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Vibration Analysis of Heavy-Duty Diesel Vehicles

Christopher Jack Campbell
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Christopher Jack Campbell entitled "Vibration Analysis of Heavy-Duty Diesel Vehicles." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biomedical Engineering.

J.A.M. Boulet, Major Professor

We have read this thesis and recommend its acceptance:

Jack F. Wasserman, Joshua S. Fu

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Vibration Analysis of Heavy-Duty Diesel Vehicles

A Thesis Presented
For the Master of Science Degree
The University of Tennessee, Knoxville

Christopher Jack Campbell
December 2009

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Abstract

Truck drivers are more susceptible than other workers to lower back pain and spinal disorders caused by whole body vibrations, which are among the most common long term health effects for drivers. The dynamic behavior of trucks can be modeled and simulated to improve the design of the trucks, which can reduce the exposure of drivers to whole body vibrations.

The main purposes of this study are to analyze vibrations for different manufacturers and road types, and to create a computer-based model using Adams to predict vibration anywhere on the model using acceleration data collected previously from on-road tests of real vehicles. Another objective of this study is to develop a method for validating an Adams model of trucks tested. Also, this study examines the results predicted by the simulations.

This study uses vibration measurements that were made on twenty-two heavy-duty diesel vehicles from four different manufacturers, each driven on the same route, which include rural and interstate roads. Road types and manufacturers are compared using data from an accelerometer located underneath the driver seat. Vertical vibrations in five trucks are simulated using Adams, one truck from each manufacturer and one without a trailer. Vibrations in three orthogonal directions are compared for of the trucks.

Results show that the vibrations on the roads of US-27 and I-75 are similar to each other, while the manufacturers show significant differences between one another. Two basic models were developed with Adams that use collected data to “drive” the model. Results are more accurate when the data from the transducers located on the body of interest are used as impact. Only one transducer is needed on the body of interest to provide accurate results. Since the mechanical properties of the trucks tested were not available, the model has not been validated. However, the model could be validated if the specifications of a tested truck were given.

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Chapter 1 Introduction

Truck drivers are exposed to whole-body vibration (WBV), which can affect their comfort, performance and health. WBV are mostly caused by impacts and other mechanical disturbances encountered on the road, and are commonly distributed from the floor of the cab to the seat surfaces and backrests. The exposure to excess WBV commonly leads to lower back pain, which is found more often in truck drivers than in non-driver workers.

Designing vehicle models by computer simulation is more cost and time efficient compared to the traditional process of conceptual design, prototype construction, sample testing, and then modification. Real world conditions can be replicated using computer simulation to model vehicle systems. The accuracy of a model can be high or low depending on the amount of information that is present to create the model. Vehicle models can be simulated using finite element analysis (FEA) and multi-body simulation (MBS). FEA is a general simulation process that is used to verify the ability of a system to withstand the work loads. MBS is able to show the dynamic behaviors and interactions between multiple mechanical systems connected to each other. This study uses a MBS/FEA software package from MSC called Adams to create models of heavy-duty diesel vehicles (HDDV) and simulate responses to collected input.

This study is a continuation of another study performed by Pan, Liangming (2009) at the University of Tennessee at Knoxville. The previous project studied the human response to WBV using the HDDV used for this study. During the study, the accelerometers were attached at various positions throughout the trucks and the data was collected for the modeling portion of this study. Setup was the same for each truck used in the study.

The objectives of this research were to create a model of the HDDV using MSC Adams software that can predict the vibration at any selected point on the truck; to compare vibrations underneath the driver seat on rural and interstate roads; to develop a method for validating an Adams model of one of the tested trucks and use the model to improve the design of the trucks. This is the second part of a two part study to improve the overall ergonomics of HDDV, including air quality, vibrations and acoustics. Along with the WBV study performed by Pan, Liangming (2009), Fu, Joshua et al. (2009) studied the air quality of the HDDV while idling and in transit. Nitrogen oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO) and particulate matter less than 2.5 microns ($PM_{2.5}$) were collected and analyzed for the study.

Twenty-two HDDV manufactured by four different companies were tested and analyzed for this study. The Environmental Protection Agency (EPA) classifies a HDDV if the weight of the vehicle is over 14,000 pounds. Every truck in this study was weighted the same using a fifty-three foot trailer. The tests were performed in transit using the same route, including rural and interstate roads, along with an idle test. Three separate tests were conducted using trucks, each from a different manufacturer, without trailers to compare to weighted trucks.

The University of Tennessee was funded by the Federal Motor Carrier Safety Administration (FMCSA) to perform this study at the beginning of August in 2007 to measure and analyze vibrations, acoustics and air quality of HDDV. Financial assistance came from Dr. Joshua Fu and Dr. J.A.M. Boulet of the University of Tennessee at Knoxville. This project is a baseline test to provide information for improvement of HDDV in the future.

Chapter 2 Background

Long-haul truck drivers are required to rest for extended periods because the FMCSA issues Hours-of-Service (HOS) regulations. The HOS limits driving time to fourteen consecutive hours per day with no extensions for intervening off-duty periods. During this rest period, some truck drivers sleep in the sleeping berth of the truck, idle the engine to provide heat, cooling, or power for appliances, and keep the engine warm. However, drivers can potentially be exposed to air pollution, vibration and noise within the cab and sleeping berth both while driving and while idling [24].

2.1 Whole body vibrations

WBV are transmitted to a person that is supported by an oscillating surface. Truck drivers experience WBV while in transit and idling from the vibration of the truck and road imperfections. The vibration travels through the vehicle to the seat and footrest, where the driver is exposed. WBV affect the body and are experienced through large sudden spikes or continuous low peak exposures. Drivers commonly experience WBV from various vibration magnitudes, waveforms and durations, and are usually exposed while seated.

WBV has led to many long and short term effects for many vehicle drivers or operators of vibrating equipment. It is estimated that there are one million workers in the United States that are exposed to hand-arm vibrations, and six million that are subjected to WBV that can cause spinal problems [20]. Low back pain and spinal disorder are the two main long term health effects, which mainly results from harm to the lumbar part of the vertebral column and thoracic region. Also, women that are exposed to long term vibrations are at risk of damaging the function of the reproductive organs. The long term risks associated with WBV are low back pain, degenerative spinal changes, lumbar scoliosis, disc disease, disorder of gastro intestinal systems, herniated disc and abnormalities in reproductive organs. Short term effects are more common and include head ache, abdomen pain, nausea, chest pain, discomfort, blurred vision, muscle fatigue and loss of balance [3] [16] [22].

An international standard, ISO 2631-1: Mechanical Vibration and Shock –Evaluation of human exposure to whole body vibration (1997), was developed to provide explanation of measurements and methods to measure random, periodic and transient WBV. The most common measure used in making health evaluations is the frequency-weighted RMS acceleration, which is determined for the three translational axes on the seat. Table 2-1 shows the approximate indication of likely reaction to various magnitudes of overall total vibration values in public transport according to ISO 2631-1 (1997). If a driver is exposed to vibration around the level of 1.15 m/s^2, a company could be prosecuted [10].

Table 2-1 Approximate indication of likely reaction to various magnitudes of overall vibration

Frequency-Weighted Vibration Magnitude	Likely Reaction in Public Transport
Less than .315 m/s^2	Not uncomfortable
.315 m/s^2 to .63 m/s^2	A little uncomfortable
.5 m/s^2 to 1 m/s^2	Fairly uncomfortable
.8 m/s^2 to 1.6 m/s^2	Uncomfortable
1.25 m/s^2 to 2.5 m/s^2	Very uncomfortable
Greater than 2 m/s^2	Extremely uncomfortable

WBV is known as a non-specific health hazard because the vibrations do not affect only one area of the body. Although awareness of WBV is growing, measuring and evaluating it are expensive, complicated and difficult. WBV is a major concern for vehicle operators because of the long and short term effects it can cause. The effects come from the amount, frequency, direction, and size of the vibrations, along with the posture of the driver [19].

2.2 Computer Simulation

Computer simulation is the use of a model created through computer programming to derive conclusions that forecast the behavior of any real system. A computer model is based on applied mathematics and is used to describe a system to predict what could happen if certain events took place. We can solve many complex systems by using the power of a computer with mathematical and analytical models. Simulation decreases the risks associated with constructing a new system or modifying an older system. Also, simulation is used to reduce cost on prototypes that are expensive, take a lot of time to build or are hazardous to make [15].

Modeling and simulation start with the development of a system model in which experimental frame, validity, simplification, credibility and tractability should be taken into account. The components of the system model are defined as input, state and output variables, which make up the experimental frame. One of the major problems with computer simulation is to have a valid model, since models only yield approximate answers. Models are considered I/O valid if the outputs from the simulation and the real system are “sufficiently” close, which is decided by the person designing the model. Ultimately, the best method to validate a model is to compare the output or behavior of the model and a real system. Using incorrect assumptions usually leads to an invalid model. Simplification makes the model easier to validate, but can idealize the real system too much and provide inaccurate results. Also, the credibility of the results of the model should be considered. The model can give results similar to the real system, but still might not be verified. Finally, the tractability of the model should be considered because of the technical restrictions of computer hardware. Some models produce a computational complexity that increases faster than exponentially with the number of variables and can not be solved [21].

Computer simulations can be either discrete or continuous [21]. A system that uses algebraic, differential or difference equations to represent a system over time is considered continuous. Continuous simulation represents the modeling over time in which state variables change continuously with respect to time. In a discrete simulation, instantaneous, dynamic events are separated by intervals of time. The intervals of time can be equal or unequal increments [15]. Both methods of simulation are commonly used engineering design and analysis.

