI's Transit Test Track (TTT) in Pueblo, Colorado. It also includes a discussion on the effect of data processing on the auto spectrum of the data, in terms of mid-cord offset (MCO) measurements.

5.2.1 Track Data Comparison

To determine how well TRAKVU reproduces the characteristics of a track, we directly compared a section of track created by TRAKVU with an actual track of the same class. The comparison was made using statistical measures as well as frequency contents for each section.

A 10,000-foot (3,048-meter) section of tangent, class 5 track was created using TRAKVU. This was compared to a 10,000-foot (3,048-meter) tangent section of the TTT, a class 5 track. The statistical analysis performed on each track consisted of calculating the sample mean, sample standard deviation, minimum, and maximum values. The results of the two tracks compare well, as shown in Table 5.1. The means are zero, the standard deviations are within +/- 0.02 in (0.05 cm), and the minimum and maximum values are comparable.

Table 5.1 Statistical Analysis Comparing TRAKVU Track and Actual Track

	TTT, Class 5		TRAKVU, Class 5	
	Alignment	Profile	Alignment	Profile
Mean	0.00 in (0.00 cm)	0.00 in (0.00 cm)	0.00 in (0.00 cm)	0.00 in (0.00 cm)
Standard Deviation	0.08 in (0.20 cm)	0.12 in (0.30 cm)	0.10 in (0.25 cm)	0.10 in (0.25 cm)
Minimum	-0.31 in (-0.79 cm)	-0.41 in (-1.04 cm)	-0.33 in (-0.84 cm)	-0.34 in (-0.86 cm)
Maximum	0.37 in (0.94 cm)	0.44 in (1.12 cm)	0.38 in (0.97 cm)	0.36 in (0.91 cm)

The frequency analysis involved calculating the auto spectra of the two tracks. The procedure was the same as that of the original frequency analysis, however, the sample size was set to 1024 for both tracks. This created 18 windows, which were sufficient to provide an acceptable average and reduce any noise. The results are shown in Figs. 5.1-5.2. Each figure compares the auto spectrum of the TTT track data to that of the TRAKVU-created track data.

It is worth noting that the created track was not intended to have the exact frequency content as the actual track, but rather to possess the same frequency characteristics, i.e., a common bandwidth. It is clear from Figs. 5.1 and 5.2 that the created track does a reasonably good job of capturing the frequency characteristics of the actual track. The common bandwidth is obvious in both plots. There is good agreement of the amplitudes for the alignment data. The first spectral line for the TRAKVU data in both plots is surprisingly high. This is be due to the digital filter used for filtering the random data, and will be explained further in section 5.2.2.

Overall, the TRAKVU data do a reasonable job at reproducing the statistical and frequency characteristics of the actual track. The true test will be how well it performs in reproducing the input to the dynamic system.

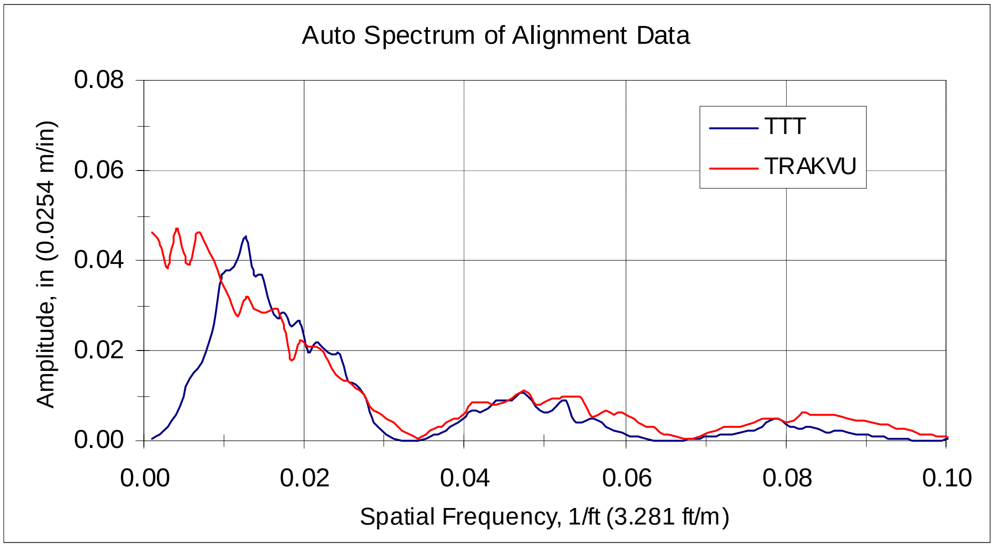


Figure 5.1 Comparison of Auto Spectrum for Alignment Data of TTT and TRAKVU-Created Track

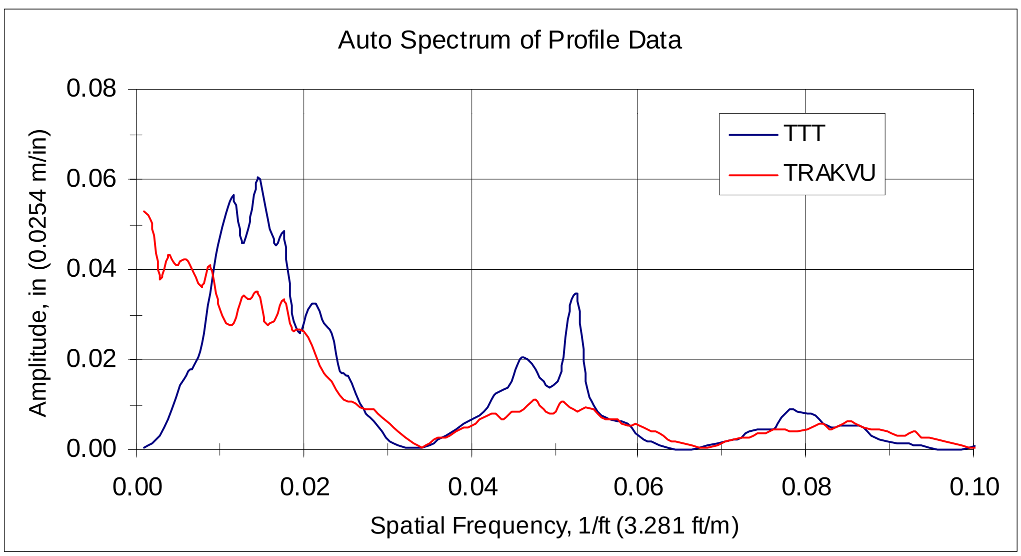


Figure 5.2 Comparison of Auto Spectrum for Profile Data of TTT and TRAKVU-Created Track

5.2.2 Effect of Data Processing on Track Data

To create the track data with irregularities for use in modeling, the track data is represented in space curve form. Space curve form describes the deviations of the track from a reference point or desired path, in contrast to 62 ft MCO data which measures the deviations from the mid-cord as described earlier. We used the statistical characteristics of the MCO data when creating the track irregularities because the MCO data was the only track data available for the data analysis. Although the data was collected using a different method, the statistical characteristics would still be similar.

The MCO form that ENSCO, Inc. uses to measure track geometry data, described in Section 3.4.3, is the industry standard used by the FRA for evaluating track safety standards. Space curve data, however, is typically used in modeling applications because it does not distort frequencies. In the creation of the track irregularities, random data was filtered such that its frequency content better resembled that of an actual track, as present in MCO measurements. Filtering the data with a digital filter had a similar effect on the frequency content of the data, as compared to the MCO method. This effect, however, is inherent in all basic digital filters, because digital filters sum up the data over a given period. This causes certain wavelengths to be attenuated, depending on the weighting factor applied, as discussed in Section 3.5. Figure 5.3 shows a comparison of a pure-tone signal with a wavelength of 35 ft (10.7 m) and the 62 ft MCO signal and filtered signal. A pure tone signal is selected to more clearly illustrate the data processing effect, although this concept can be easily extended to a broad band signal. The filtered signal in this case refers to the selected signal filtered by a 30 point moving average, as discussed in Section 3.5. Both the MCO and filtered signals are attenuated due to the wavelength of the original signal. The phase of the filtered signal is shifted due to the phase characteristics of the digital filter.