2.3 Literature Survey

Cann, Salmoni et al. (2004) investigated the predictors and levels of WBV on four different truck manufacturers to compare to the standards set by the ISO 2631-1. Each truck was tested using five-minute random samples at speeds greater than eighty km/hr on four separate highways which ranged from smooth and resurfaced to rough and potholed. Truck type, seat type, road condition, driver experience and truck age were the areas of interest to predict WBV. The trucks used in the research study were cab-over trucks, designed with a freight container attached directly to tractor, and cab-behind trucks, day cabs or bunk trucks. The research discovered that the trucks tested did not exceed the standard on average but did at certain instances on rough spots on the worst highway. The study discovered that road condition and truck type showed a statistically significant relationship with the frequency-weighted RMS acceleration ($p < 0.01$) in the regression analysis. Road condition showed a significant relationship in the x, y, and z axes and vector sum of orthogonal axes, while truck type showed significance with z axis and vector sum.

Dong, Renguang (1997) has developed two separate methods to incorporate large data sets into Adams, which is restricted to 1,250 data points. The first method is used for smaller data sets and requires splitting the data into sets smaller than 1,250 points and representing each set as a spline. Each data set needs to include points used in neighboring data sets to make the function continuous. The “IF” and “STEP” function expressions are two methods that can be used to connect the splines. This method cuts and merges the data sets together and is efficient for data sets that are small multiples of 1,250 points. For larger data sets, a second approach can be applied by creating a user_written subroutine. This method is possible by arranging the data into an array, and then defining the array as a local variable in the subroutine. Local interpolation is then used to calculate the data stored in the array, and the points can then be used as input for displacement, acceleration or dynamic forces.

Garcia-Romeu-Martinez, Singh et al. (2007) studied leaf spring and air ride suspension semi-trailer trucks to analyze vibration levels as a function of speed, payload and suspension type. This study used three different vibration analyzers, two Saver 9x30 models and one Save 3x90 model, along with the TecnoGPS global position system to measure speed. Four tests were completed, two with air ride suspension and two with leaf spring suspension, with different payloads. The tests showed that the air ride suspension has significantly lower levels of vibration, average unloaded .089G and loaded .092G RMS(G) values, than leaf spring suspension trucks, average unloaded .194G and loaded .245G RMS(G) values. The results also revealed that the vibration increased as the speed of the truck increased.

Harris et al. (2007) approached an effective way of reducing the dynamic loading of bridges in a short distance. This was accomplished by using real time control of vehicle damping within an intelligent vehicle bridge system. The bridge and vehicle interactions were studied for optimal damping for the crossing. A vehicle model, a five-axle model with eight independent DOF, was created for simulation of dynamic forces and to represent a typical European truck. In Figure 2-1 and Table 2-2 you can see the vehicle model and the parameters made to study the vehicle and bridge interaction. Once the vehicle model, bridge model and road profiles were developed, the interaction between the road and vehicle was implemented by Matlab SimuLink. The reduction of dynamic loading was achieved through modifications of damping coefficients and proved most successful for road profiles that stimulate large vibrations.

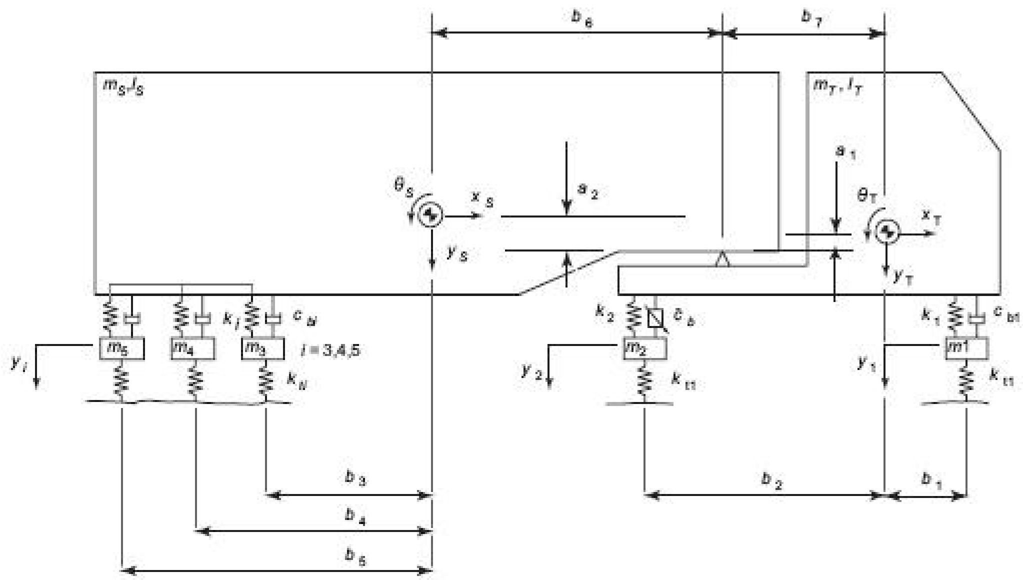

Figure 2-1 Vehicle model developed by Harris et al. (2007)

Table 2-2 Parameters of the vehicle model developed by Harris et al. (2007)

Parameters for truck model

Dimensional data (m)									
a_1	−0.13	a_2	1.10	b_1	0.50	b_2	2.50	b_3	1.30
b_4	2.40	b_5	3.50	b_6	4.15	b_7	2.15		

Mass and inertia parameters			
Mass parameters (kg)	Tractor sprung mass	m_T	4500
	Semi-trailer sprung mass	m_S	31450
	Tractor front axle mass	m_1	700
	Tractor rear axle mass	m_2	1100
	Semi-trailer tridem axle mass (individual)	m_3, m_4, m_5	750
Inertia parameters (kgm^2)	Tractor pitch moment of inertia	I_T	4604
	Semi-trailer pitch moment of inertia	I_S	16302
Suspension parameters			
Spring stiffnesses (kN/m)	Tractor, front	k_1	400
	Tractor, rear	k_2	1000
	Semi-trailer, tridem (individual axle)	k_3, k_4, k_5	750
Damping coefficients (kNs/m)	Tractor, front	c_{b1}	10
	Tractor, rear	$\hat{c}_b$	Variable
	Semi-trailer, tridem (individual axle)	c_{b3}, c_{b4}, c_{b5}	10
Tyre stiffnesses (kN/m)	Tractor, front	k_{t1}	1750
	Tractor, rear	k_{t2}	3500
	Semi-trailer, tridem (individual axle)	k_{t3}, k_{t4}, k_{t5}	3500

Hoshino, Sakurai et al. (2002) used Adams/Vibration to create a simple cab of a heavy-duty truck to do a load path analyses using NASTRAN. The model in Adams was made up of a front cross-member, a side member, a floor panel, an upper body, and connectivity elements with constant stiffness. Discontinuities and non-uniformities in the front cross-member, which decrease the stiffness of the cross-member, were found using the load path analyses. The results showed that vibration could be reduced in the floor panel by increasing the stiffness between front cross-member and the upper body.

Hoy, Mubarak et al. (2005) studied the health hazards of forklift truck drivers from WBV and posture demands for low back pain (LBP) by performing a cross-sectional study. Postural analyses of the forklift drivers, using the OWAS and RULA techniques, were completed to measure their sitting posture, including frequency of the different positions that were adopted, which were bending, leaning and twisting. The vibration measurements were taken at the seat of the forklifts measuring x-fore and aft, y-lateral and z-vertical. These measurements were conducted using the recommendations of ISO 2631-1 and were taken place under actual working conditions. Normal driving, aligning forks posture, reverse posture and stowing posture were the four different sitting positions measured. The results showed that forklift drivers were at a higher risk of developing LBP than non-drivers. Also, it was discovered that the trunk twisted and trunk bent forward driving postures were associated to the highest risk of getting LBP. The study showed that the drivers did not undergo acceptable levels, below .5 m/s^2 of vibration in the z-direction, but did in the x- and y- directions. The measured vibration exposure suggests that severe shock loading is present, and the results show that WBV acts associatively with other factors to cause sudden LBP.

Lemerle, Boulanger et al. (2002) developed a suspended cab model of a forklift using Adams to increase the efficiency of the suspension system. The three degrees of freedom, linear motion in the vertical axis, roll and pitch, were measured underneath the seat of the driver. A model was created using Adams as close to the test forklift as possible. The natural frequency, variation in static deflection, vibratory transmission ratios and the maximum dynamic stroke were all compared to seven different spring stiffness values (5000, 7500, 15,000, 20,000, 25,000 and 30,000 N/m). The suspensions performance is linked to the natural and excitation frequency. There is a reduction in vibration when the ratio is closer to one. It was discovered using Adams that the natural frequency of the forklift can be lowered from 6 to 2.35 Hertz by increasing the stiffness of the springs to 20,000 N/m and cab mass to obtain a ratio of one between natural and excitation frequency. Compression springs with stiffness values of 20,000 N/m were then added to the forklift to compare to the Adams model. Both models gave very similar results and the objective of filtering about 50 percent of the vibration was reached.

Li and Li (2007) designed a model with twenty degrees of freedom (DOF) of a commercial vehicle using Adams to evaluate vibration analyses. The model was design to be very similar to commercial vehicle suspensions and consisted of twenty movable parts, twenty DOF, seat mounted to the chassis with bushing force and each tire connected to the ground with bushing force. The vibration input was applied by using the swept sine function, with 1,000N as the starting force and a zero degree starting phase angle. A frequency response of the seat was performed using input frequency from 0.1 to 200 Hertz. This simulation was easy to run and could lead to improvements to reduce vibration peaks.