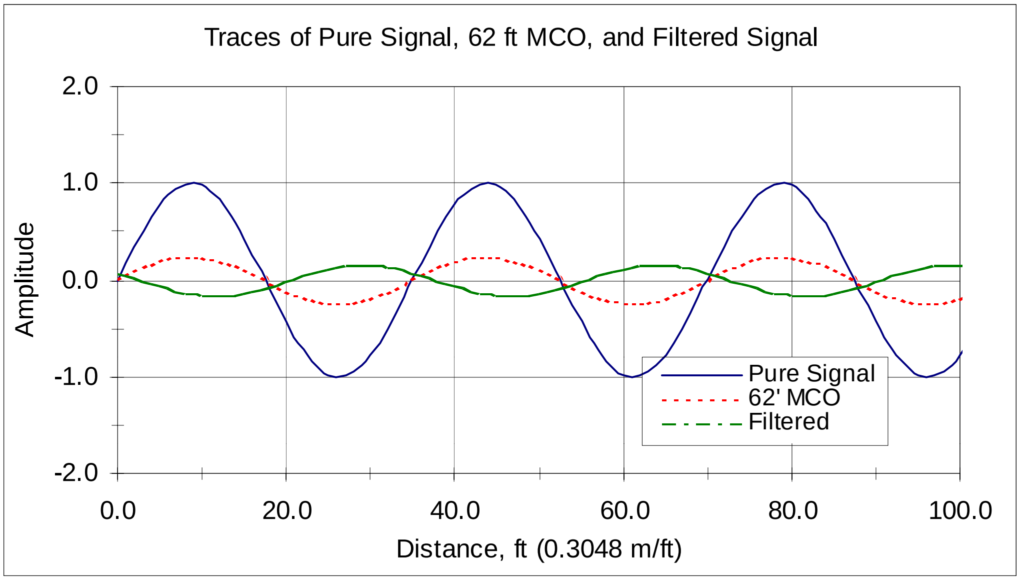


Figure 5.3 Comparison of Pure Signal, 62 ft MCO Signal, and Filtered Signal

As shown in Fig. 5.4, although both the MCO method and digital filter attenuate certain wavelengths, the digital filter does not remove the large wavelengths, or low frequencies. This is because the 30 point moving average works as a low-pass filter, as discussed earlier in the Section 3.5. The low frequencies, however, are removed by the MCO method. Figure 5.5 shows the auto spectrum of random data processed using the digital filter and the 62 ft MCO method. The scalloped effect can be seen in both spectra. The difference in the low frequency content is also very evident, which of course is caused by the difference in the low frequency responses of the 30 point moving average filter and MCO processing. The track parameters simulated by TRAKVU contain the low frequency content observed in Fig. 5.5 because they do exist in practice, even though they are not reflected in MCO measurements.

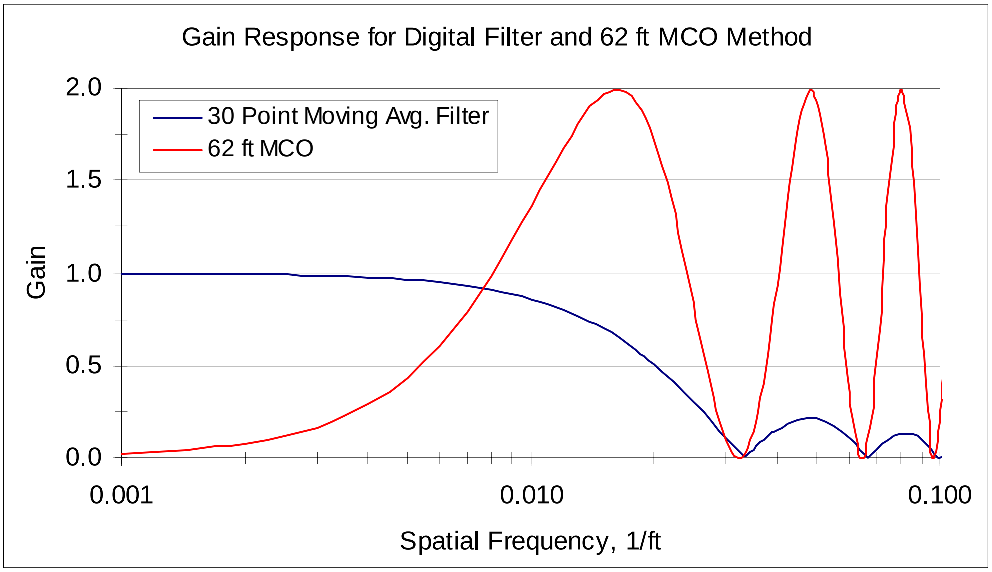


Figure 5.4 Comparison of Gain Response for Digital Filter and 62 ft MCO Method

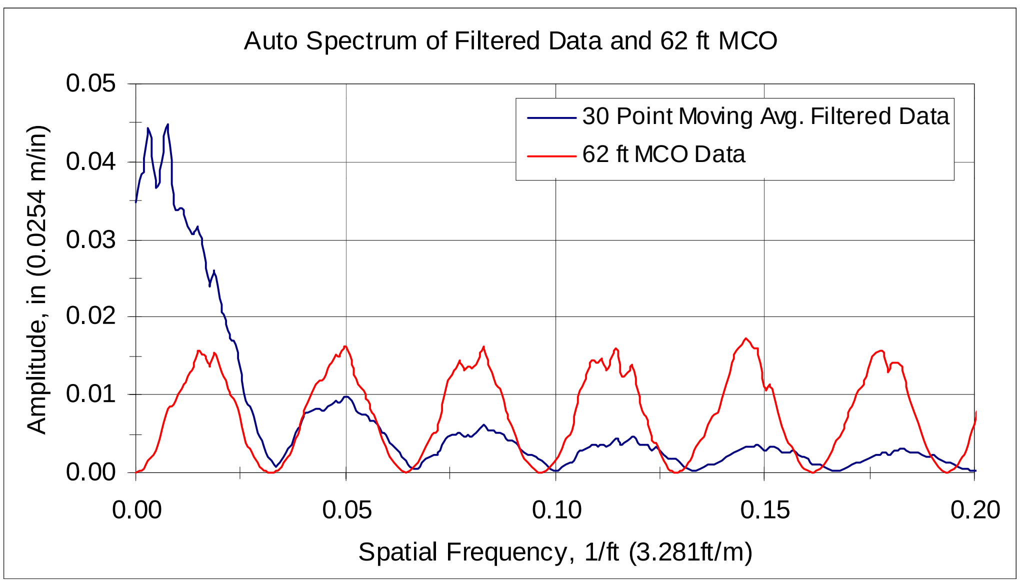


Figure 5.5 Comparison of Auto Spectrum of Filtered Data and 62 ft MCO Data

Figure 5.6 shows that indeed if the TRAKVU simulated signal (which is space curve data) is processed using the MCO method, it would contain the same low frequency characteristics as the measured data. The humps or scallops are again evident in both plots, proving that the TRAKVU space curve data can be manipulated to resemble the MCO data, if so desired. As mentioned earlier, the common practice however, is to use the space curve data, in order to represent the low frequency (or long wavelength) characteristics of the track.

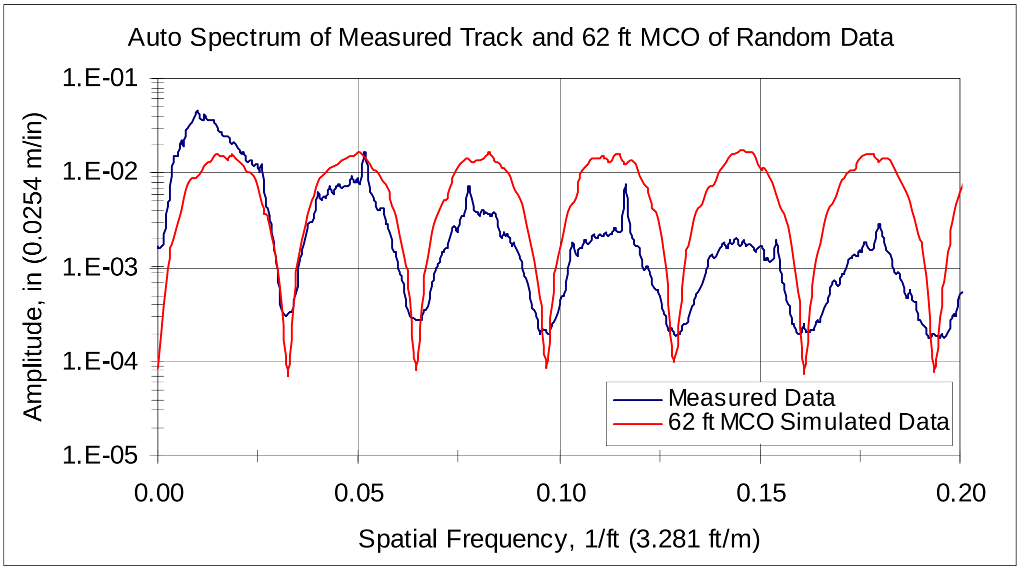


Figure 5.6 Comparison of Auto Spectrum of Actual Track and 62 ft MCO of Random Data

5.3 Dynamic Response Validation

In order to evaluate how well the track data created by TRAKVU model the input into a dynamic system, it was necessary to perform a dynamic response comparison. This provides a measure of how well the characteristics of the track, identified by the data analysis, influence the dynamic system. This portion of the validation consisted of two parts. The first was comparing the dynamic response of a rail vehicle in NUCARS using track data created by TRAKVU with the actual dynamic response of a similar rail vehicle. This comparison was intended to show how well the track created by TRAKVU recreates the input from actual track. This method, however, is dependent on the accuracy of the dynamic model. The second part of the validation involved comparing the dynamic response of a rail vehicle modeled in NUCARS, again using the same track data created by TRAKVU, with the dynamic response from the same NUCARS model, but using measured track data. This comparison was intended to evaluate how much additional realism TRAKVU includes in a given NUCARS model.

To compare the dynamics responses, the lateral and vertical forces for each of the two wheels on the lead axle were examined.

5.3.1 Description of Track

The choice of track is very important because, as stated before, it provides the dynamic input to the rail vehicle. For this reason, it was decided to use two sections of the Precision Test Track, or PTT: the pitch and bounce, and the twist and roll. Although the PTT was not analyzed in the data analysis, it was selected because it provides dramatic inputs to the vehicle.

The pitch and bounce and twist and roll sections both consist of ten vertical 0.75-inch (1.905-cm) dips every 39 feet (11.9 m). For the pitch and bounce, the dips are in phase, as shown in Fig 5.7. Depending on the configuration of the rail vehicle, this track will induce a bounce, where the front and rear of the car move up and down in phase, or a pitch, where the movement is out of phase. The dips on the twist and roll are 90 degrees out of phase, as illustrated in Fig 5.8. This track will induce either a twisting, where the front and rear of the car rock side-to-side out of phase, or a rolling, where the movement is in phase. The amplitude of these movements is dependent on the speed of the vehicle, with the largest amplitude occurring at or near the resonance frequency [15].

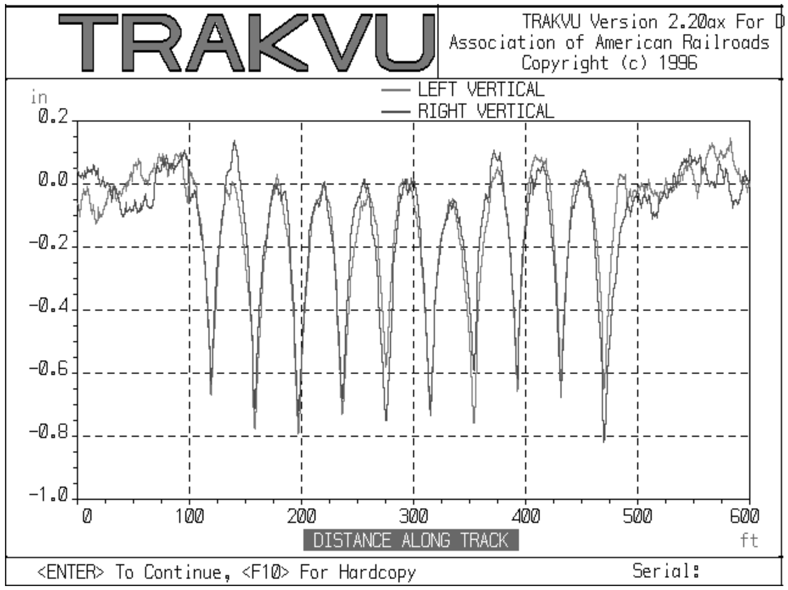


Figure 5.7 Plot of Pitch and Bounce Track Section

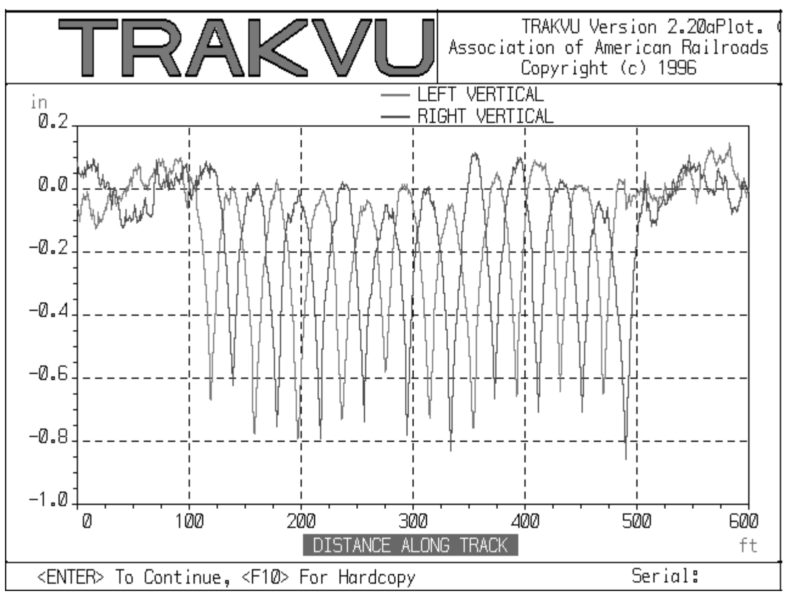


Figure 5.8 Plot of Twist and Roll Track Section

For the simulation using measured track data, the TRK files included with NUCARS were used. These files were created from measured track geometry obtained previously by TTCI. For the simulation using track data created by TRAKVU, the track was created using the criteria in Table 5.2. There is no true class designation for the PTT because it contains the large perturbations. The remaining track irregularities, however, are kept to high standards. For this reason, class 6 irregularities were added to the analytical track.

Table 5.2 Criteria Used for Creating Pitch and Bounce and Twist and Roll Tracks

	Pitch and Bounce	Twist and Roll
Length of Track	800 feet (244 m)	800 feet (244 m)
Track Prior to Perturbed Section	100 feet (30 m)	100 feet (30 m) left rail / 119.5 feet (36 m) right rail
Length of Perturbed Section	390 feet (119 m)	390 feet (119 m)
Track After Perturbed Section	310 feet (94 m)	310 feet (94 m) left rail / 290.5 feet (89 m) right rail
Track Irregularities	Class 6	Class 6
Shape of Perturbation	Cusp	Cusp
Start and End Base Amplitudes	0.0 in (0.0 cm) / 0.0 in (0.0 cm)	0.0 in (0.0 cm) / 0.0 in (0.0 cm)
Steepness of Perturbation (Coefficient 1)	8.0	8.0
Wavelength of Perturbation (Coefficient 2)	39.0	39.0
Amplitude of Perturbation	-0.75 in (-1.91 cm)	-0.75 in (-1.91 cm)

5.3.2 NUCARS Model

The rail vehicle used for this comparison was a Trilevel Autorack built by TTX, a vehicle used for transporting automobiles. For testing and modeling, the vehicle was loaded with five cars on each of its three levels. This vehicle was tested on the PTT by engineers at TTCI for purposes other than this study. The NUCARS model of the Autorack was also developed by engineers at TTCI, and was provided, along with the dynamic response data, for this study. The NUCARS files used in the simulation are included in Appendix C. Figure 5.9

shows a picture of the vehicle geometry. The picture was generated using PREVU, a NUCARS pre-processor that allows users to preview SYS and INP files [8].

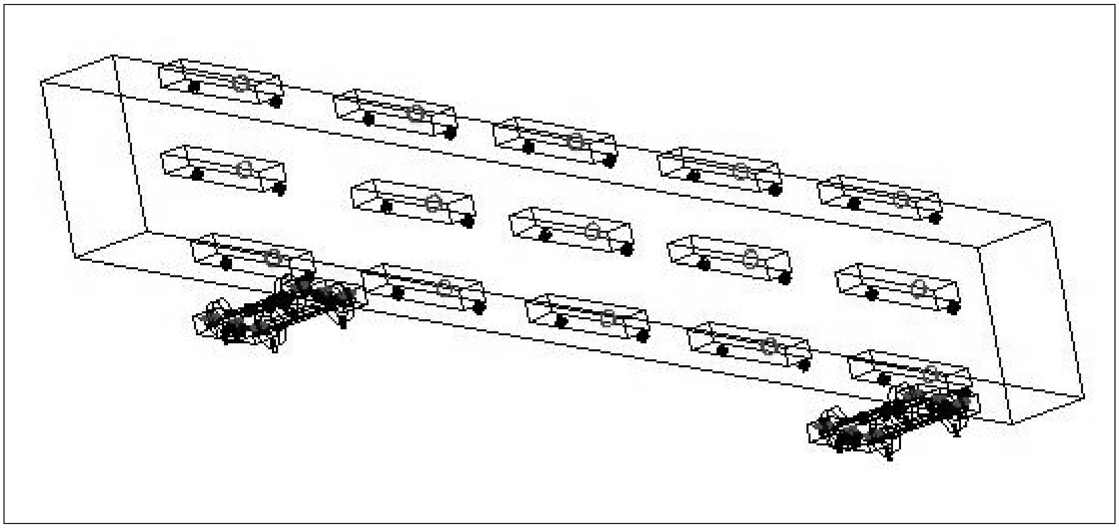


Figure 5.9 PREVU Picture of Trilevel Autorack

The speeds that were used for this study were 65 MPH (105 km/hr) on the pitch and bounce, and 20 MPH (32 km/hr) on the twist and roll. These speeds were used because they produced the most dramatic responses in the testing of the vehicle.