Massaccesi, Pagnotta et al. (2003) studied seventy-seven male truck drivers that drove rubbish collection and street-cleaning vehicles by using RULA, a method for evaluating the exposure to risk factors associated with work-related upper-limb disorders, to observe a high incidence of spinal disorders in professional drivers. This method in particular showed that back and neck pain result in high rates of morbidity and low retirement age. The rubbish collection trucks allow for standard sitting, while the street-cleaning vehicles usually consists of driving while twisting and bending the neck and trunk. RULA results showed a significant relationship with neck and trunk pain, while every truck driver reported pains, aches or discomforts in the trunk or neck region. Neck pain was significant in both rubbish collection and street-cleaning vehicles, revealing high loading of the neck. RULA showed that the posture adopted in street-washing trucks, especially with non-adjustable seats, was linked to a high risk for back pain.

Neto et al. (1998) developed a model of a medium size truck using Adams and NASTRAN. The design process began with a basic truck model that contained five bodies and eight degrees of freedom. A power train model, two cab models, one with cab and hood to be rigidly attached and the other with cab and hood separate, two frame models, one finite element (FE) model using NASTRAN with 30,000 DOF and the other made in Adams using the FE model, and a full Adams model were then developed. The full model was made using the power train, cab and the frame models developed in Adams. The model was then validated by analyzing time histories and frequency domain spectral analysis using terminated ramp input. A comfort test based on the ISO Standard was simulated using a random road profile made in MATLAB and compared to real road tests. It was observed using the model that a significant amount of vibration came from the frame bending. It was discovered that increasing the stiffness of the frame and softening the cab suspension lead to lower frequencies of vibrations, because the results showed that frame bending produced higher frequencies. The changes made in the model led to a lower vibration level of the truck.

Okunribido, Magnusson et al. (2006) examined the exposures of occupational drivers by investigating posture demands, manual materials handling (MMH) and vibration as risk factors for low-back pain (LBP) among short-haul delivery drivers. Driving experience, driving (sitting) posture, MMH, and health history were determined for sixty-four drivers by using a validated questionnaire. Twelve different drivers were monitored by videotape during their work in three types of delivery in vehicles less than three years old. Vibration measurements were made in accord with the ISO 2631 standard. The results indicated that systematic observation of the driving activity, particularly duration, and MMH is necessary alongside any subjective questionnaire assessments. Short-haul drivers commonly experience LBP. However, short-haul drivers are more likely to experience non-permanent LBP, which lasts for less than a week, than permanent LBP. Only about thirty percent of short-haul delivery work day consists of actual driving, which avoids excessive amounts of rapid movement of loads during handling, shock and jerking events and reduces twisting of the torso during driving.

Pan, Liangming (2009) studied seventeen different HDDV from four different manufacturers to collect the exposure of the truck driver to WBV and analyze levels of excitation from the different manufacturers. This study collected data according to the international standards ISO 2361-1 while idling and while in transit. Transducers were placed on the seat cushion and back of the driver and passenger seat, along with various placements on the frame and in the cab. Vibrations were recorded using the DEWETRON data acquisition system along with HDV-100 on the seat cushions. The minimum eight hour and eleven hour vibration exposure standard limits set by the standard for health, which requires medical examination, were exceeded several times, while comfort levels were exceeded many times. Roadway condition was considered to be the main cause for the vibration exposure to the driver. The driver was overall considered to be in a safe environment according to the ISO 2361-1, but it was recommended to take action to increase the comfort level.

Singh, Singh et al. (2006) conducted a study that evaluated the vibrations of tractor-trailers traveling on North American highways, each loaded with 46,000 pounds, in regards to reducing damage to transported items. The study used fourteen different commercially available tractor-trailers, five with leaf spring suspensions and nine with air ride suspensions, all traveling different routes. Measurements of vibration, temperature and humidity were collected using two of the same data recorders, Lansmont SAVERS model SV-I. The air ride suspension cabs showed lower vibration levels than the leaf spring suspensions overall. The highest G_{rms} value recorded using an air ride suspension was 0.5G, while the highest using a leaf spring suspension was 0.89G. Also, the composite spectrum levels showed that the air ride had lower high and low G_{rms} levels than leaf spring suspensions.

To summarize the results cited above, WBV exposure is affected mainly by road condition, vehicle design, body weight, and measurement site. However, WBV are not affected by gender. Low back pain and spinal disorder are directly related to exposure to WBV. The sitting posture, seatback inclination and rocking of the pelvis of a driver are effected by the frequency response. Back disorders are connected to both WBV and non-vibration factors like age, heavy labor, previous pain or injury history, smoking and stress related factors such as job satisfaction. WBV exposure can be decreased by reducing time spent sitting on an oscillating surface and improving the roadway, seats, cabs, tires and suspensions. Modeling and simulation can be used to evaluate continuous and discrete systems, reduce costs and time, reduce vibration peaks and lead to improvement in design.

Chapter 3 Methodology

3.1 Data collection

Vibration data were collected by Pan, Liangming (2009) by placing tri-axial accelerometers on the frame and inside the cab and seat pads on the driver and passenger seat cushions of the HDDV. The positions of the accelerometers and seat pads were the same for each truck tested and are listed in Table 3-1. Figure 3-1 shows the placement of each sensor and Figure 3-2 shows a test transducer underneath the driver seat. The data from the accelerometers was recorded using the DEWETRON data acquisition, model DEWE-5001, and the seat cushions were recorded using a Human Vibrator Meter, model HVM-100. Due to the large file size created, the test would have to be stopped and the data saved about every ten minutes, rendering the data discontinuous. Also, a Global Positioning System (GPS) was used in each on-road driving test to locate the position of the truck at any desired time.

Twenty-two HDDV four different truck manufacturers (which will remain unnamed) were used in the study from. The trucks were manufactured in 2006, 2007 and 2008 and all made for long haul driving. Figure 3-3 shows a HDDV used in one of the tests. Every truck was weighted using approximately 30,000 pounds of topsoil in a fifty-three foot trailer. Each truck was driven on the same route that included interstate and rural roads traveling on flat and sloped terrain. There were three trucks that repeated the routes without a trailer to compare to weighted trucks.

Figure 3-4 shows a map with the complete route that was traveled for each on-road test. The route begins approximately one mile outside the Knoxville, Tennessee, city limit at mile marker (MM) number 376. Each truck began the route and went fifty-five miles west on I-40 into the Crossville, Tennessee, city limits. The conditions of the interstate road of the first fifty-five miles would be considered rolling hills and steep terrain. The trucks would then exit at MM 322 and turn around and travel east on I-40. Each truck then exited at MM 347 and followed highway US-27 for twenty-five miles towards Rockwood and Spring City. Right past Spring City, a left was made onto highway TN-68 and each truck traveled about 20 miles. The conditions of the rural roads of US-27 and TN-68 would be considered mildly rolling and flat terrain. Finally, the trucks veered onto I-75 and traveled north about thirty-five miles back towards Knoxville to end the route at MM 374. The condition of the interstate road of I-75 would be considered relatively flat but rutted.

Table 3-1 Transducer List

Channel No.	Channel	Transducer
AI 0	Triax01-CabDrv_X	T1
AI 1	Triax01-CabDrv_Y	
AI 2	Triax01-CabDrv_Z	
AI 3	Triax02-CabPsg_X	T2
AI 4	Triax02-CabPsg_Y	
AI 5	Triax02-CabPsg_Z	
AI 6	Triax03-CabDrvBack_X	T3
AI 7	Triax03-CabDrvBack_Y	
AI 8	Triax03-CabDrvBack_Z	
AI 9	Triax04- DrvSeatFrame_X	T4
AI 10	Triax04- DrvSeatFrame_Y	
AI 11	Triax04- DrvSeatFrame_Z	
AI 12	Triax05-Steering Wheel_X	T5
AI 13	Triax05-Steering Wheel_Y	
AI 14	Triax05-Steering Wheel_Z	
AI 18	Triax06-FrameLeft_X	T6
AI 19	Triax06-FrameLeft_Y	
AI 20	Triax06-FrameLeft_Z	
AI 21	Triax07-FrameRight_X	T7
AI 22	Triax07-FrameRight_Y	
AI 23	Triax07-FrameRight_Z	
AI 24	Triax08-FrameFrontLeft_X	T8
AI 25	Triax08-FrameFrontLeft_Y	
AI 26	Triax08-FrameFrontLeft_Z	
AI 28	String Pot	ST
AI 32	Pad01-DrvBack_X	S1
AI 33	Pad01-DrvBack_Y	
AI 34	Pad01-DrvBack_Z	
AI 35	Pad02-DrvCushion_X	S2
AI 36	Pad02-DrvCushion_Y	
AI 37	Pad02-DrvCushion_Z	
AI 38	Pad03-PsgCushion_X	S3
AI 39	Pad03-PsgCushion_Y	
AI 40	Pad03-PsgCushion_Z	