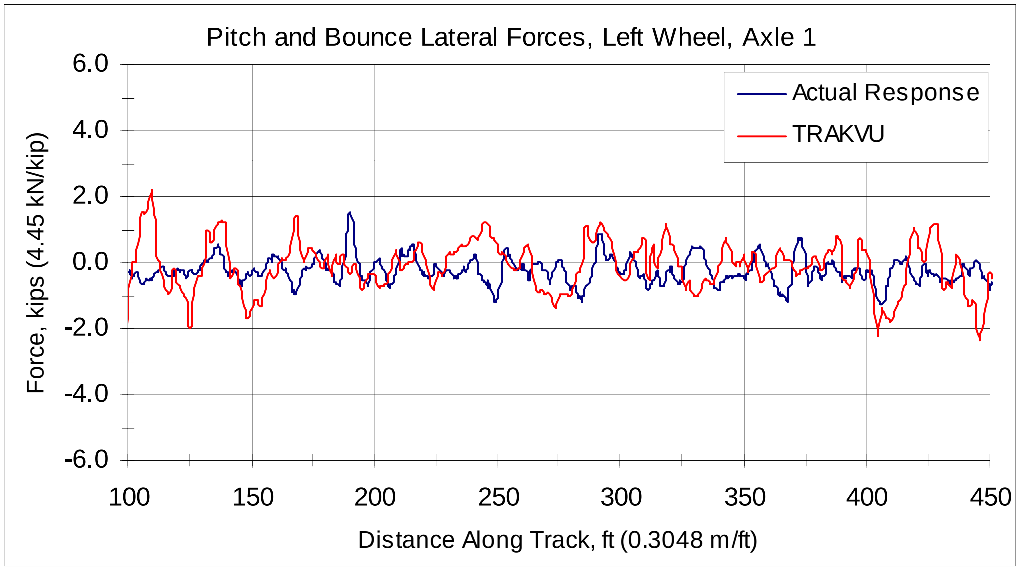
5.3.3 Actual vs. TRAKVU

It has been shown that track data created by TRAKVU does a reasonable job at recreating the characteristics of actual track. But how well does it model the input to a dynamic system? By comparing the predicted response from a NUCARS simulation using track data that was created using TRAKVU with actual vehicle response data, it can be determined how well TRAKVU models actual track. Of course, such a comparison is also dependent on the accuracy of the dynamic model.

5.3.3.1 Pitch and Bounce

The results for the comparison of actual dynamic response with NUCARS-predicted response, using TRAKVU, are shown in Figs 5.10-5.11 for the pitch and bounce track. The figures show a comparison of the vertical and lateral forces acting on the left wheel of the lead axle, and the forces acting on the right wheel of the lead axle. The x-axis corresponds to the distance along the track for the pitch and bounce section.

The lateral wheel forces in Fig. 5.10 show a reasonably good comparison between the amplitudes, even though the pitch and bounce track does not generate very large lateral forces. The vertical forces generated by the pitch and bounce track, shown in Fig. 5.11, are much larger than the lateral forces. These forces show a much better comparison between the actual response data and predicted data. The data is relatively periodic and the amplitudes of the oscillations are nearly the same for the actual data and TRAKVU. A quantitative evaluation of all comparisons will be discussed in Section 5.4.



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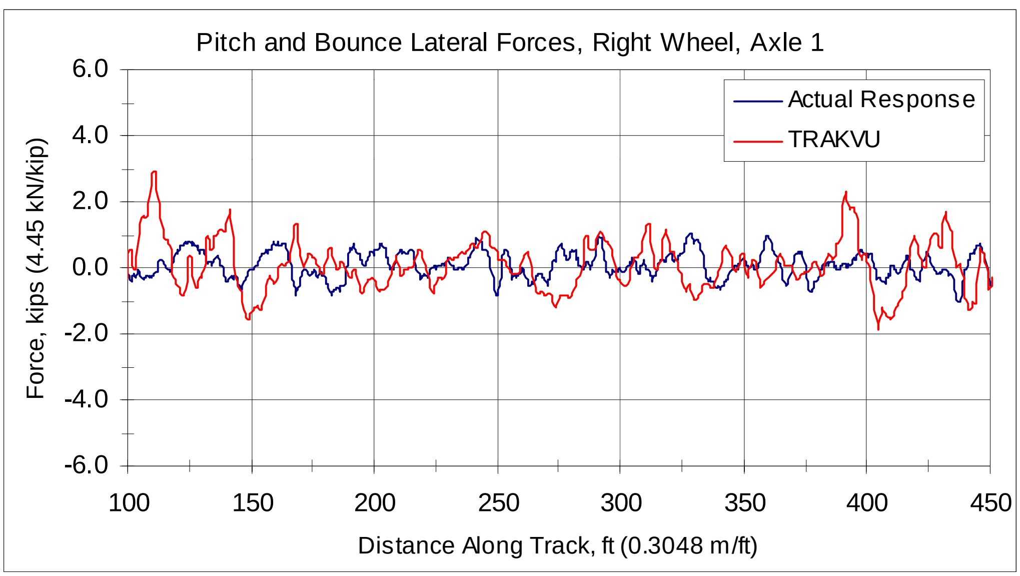
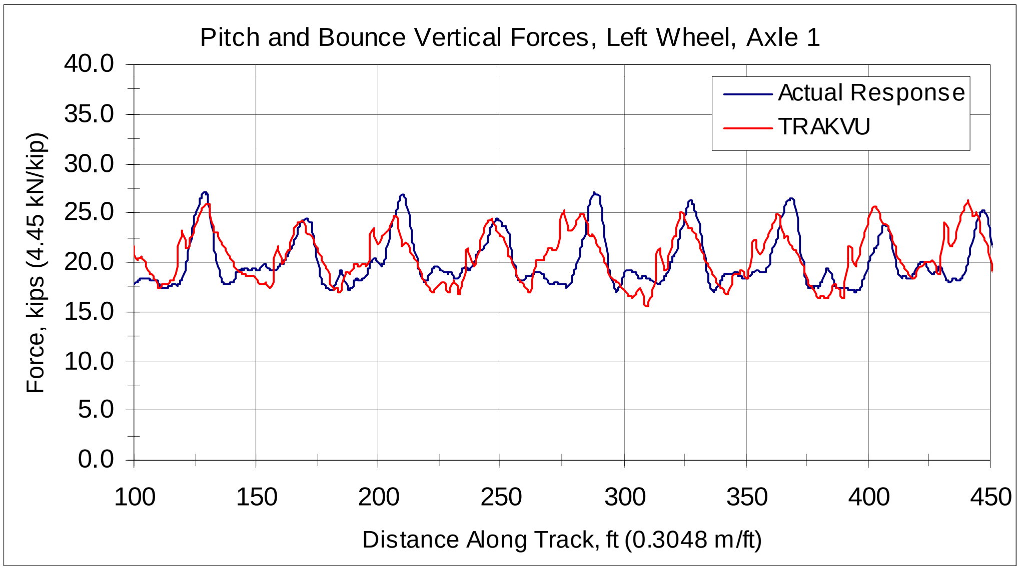


(b)

Figure 5.10 Comparison of Pitch and Bounce Lateral Wheel Forces for Actual Vehicle Response and Predicted Response Using TRAKVU Track; (a) Left Wheel, (b) Right Wheel



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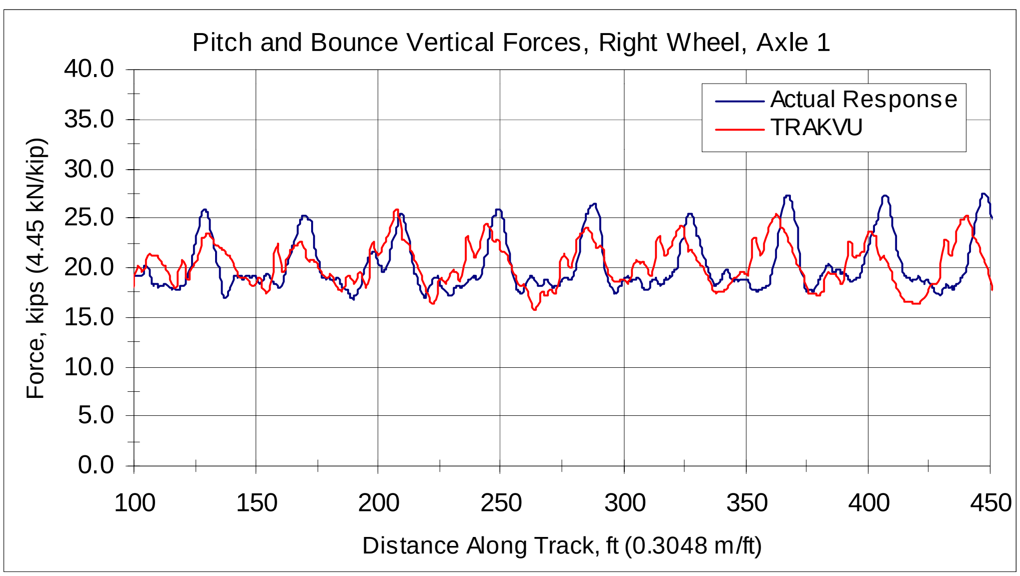


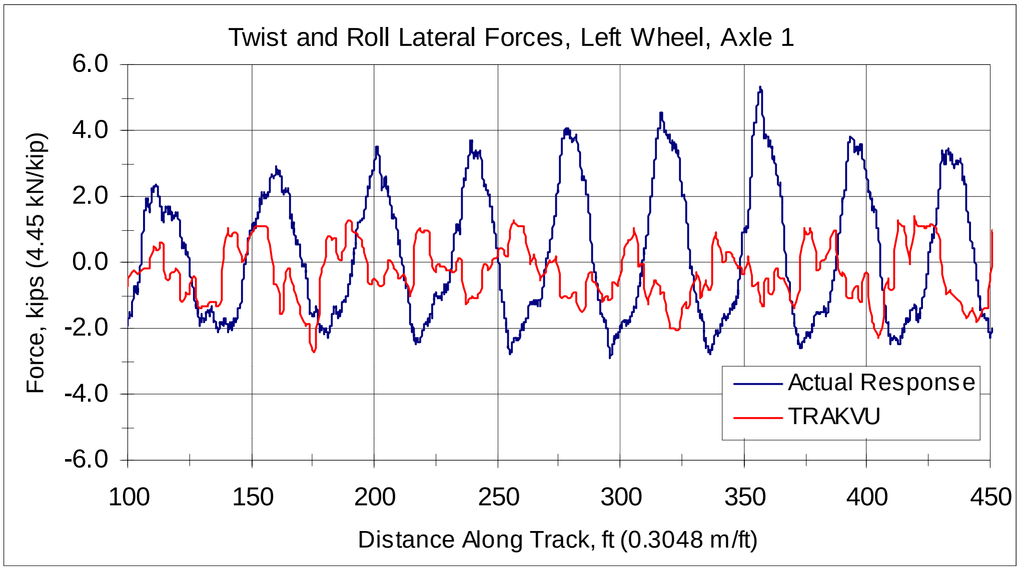
(b)

Figure 5.11 Comparison of Pitch and Bounce Vertical Wheel Forces for Actual Vehicle Response and Predicted Response Using TRAKVU Track; (a) Left Wheel, (b) Right Wheel

5.3.3.2 Twist and Roll

The results for the twist and roll comparison of the actual response data with the predicted response data using TRAKVU-generated track are shown in Figs 5.12-5.13. Unlike the pitch and bounce forces, there is relatively poor agreement of the lateral forces for the twist and roll, shown in Fig. 5.12. Although there appear to be periodic oscillations in both wheels for the predicted forces, there is a much more defined period in the actual forces. These differences in response may be explained by an inaccuracy in modeling the lateral dynamics of the vehicle.

The predicted vertical forces, shown in Fig. 5.13, show a slightly better agreement with the actual wheel forces, although they are not as good as the vertical forces on the pitch and bounce. There is a more defined periodicity in the oscillations of the forces than with the lateral forces, however, the amplitudes differ by as much as 10 kips (44.5 kN). Again, this may be attributed to an inaccuracy in the model. Such inaccuracies may be due to the suspension characteristics. A mass or stiffness could be modeled incorrectly, or the value of the mass or stiffness may be represented incorrectly. This would result in the modeled vehicle having a different natural frequency than the actual vehicle, which can cause significant errors, particularly since the test data are collected at speeds that correspond to the vehicle twist and roll resonances.



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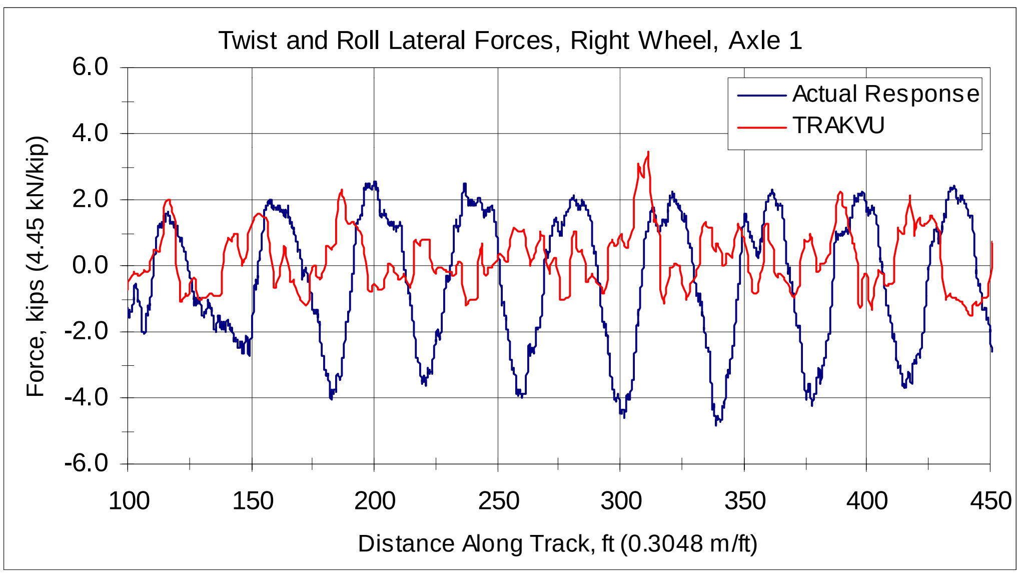
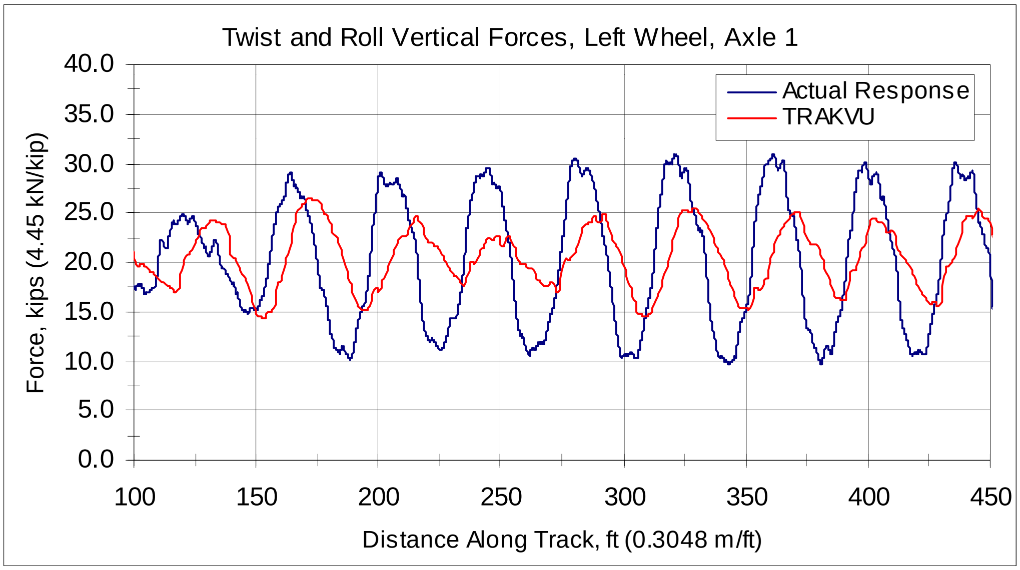


(b)

Figure 5.12 Comparison of Twist and Roll Lateral Wheel Forces for Actual Vehicle Response and Predicted Response Using TRAKVU Track; (a) Left Wheel, (b) Right Wheel