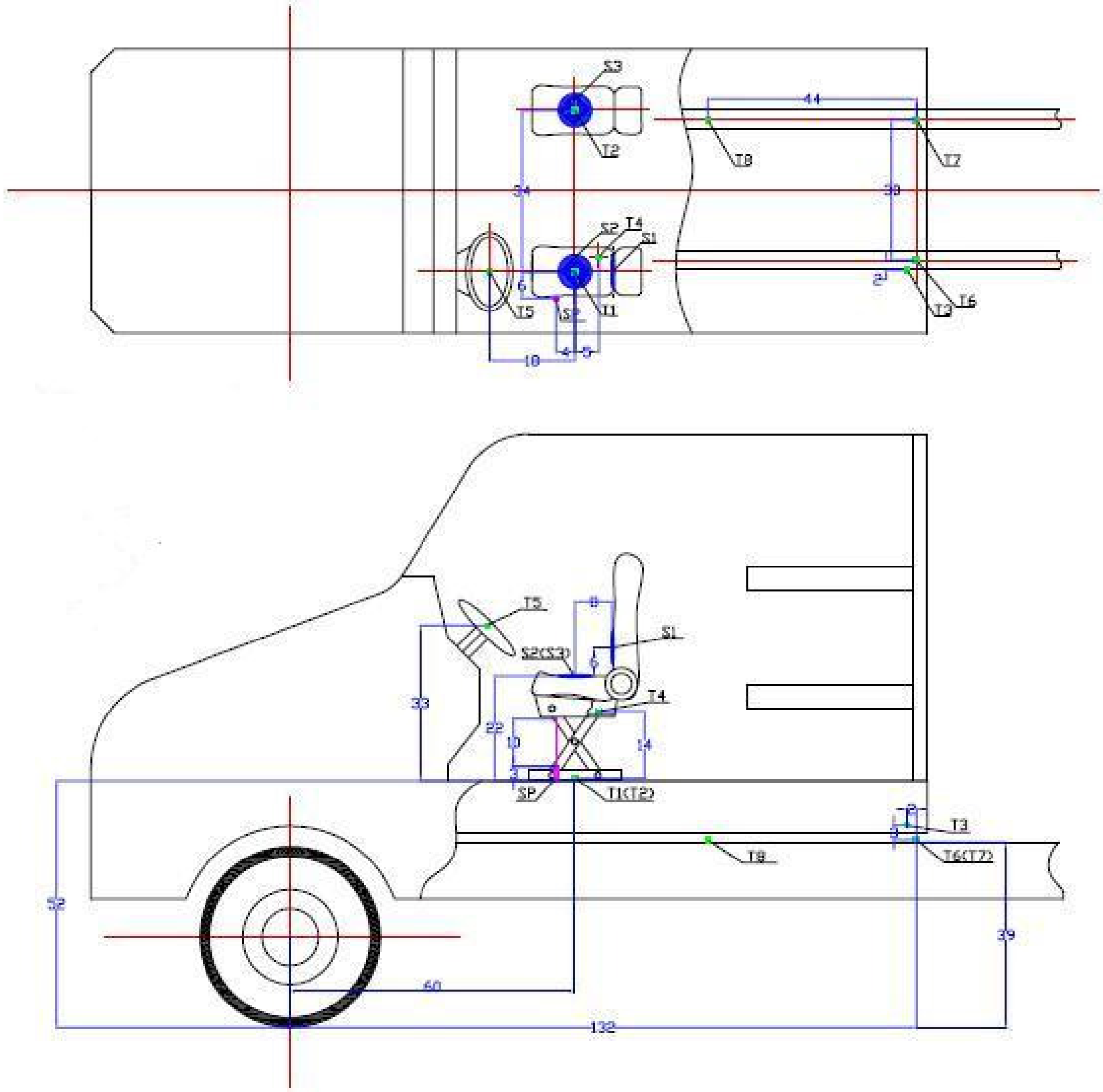

Figure 3-1 Transducer placement on each HDDV

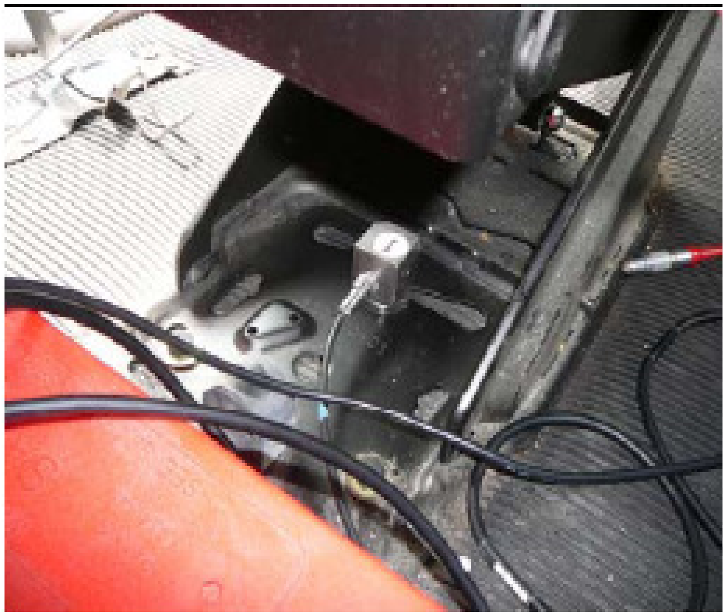

Figure 3-2 Tri-axial accelerometer underneath driver seat

Figure 3-3 HDDV used in study

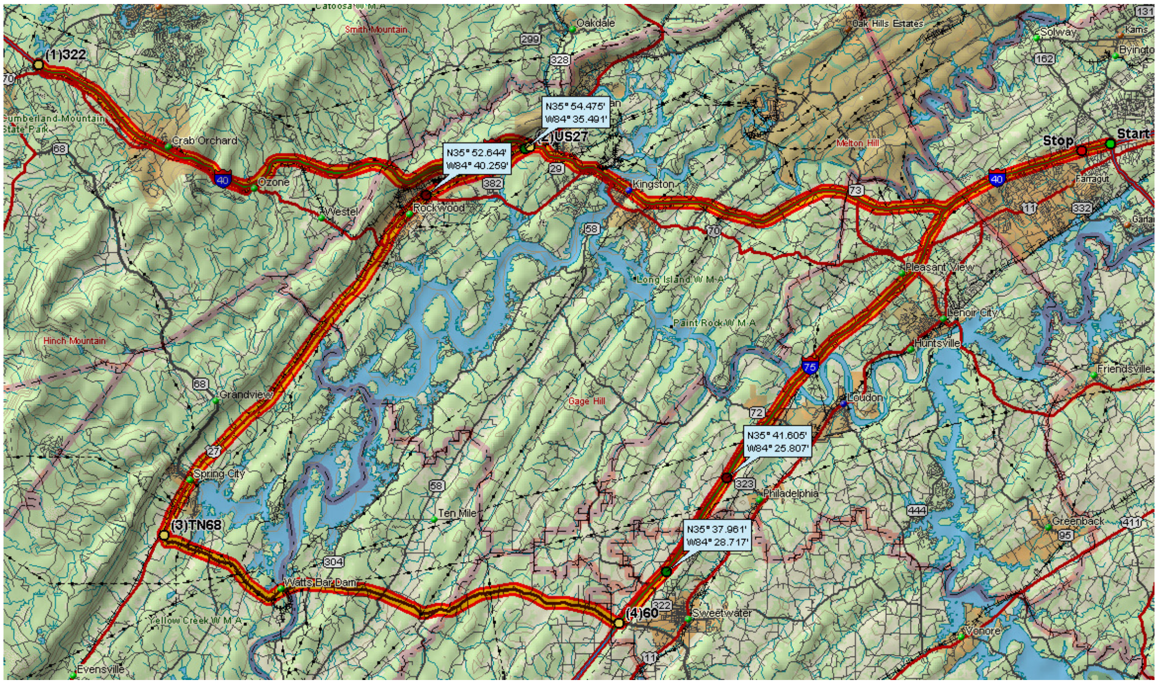

Figure 3-4 The full truck route (I-40, US-27, TN-68 and I-75)

3.2 Interstate and rural road comparison

The route that was selected for this study required each HDDV to travel over interstate and rural roads. The level of vibrations underneath the driver seat on each road type was evaluated for every truck over a selected five mile stretch. As mentioned above, five miles of each road type was selected because the equipment used to record accelerometer output for this study could record only ten minutes of data before it was necessary to stop recording, move data to storage and restart recording. Thus, it was difficult to find a single portion of the route for which data had been collected for every truck. However, there was a five-mile length on each road type, for which data was available for every truck. Both routes selected are fairly straight paths to ensure a good comparison of the road types. The rural route, located on highway US-27, can be seen in Figure 3-5, along with the latitude and longitude of the start and finish points, N35.54475 / W84.35491 and N35.52644 / W84.40259, respectively. Figure 3-6 shows the interstate route, located on I-75N, along with the latitude and longitude of the start and finish points, N35.37951 / W84.28717 and N35.41605 / W84.25807 respectively. Also, Figure 3-4 shows the full route with the longitude and latitude of both rural and interstate roads.

The time and location of each truck was determined using the GPS data that was collected during each test. This data showed the exact time that each truck reached a start and finish point of the five-mile stretches. These times were then used with the DEWE-5001 data to obtain the exact data needed for each five mile stretch. MATLAB was then used to calculate the root mean square (RMS) of the vibration data underneath the driver seat in the X, Y and Z directions. For a set of *n* values of a variable *x*, the RMS value is

$$x_{\mathrm{rms}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} {x_i}^2} = \sqrt{\frac{{x_1}^2 + {x_2}^2 + \cdots + {x_n}^2}{n}}.$$

3.3 MSC Adams software

Adams is a MBS/FEA software package that can import geometry from most major CAD systems or allow the user to build from scratch a solid model of a mechanical system. Adams provides a wide range of joints and constraints for articulated mechanisms. The software package has the capability to check the model that has been created and run simultaneous equations for kinematic, static, quasi-static, and dynamic simulations. The results of the simulations can be shown as graphs, data plots, reports or animations and can be used with multiple FEA programs to optimize the design of a system. Adams is a multi-body dynamics program packaged with specific products such as: Adams/View, Car and Engine, along with extension products such as: Adams/Flex, Controls and Vibrations. Adams/View and Car are the two products of interest for this study.

The Adams/View interface and point-and-click operation enable all experienced users to create complete and accurate mechanical models easily. Users can create sketches of rough models without defining numerical coordinates at every step by using the drag-and-drop positioning. Models are made the same with Adams/View as a physical system; by creating and assembling parts, connecting them with joints, and "driving" them with motion generators. Users may also define forces and apply them to individual parts in a full system design. Design sensitivities can be measured when the user selects model parametric properties, which allow design variables to be selected, sweep them through a range of values and initiate parametric simulations.