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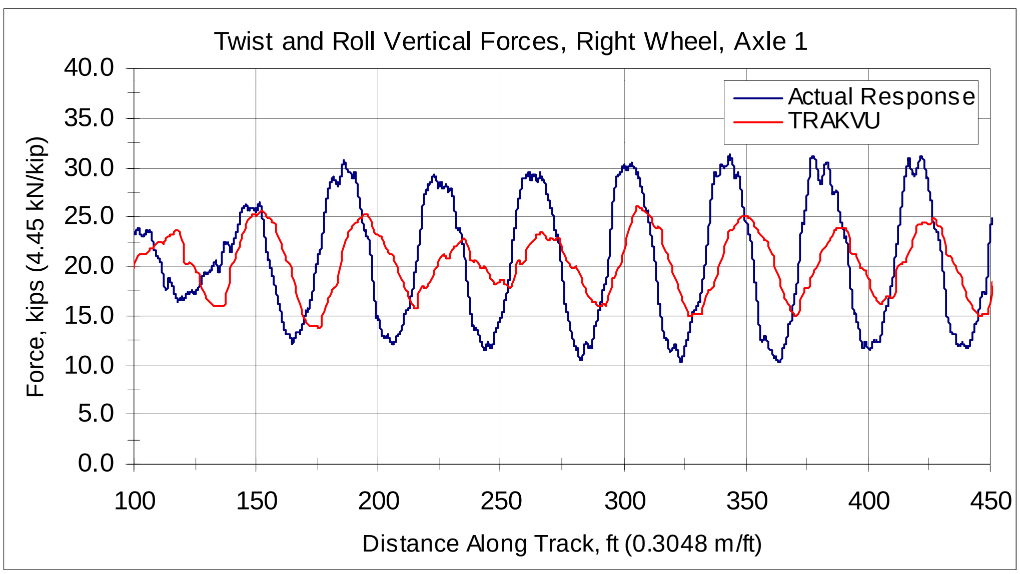


(b)

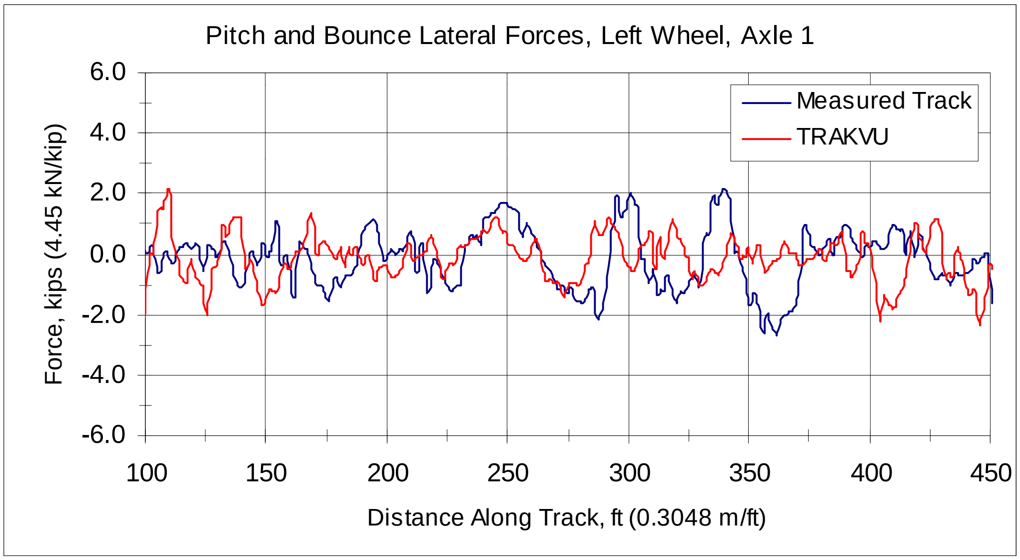
Figure 5.13 Comparison of Twist and Roll Vertical Wheel Forces for Actual Vehicle Response and Predicted Response Using TRAKVU Track; (a) Left Wheel, (b) Right Wheel

5.3.4 Measured vs. TRAKVU

We just showed that the track data created by TRAKVU do a reasonable job at representing the actual track input. Our comparison, however, was limited by the accuracy of the NUCARS model we used. The next comparison attempts to remove the uncertainty of the NUCARS model by running both simulations with the same model. This comparison will show how well TRAKVU can duplicate the measured track data as input to the dynamic model.

5.3.4.1 Pitch and Bounce

The results for the comparison of the NUCARS-predicted dynamic response, using measured track data, with NUCARS-predicted response, using TRAKVU track, are shown in Figs 5.14-5.15 for the pitch and bounce. The figures show a comparison of the vertical and lateral forces acting on the left wheel of the lead axle, and the forces acting on the right wheel of the lead axle. The two figures are presented first, followed by an interpretation of the results.



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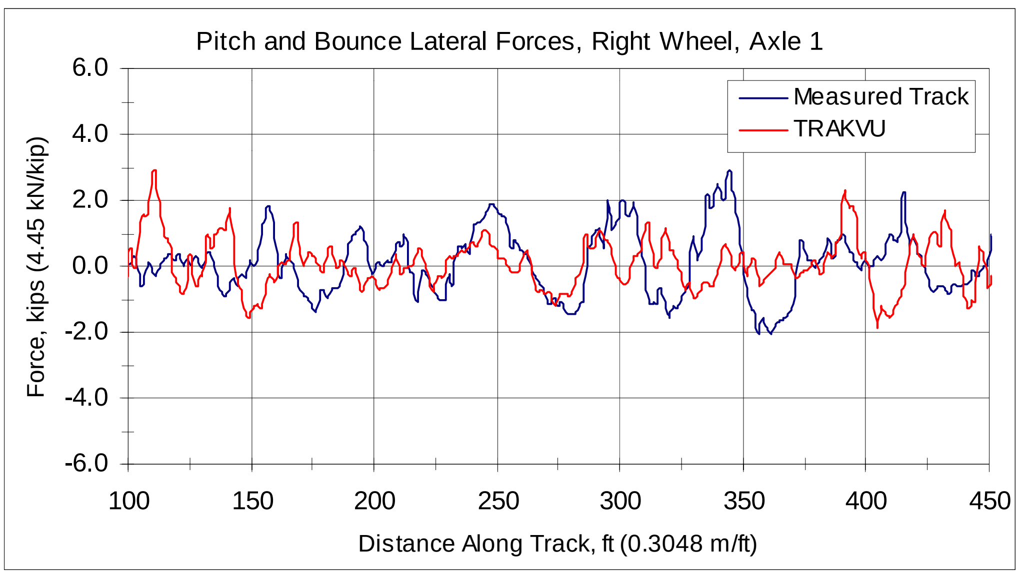

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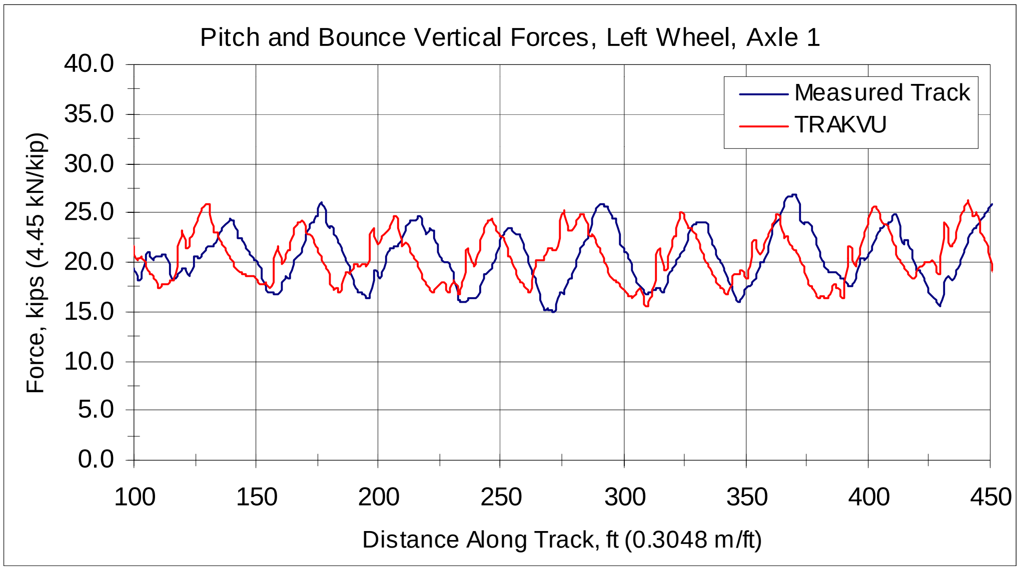
Figure 5.14 Comparison of Pitch and Bounce Lateral Wheel Forces for Predicted Response Using Measured Track and TRAKVU Track; (a) Left Wheel, (b) Right Wheel