Adams/Car allows teams to create and test "prototypes" of vehicles and subsystems of vehicles quickly. The vehicles or subsystems can then be tested under various road conditions and undergo the same tests normally ran in the lab or on a test track, but all computed in a fraction of the time in Adams/Car. Adams/Car has the capability to analyze suspension, steering, handling characteristics, general actuators, vehicle states and other characteristics through animation, tables and plots. It offers shareable templates, extensive library of joints and constraints and easy integration of component geometry and control systems into vehicle models.

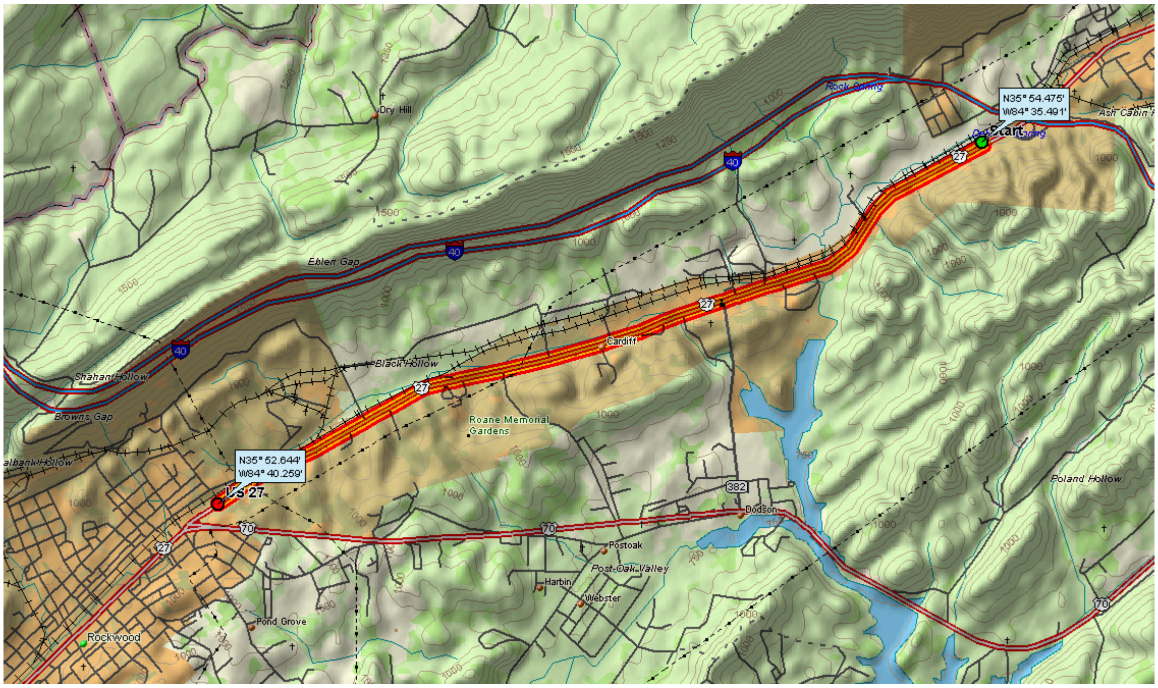

Figure 3-5 Five rural miles analyzed (US-27)

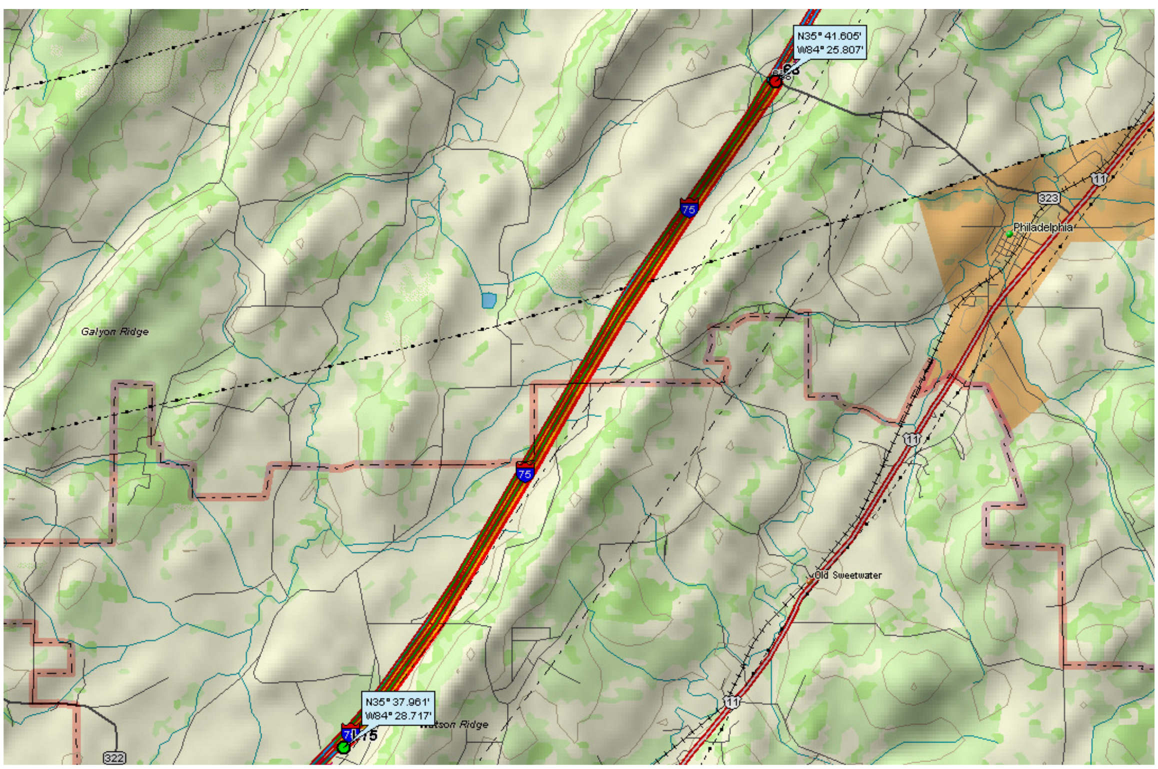

Figure 3-6 Five interstate miles analyzed (I-75)

There are many benefits when using Adams software. It can generate design useful information at every stage of the developing process, which reduces risks. Adams lets the user make quick changes to the design without building a physical prototype. Quick changes also allow the user to make more variations in the product, which can lead to an improvement in the product. Adams, Adams/Car, and their add-on modules are the most widely used multi-body dynamics software in the world. Adams is improving costs and time for many companies in almost every industry, from automotive and aerospace, to wind turbines and biomechanics. Adams is a proven solution that can supplement or even replace physical prototypes and testing by improving product quality and performance.

3.4 Basic HDDV model

Using Adams/View, a six mass and twelve spring-damper system was created to represent a basic model of the HDDV without a trailer. The basic model with dimensions is illustrated in Figure 3-7. The springs connecting the frame and the cab and the tires and the cab are considered bushings in Adams. Bushings provide a six degree-of-freedom force relationship for connecting two components. Another model of a basic HDDV with a trailer attached was created using a nine-mass and fourteen-spring-damper system and can be seen in Figure 3-8. The parameters used for both basic HDDV models are located in Table 3-2. The distance parameters were obtained by measurements taken during setup of instrumentation, while the spring and damping coefficients were determined through literature review. Figure 3-9 shows the basic HDDV model without a trailer that was built in Adams/View.

The basic models simulated in Adams/View are "driven" by the data previously collected by the transducers while in transit on interstate and rural roads. Motion sensors were created on each model corresponding to the transducers used for each road test. Impact to the model can be from any number of the transducers. Simulations run in Adams/View can predict vibration at any desired point on the model. The models can predict forces, torques, accelerations, velocities, displacements and deformations at any desired points. Plots, animations and tables of the simulations can then be acquired for any part, marker or system.

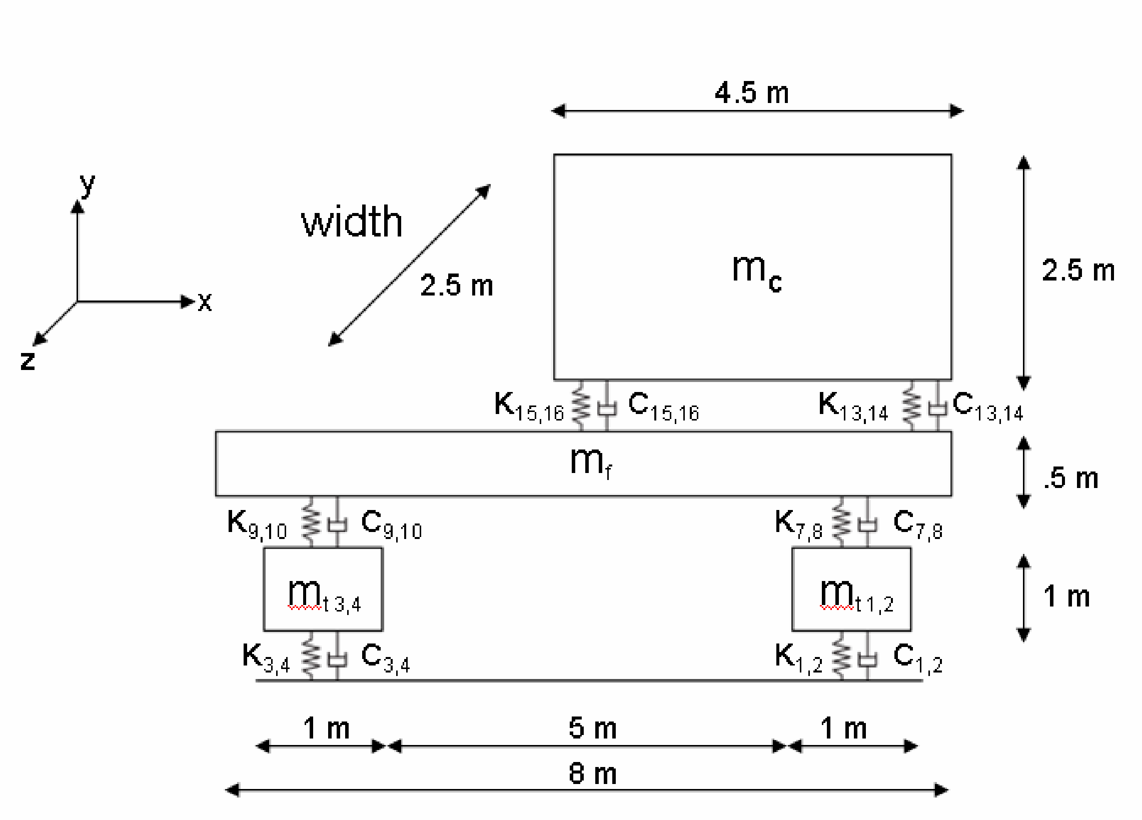

Figure 3-7 Basic HDDV design without trailer

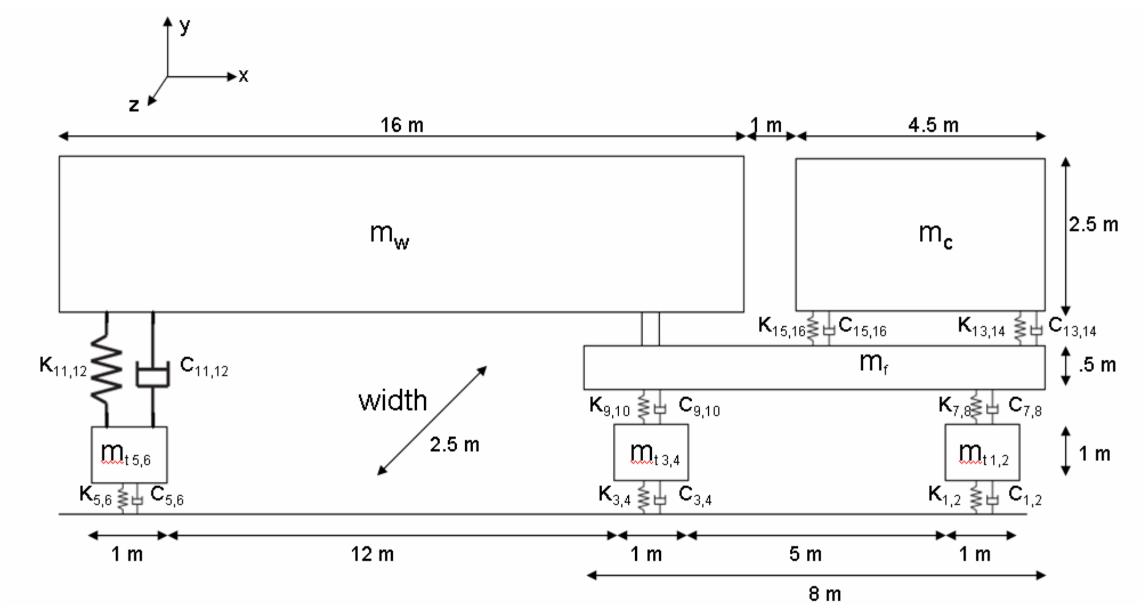

Figure 3-8 Basic HDDV Design with trailer

Table 3-2 Parameters for basic truck model

Mass Parameters (kg)			
	Cab mass (including engine)	m_c	3200
	Frame mass	m_f	1700
	Trailer mass	m_w	20000
	Front Driver Tire mass	m_{t1}	150
	Front Passenger Tire mass	m_{t2}	150
	Rear Driver Tires mass	m_{t3}	600
	Rear Passenger Tires mass	m_{t4}	600
	Trailer Driver Tires mass	m_{t5}	600
	Trailer Passenger Tires mass	m_{t6}	600
Spring Stiffness (kN/m)			
	Road to Front Tires	k_1, k_2	1750
	Road to Rear Tires	k_3, k_4	3500
	Road to Trailer	k_5, k_6	3500
	Front Tires to Front Frame	k_7, k_8	1100
	Rear Tires to Rear Frame	k_9, k_{10}	2200
	Trailer Tires to Trailer	k_{11}, k_{12}	2200
	Frame to Cab	k_{13}, k_{14}, k_{15}, k_{16}	923
Damping Coefficients (kNs/m)			
	Road to Front Tires	c_1, c_2	0.175
	Road to Rear Tires	c_3, c_4	0.35
	Road to Trailer	c_5, c_6	0.35
	Front Tires to Front Frame	c_7, c_8	19
	Rear Tires to Rear Frame	c_9, c_{10}	30
	Trailer Tires to Trailer	c_{11}, c_{12}	30
	Frame to Cab	c_{13}, c_{14}, c_{15}, c_{16}	6

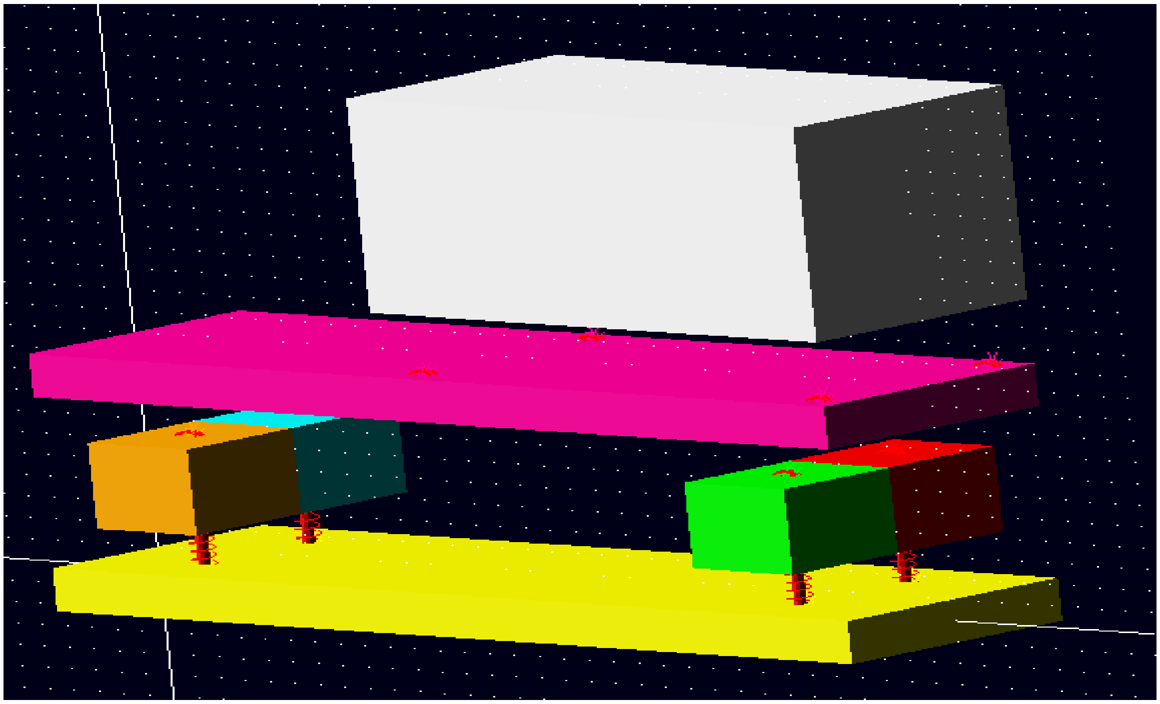

Figure 3-9 Basic model without trailer made using Adams

In the Adams models, the tires are assumed to move only in the vertical direction, neglecting any movement in the horizontal direction. This also means that spring-dampers below each tire can only move in the vertical direction. The tire and the road connection are considered to act as a spring-damper system. Also, the typical leaf spring suspension of a HDDV is considered to be a coil spring-damper system. Each spring-damper is preloaded with the static force of the weight that acts on it. It is also assumed that dual tires, as are found at the rear of the truck and the trailer, are bundled together as one whole tire. The attachment at the fifth wheel coupling where the trailer and the truck connect is assumed to prohibit motion of the trailer for the basic model with a trailer attached.

3.4.1 Preloads

Preloads represent the constant forces acting on a spring or bushing. Their values are entered when the spring or bushing is defined. They are important to the model to provide accurate results and do not add any undesired motion. These can be calculated by using Newton's first law. For example, the preloads acting on the four bushings holding the cab are the easiest to calculate because there is only one body acting on the four bushings. The force acting on the bushings can be calculated by taking the mass of the cab and multiplying by the acceleration of gravity, 9.81 m/s^2. Since there are four bushings symmetrically spaced supporting the cab, the preload for each bushing equals the force divided by four. Preloads with multiple bodies acting on springs or bushings can be solved the same way a supported beam with non-symmetrical loads, Figure 3-10, would be solved.