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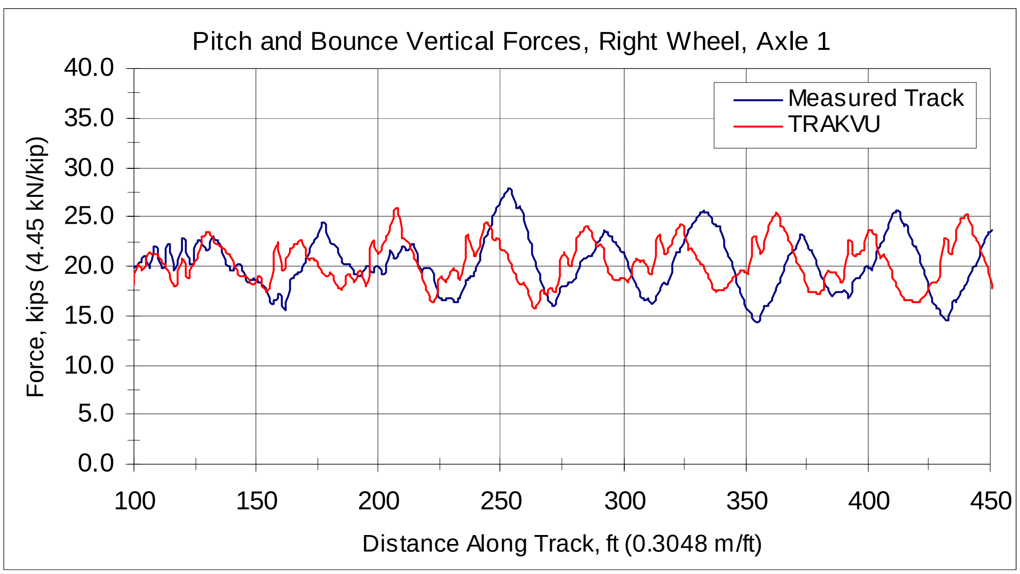


(b)

Figure 5.15 Comparison of Pitch and Bounce Vertical Wheel Forces for Predicted Response Using Measured Track and TRAKVU Track; (a) Left Wheel, (b) Right Wheel

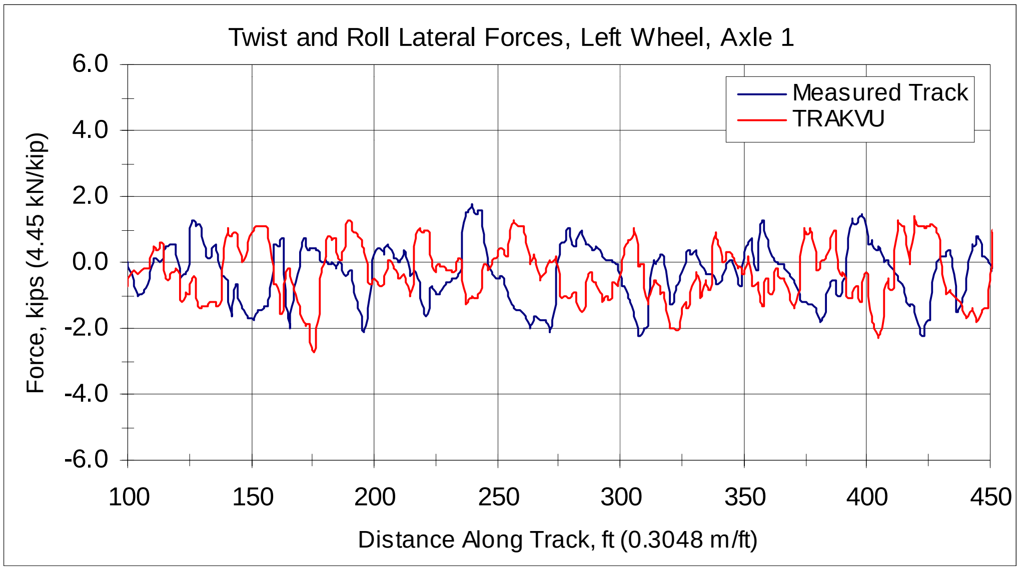
Figure 5.14 shows a reasonably good agreement between the amplitudes of the lateral wheel forces from the pitch and bounce. The lateral wheel forces generated by the pitch and bounce are relatively small when compared with the lateral wheel forces produced during the twist and roll. This is due to the fact that the vehicle movement generated by the pitch and bounce is concentrated in the vertical direction. It is therefore safe to say that the lateral wheel forces experienced on the pitch and bounce are primarily caused by the lateral track irregularities.

The vertical wheel forces, shown in Fig. 5.15, show a much better agreement between the two predicted responses. There is a definite periodicity in the oscillations, and the amplitudes compare well. There is, however, an apparent phase shift. This is most likely due to a lack of data synchronicity. As described in Table 5.2, the created track has a 100-foot (30 m) section of tangent track before the pitch and bounce. The measured track, however, has a slightly different length of tangent track prior to the perturbed section. Therefore, the modeled vehicles encounter the first dip at different times. This obvious phase shift, however, is not significant to the comparison because it does not affect the overall response of the vehicle.

5.3.4.2 Twist and Roll

The results for the twist and roll comparison of the predicted response data using measured track data with the predicted response data using TRAKVU-generated track are shown in Figs 5.16-5.17. As before, the figures show a comparison of the lateral and vertical wheel forces. Unlike the twist and roll comparison with the actual response data, there is better agreement of the lateral forces for the two predicted responses, as shown in Fig. 5.16. The overall response of both vehicles is very similar. Because the uncertainty of the model's accuracy has been removed, it is safe to say that the track data generated by TRAKVU does an acceptable job of reproducing the track characteristics. There does not seem to be much periodicity in the lateral forces, which again suggests that the model was not excited at its resonance frequency.

The vertical wheel forces generated in the twist and roll also compare reasonably well between the two predicted responses, as shown in Fig. 5.17. There is much better agreement between the forces generated by the TRAKVU track and the forces generated by the measured track than there is with the actual response data. Again, this can be attributed to the removal of the uncertainty created by the difference between the model and actual system. There is, however, a very noticeable phase shift, more severe than the phase shift in the pitch and bounce responses. Once again, this can be attributed to a lack of data synchronicity, and does not take away from the comparison of the two responses.



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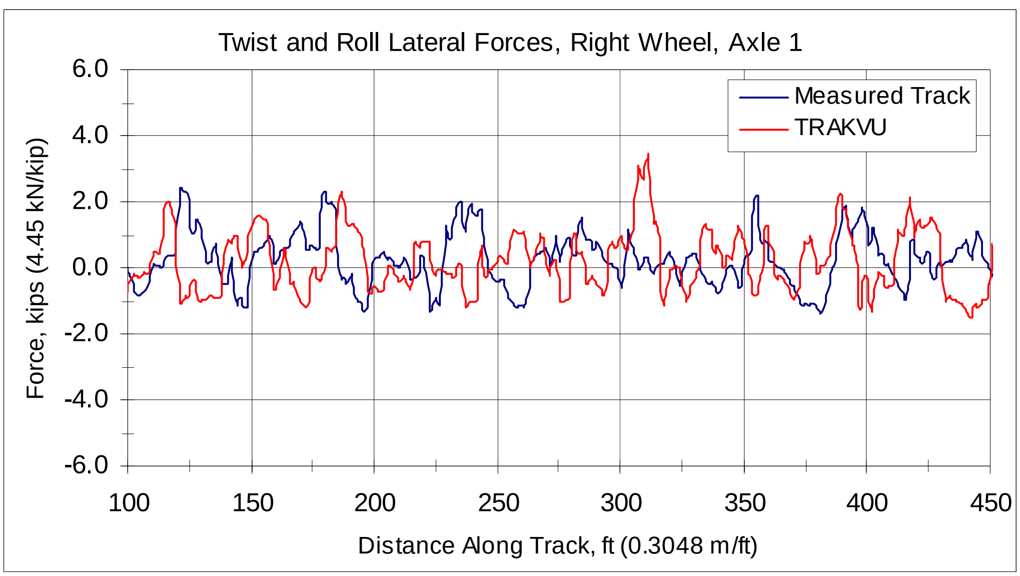
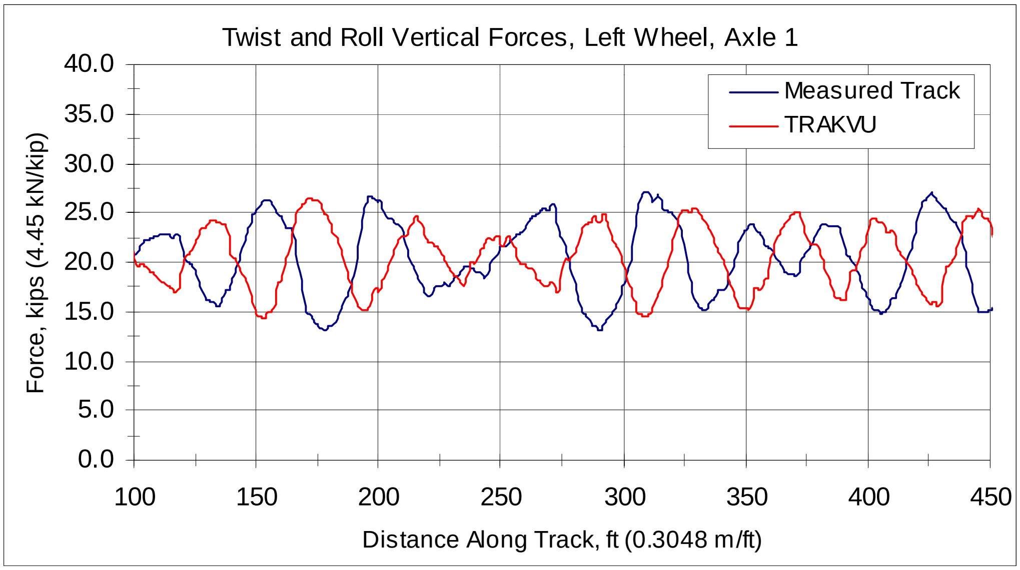