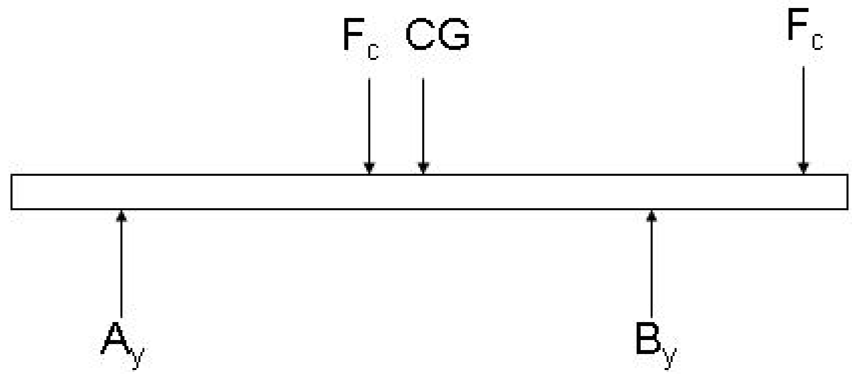

Figure 3-10 Supported beam with non-symmetrical loads

3.4.2 Splines

Raw data was imported into Adams by taking the desired data recorded with the DEWE-5001 and saving it to a tab delimited text file. Each X, Y and Z direction required a new text file including the time and vibration data. Once the data were imported, Adams creates a spline to keep the data continuous. The units of the spline data were acceleration, m/s^2. As mentioned above, motion sensors were then created on the basic model at the same distances the transducers were placed for the actual on-road tests. Transducer placement can be seen in Figure 3-1. A motion sensor was made for each direction. The motion sensors were selected to detect acceleration and call the spline data imported using the AKSIPL function. This function uses the Akima cubic-curve fitting method to interpolate data from the spline imported. The Akima cubic-curve fitting method was chosen because it is stable to the outliers, unlike generic cubic splines that can oscillate when close to an outlier. The vibration data collected has many outliers due to the variability in the road and traffic. Adapting to changes in data distribution and non-linearity of the spline interpolation are two important properties that make the Akima spline so powerful and stable to outliers.

3.5 Advanced models

For more accurate modeling, detailed specifications, such as CAD drawings and the mechanical properties of a specific vehicle, can be imported into Adams/Car. Adams/Car is a virtual prototyping product that can take the advanced models and analyze full vehicles and vehicle suspensions. Adams provides a template made for the trucking industry that uses flexible frames, leaf spring suspensions, and other specifications to make a highly accurate model. Figure 3-11 shows the sample truck model provided by Adams. The template is provided to show how to model multi-axle, multi-subsystem assemblies that are used in the trucking industry today. The template can be modified and used for a full vehicle analysis or only a single part analysis.

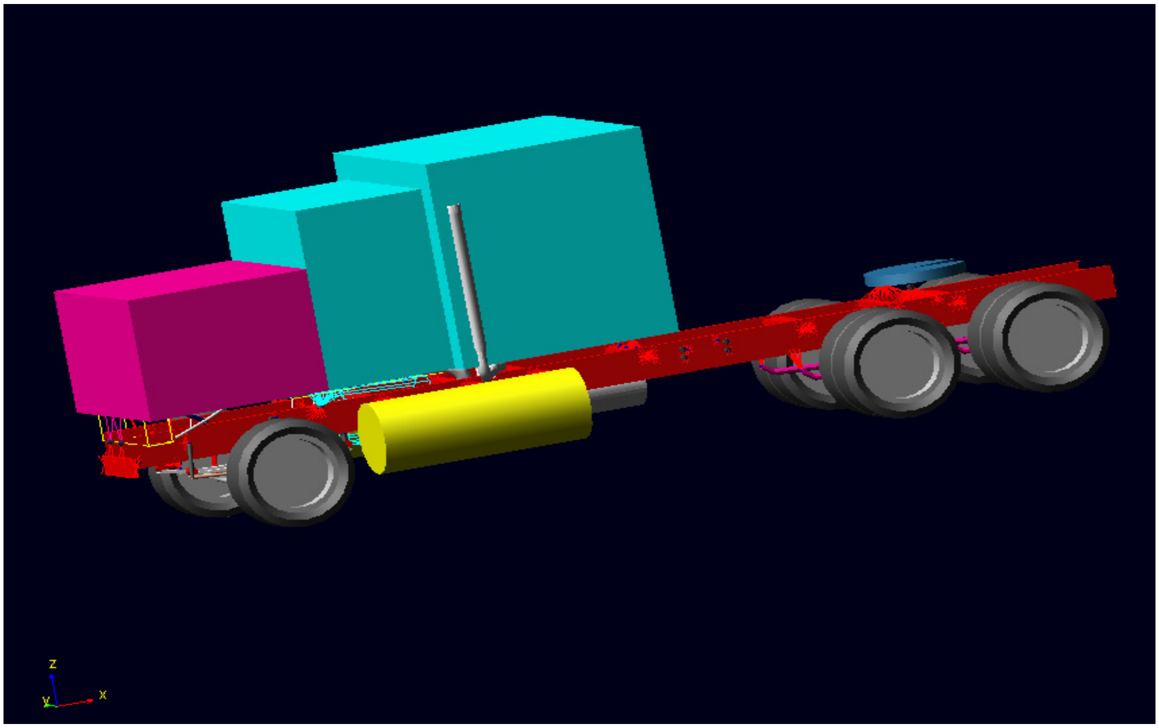

Figure 3-11 Adams/Car sample truck

Adams/Car uses a different approach to building models than Adams/View. Adams/Car uses templates and then assembles the subsystems made in the templates for a full car assembly. In contrast, Adams/View uses a point-and-click operation to create mechanical models easily. The user can create sketches of rough models in Adams/View. Motion sensors are used to “drive” the model in Adams/View, however, in Adams/Car, actuators are used for simulation. A vibration actuator applies force input or a displacement, velocity, or acceleration to vibrate the system. Before running a simulation in Adams/Car with the sample truck provided, the frame template or any desired template needs to be modified with the Adams/Car template builder. This is where one can add motion by creating an actuator to the template. Once the changes have been made, the template then needs to be saved where the original template resided. A/Car will run the simulation and post processing the same is it is in Adams/View. For this project, the actuator has been built and an analysis has been done on the frame only, but not on the full truck assembly. With more time, this process could take place with the given data.

Chapter 4 Results and discussion

4.1 Road type comparison

Measurements were made on the same stretches of roadway for each truck to determine differences in road type and in the manufacturers. Analysis of the vibration on the different road types focused on vibration the driver seat to determine an understanding of how the vibration is transmitted to the cab. Also, this is the direct source of vibration targeted at the driver before the seat dampens the vibration.

The RMS values of the vibration data in the X, Y and Z directions can be seen in Table 4-1 and the average RMS values for each manufacturer with and without the weighted trailer attached can be seen in Table 4-2. The bold numbers in Table 4-1 are overall RMS values for tests without the weighted trailer attached. Manufacturer C did undergo a test performed without a trailer, but unfortunately the recording of GPS was improperly collected for the test. The average vibrations in the interstate and the rural roads are similar to each other and can be compared in Figures 4-1 and 4-2. This was expected because Fu, Joshua et al. (2009) discovered that the total vibrations on I-75 North and total vibrations on the rural roads were similar. However, vibrations on the roadway of I-40 were significantly lower than the two roads. Each truck manufacturer shows consistent results for both interstate and rural roads, which should be expected and can also be seen in Figures 4-1 and 4-2.

Table 4-1 The RMS values for each on-road test

Manufacturer	Date	Rural			Interstate		
		Acceleration X-Direction (m/s^2)	Acceleration Y-Direction (m/s^2)	Acceleration Z-Direction (m/s^2)	Acceleration X-Direction (m/s^2)	Acceleration Y-Direction (m/s^2)	Acceleration Z-Direction (m/s^2)
A	1/31/2008	0.7437	0.9473	0.9427	0.7208	1.3041	0.9765
	2/8/2008	0.6715	1.2381	0.7955	0.7311	1.175	1.0019
	2/22/2008	0.6101	1.0217	0.7009	0.7415	1.2802	1.0583
	2/27/2008	0.7955	1.2568	0.9355	0.9079	1.6802	1.1501
	11/20/2008	**0.6187**	**0.8014**	**0.8067**	**0.5884**	**0.925**	**0.9083**
	11/21/2008	0.7209	1.053	0.9555	0.663	1.1811	1.041
B	4/4/2008	0.5846	1.5801	0.6716	0.6638	1.8185	0.7031
	4/10/2008	0.7133	1.6279	0.8456	0.7327	1.4918	0.7514
	4/16/2008	0.667	1.5737	0.6759	0.8175	1.7812	0.721
	5/28/2008	0.6179	1.2241	0.6446	0.8284	1.7628	0.9034
	5/29/2008	**0.6669**	**1.071**	**0.6467**	**0.639**	**1.1988**	**0.7137**
	8/8/2008	0.7099	1.5389	0.7143	0.7993	1.8341	0.8253
	11/5/2008	1.0673	1.8686	0.709	1.013	1.5052	0.7116
C	4/25/2008	0.3517	0.4223	0.371	0.3593	0.4593	0.3545
	6/4/2008	0.5634	0.8346	0.5924	0.6129	0.9858	0.7864
	7/17/2008	0.4222	0.8276	0.4976	0.6233	1.1946	0.7527
	8/20/2008	0.7716	1.0843	0.6198	0.8002	1.2621	0.7414
	10/15/2008	0.5619	0.7729	0.5462	0.5063	0.9345	0.6765
D	1/23/2009	0.5692	0.6325	0.6288	0.4431	0.6479	0.5276
	2/3/2009	0.5916	0.677	0.6809	0.718	0.9446	0.7152
	2/5/2009	0.5115	0.6437	0.6422	0.772	0.87	0.844
	2/17/2009	0.6881	0.6857	0.6257	0.6224	0.858	0.7508
	2/19/2009	**0.53**	**0.6698**	**0.5568**	**0.6013**	**0.8192**	**0.5911**
	2/19/2009	0.5964	0.6912	0.6396	0.8707	1.1149	0.9285
	2/27/2009	0.5054	0.5969	0.5257	0.6373	0.9374	0.8116
Bold is without trailer							