(b)

Figure 5.16 Comparison of Twist and Roll Lateral Wheel Forces for Predicted Response Using Measured Track and TRAKVU Track; (a) Left Wheel, (b) Right Wheel



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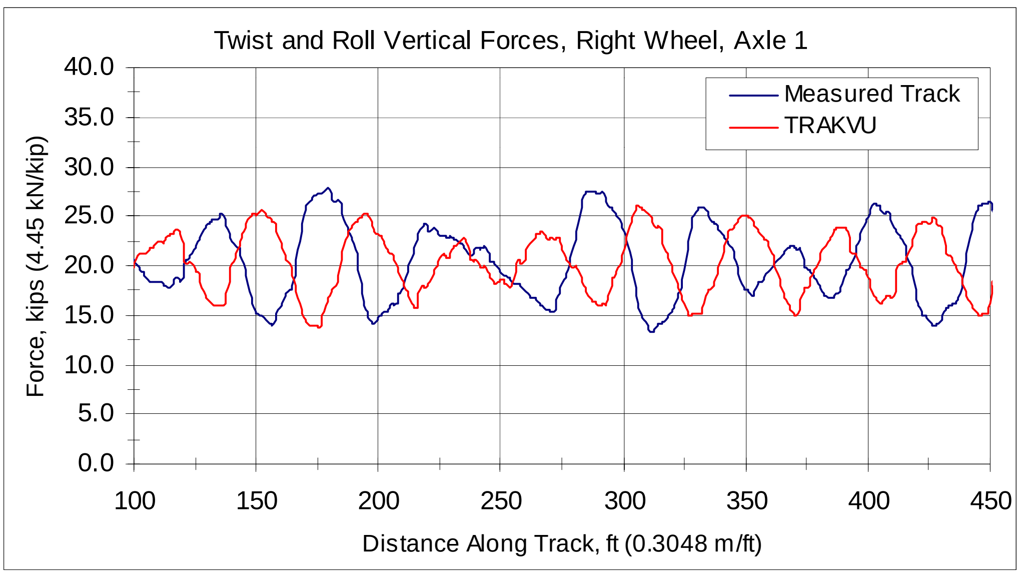

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Figure 5.17 Comparison of Twist and Roll Vertical Wheel Forces for Predicted Response Using Measured Track and TRAKVU Track; (a) Left Wheel, (b) Right Wheel

5.4 Concluding Remarks

Tables 5.3-5.6 quantify the relationship between the actual response data and the response generated by the TRAKVU data, as well as the relationship between the responses generated by the measured track data and the TRAKVU data. The mean and standard deviations for the left and right lateral and vertical wheel forces are shown.

5.4.1 Actual vs. TRAKVU

The values in Table 5.3 indicate that the model does not perform as well in predicting lateral forces as it does in predicting the vertical forces for the pitch and bounce track. Table 5.4 shows that the model does even worse at predicting both lateral and vertical forces for the twist and roll. Although at first glance this may be a disappointing performance of TRAKVU, one needs to bear in mind that the accuracy of these results is also affected by the NUCARS model that we used. In fact, as Tables 5.5 and 5.6 will show, a significant portion of the differences between the actual and TRAKVU responses shown in Tables 5.3 and 5.4 may be due to the model and not to TRAKVU performance.

Table 5.3 Statistical Comparison of Actual and TRAKVU Pitch and Bounce Wheel Forces

Pitch and Bounce		Left Wheel		Right Wheel	
		Mean	Standard Deviation	Mean	Standard Deviation
Lateral	Actual Response	-0.26 kips (-1.16 kN)	0.39 kips (1.74 kN)	0.08 kips (0.36 kN)	0.40 kips (1.78 kN)
	TRAKVU Track	-0.12 kips (-0.53 kN)	0.75 kips (3.34 kN)	0.08 kips (0.36 kN)	0.77 kips (3.43 kN)
Vertical	Actual Response	20.13 kips (89.58 kN)	2.63 kips (11.70 kN)	20.24 kips (90.07 kN)	2.72 kips (12.10 kN)
	TRAKVU Track	20.60 kips (91.67 kN)	2.56 kips (11.39 kN)	20.40 kips (90.78 kN)	2.21 kips (9.83 kN)

Table 5.4 Statistical Comparison of Actual and TRAKVU Twist and Roll Wheel Forces

Twist and Roll		Left Wheel		Right Wheel	
		Mean	Standard Deviation	Mean	Standard Deviation
Lateral	Actual Response	0.32 kips (1.41 kN)	2.06 kips (9.15 kN)	-0.42 kips (-1.86 kN)	2.02 kips (8.97 kN)
	TRAKVU Track	-0.33 kips (-1.47 kN)	0.86 kips (3.84 kN)	0.18 kips (0.80 kN)	0.92 kips (4.10 kN)
Vertical	Actual Response	20.32 kips (90.41 kN)	6.66 kips (29.63 kN)	20.55 kips (91.46 kN)	6.42 kips (28.59 kN)
	TRAKVU Track	20.50 kips (91.22 kN)	3.17 kips (14.09 kN)	20.32 kips (90.44 kN)	3.14 kips (13.97 kN)

5.4.2 Measured vs. TRAKVU

Table 5.5 shows that the TRAKVU track data provide virtually the same input to the dynamic model as measured track data for the pitch and bounce. Table 5.6 shows that predicted forces compare even better for the twist and roll. This means that TRAKVU does an excellent job at recreating the characteristics of measured track data when used as input to a dynamic model.

Table 5.5 Statistical Comparison of Predicted Pitch and Bounce Wheel Forces

Pitch and Bounce		Left Wheel		Right Wheel	
		Mean	Standard Deviation	Mean	Standard Deviation
Lateral	Measured Track	-0.15 kips (-0.69 kN)	0.97 kips (4.33 kN)	0.07 kips (0.32 kN)	0.97 kips (4.33 kN)
	TRAKVU Track	-0.12 kips (-0.53 kN)	0.75 kips (3.34 kN)	0.08 kips (0.36 kN)	0.77 kips (3.43 kN)
Vertical	Measured Track	20.58 kips (91.59 kN)	2.83 kips (12.57 kN)	20.23 kips (90.01 kN)	2.81 kips (12.49 kN)
	TRAKVU Track	20.60 kips (91.67 kN)	2.56 kips (11.39 kN)	20.40 kips (90.78 kN)	2.21 kips (9.83 kN)

Table 5.6 Statistical Comparison of Predicted Twist and Roll Wheel Forces

Twist and Roll		Left Wheel		Right Wheel	
		Mean	Standard Deviation	Mean	Standard Deviation
Lateral	Measured Track	-0.33 kips (-1.47 kN)	0.88 kips (3.90 kN)	0.24 kips (1.06 kN)	0.81 kips (3.61 kN)
	TRAKVU Track	-0.33 kips (-1.47 kN)	0.86 kips (3.84 kN)	0.18 kips (0.80 kN)	0.92 kips (4.10 kN)
Vertical	Measured Track	20.43 kips (90.91 kN)	3.82 kips (17.00 kN)	20.42 kips (90.86 kN)	3.89 kips (17.29 kN)
	TRAKVU Track	20.50 kips (91.22 kN)	3.17 kips (14.09 kN)	20.32 kips (90.44 kN)	3.14 kips (13.97 kN)