Table 4-2 Average RMS values for each manufacturer with trailer

Manufacturer	Rural			Interstate		
	Acceleration X-Direction (m/s^2)	Acceleration Y-Direction (m/s^2)	Acceleration Z-Direction (m/s^2)	Acceleration X-Direction (m/s^2)	Acceleration Y-Direction (m/s^2)	Acceleration Z-Direction (m/s^2)
A	0.708	1.103	0.866	0.753	1.324	1.046
B	0.718	1.498	0.701	0.785	1.627	0.761
C	0.534	0.788	0.525	0.580	0.967	0.662
D	0.577	0.655	0.624	0.677	0.895	0.763

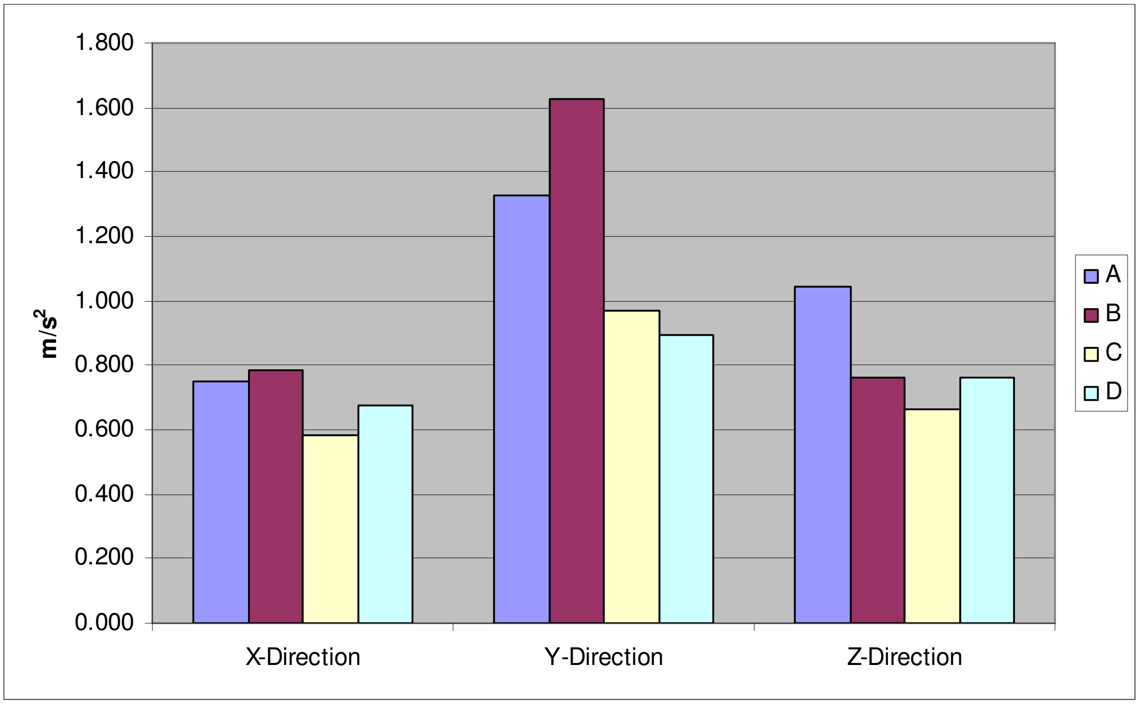

Figure 4-1 Comparison of Average Vibration on Interstate Roads

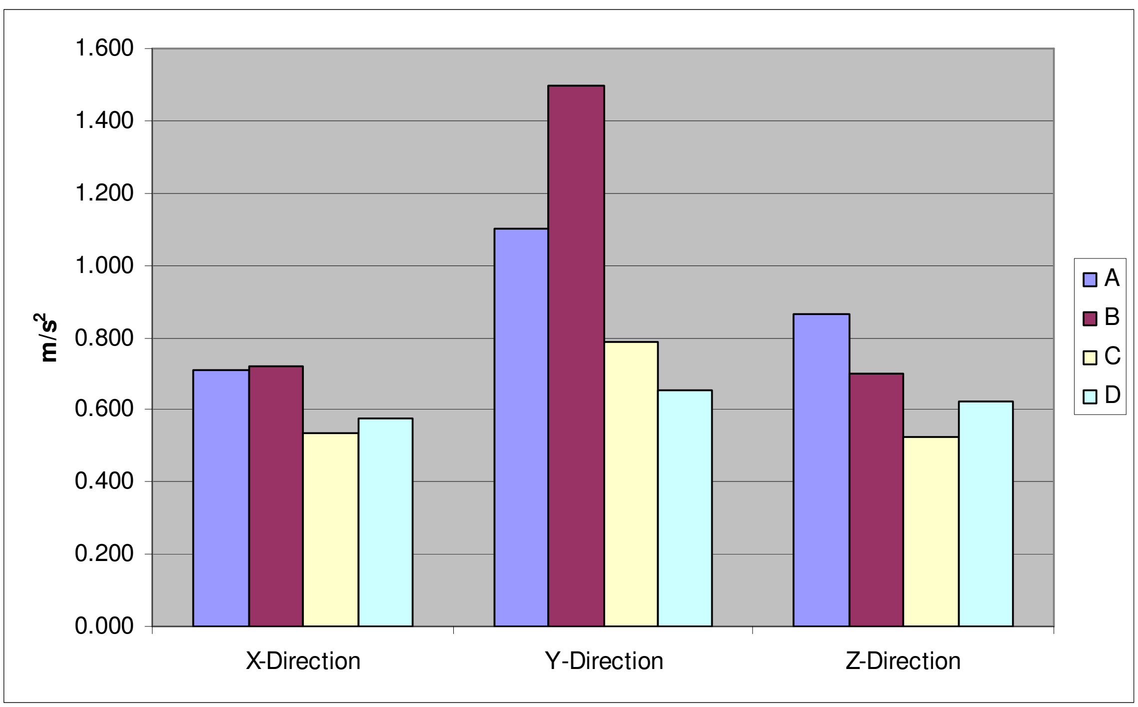

Figure 4-2 Comparison of Average Vibration on Rural Roads

Statistical analysis of variance and the Student t-test were calculated using the software JMP version 7.0.2 and used to compare the different manufacturers on each road type in the X, Y and Z directions. The statistical analysis uses the different manufacturers as the independent groups and tests for differences between each. The Student t-test assumes the manufacturers are equal, independent samples and assesses whether the means of the group are statistically different from one another. The Student t-test uses an alpha of .05 and a t-value of 2.10092. Tables 4-3, 4-4 and 4-5 show the Student test comparing manufacturers in the X, Y and Z directions, respectively. The positive numbers in the Student t-test represent the pairs are significantly different. Figures 4-3 and 4-4shows the results from the statistical analysis of variance and Student t-test performed in the X direction on the rural and interstate roads, respectively. The two tests performed show that there is no significant difference between the rural and interstate routes for any of the manufacturers in the X direction. The results from the two statistical tests in the Y and Z directions on rural and interstate roads are shown in Figures 4-5, 4-6, 4-7 and 4-8. There is a significant difference between the manufacturers in the Z direction on both rural and interstate roads. Both figures and tables in the Z direction show that Manufacturer A had significantly higher vibrations than the rest of the manufacturers. Also, on the rural roads Manufacturer B is considered to have significantly higher vibrations than C. However, Manufacturer B did not have significantly higher vibration on the interstate roads. Manufacturer B has significantly higher vibration in the Y direction on both interstate and rural roads. It can also be shown that Manufacturer A has significantly higher vibration in the Y direction on both rural and interstate roads than C and D. Manufacturers C and D showed similar results and also showed the lowest amount of vibration experienced underneath the seat of the driver in each direction. It should be noted that these tests were not randomized. Unfortunately, the trucks were hard to obtain for testing, so it was not possible to randomize their selection. However, the differences among the manufacturers may be significant.

The RMS data from each test were compared to the ISO 2631-1 (1997) in the X, Y and Z directions and is shown in Figure 4-9. The results are expected to be high compared to ISO 2631-1 (1997) because the standard is considered at the seat, while the data collected was underneath the seat. Manufacturer D showed that all of the X, Y and Z results stayed in the fairly uncomfortable range before vibrations were even dampened by the seat. Manufacturer C showed the same results except that the Y direction RMS exceeded the uncomfortable range several times. Manufacturers A and B both exceeded the very uncomfortable range in the Y direction and frequently surpassed the uncomfortable range in the X and Z directions.

Table 4-3 Comparison for each pair in X-direction using Student's t-test

	X-Direction on Rural Roads				X-Direction on Interstate Roads			
Manufacturer	B	A	D	C	B	A	D	C
B	-0.15615	-0.14545	-0.00652	0.02873	-0.16069	-0.11227	-0.02882	0.06019
A	-0.14545	-0.17106	-0.03247	0.00312	-0.11227	-0.17602	-0.09292	-0.00356
C	-0.00652	-0.03247	-0.15615	-0.1209	-0.02882	-0.09292	-0.16069	-0.07168
D	0.02873	0.00312	-0.1209	-0.17106	0.06019	-0.00356	-0.07168	-0.17602

Table 4-4 Comparison for each pair in Y-direction using Student's t-test

	Y-Direction on Rural Roads				Y-Direction on Interstate Roads			
Manufacturer	B	A	C	D	B	A	C	D
B	-0.20631	0.24912	0.56416	0.70807	-0.25721	0.10505	0.46191	0.54626
A	0.24912	-0.226	0.08904	0.2325	0.10505	-0.28176	0.0751	0.15889
C	0.56416	0.08904	-0.226	-0.08254	0.46191	0.0751	-0.28176	-0.19797
D	0.70807	0.2325	-0.08254	-0.20631	0.54626	0.15889	-0.19797	-0.25721

Table 4-5 Comparison for each pair in Z-direction using Student's t-test

	Z-Direction on Rural Roads				Z-Direction on Interstate Roads			
Manufacturer	A	B	D	C	A	B	D	C
A	-0.11214	0.04848	0.13483	0.22848	-0.16219	0.12097	0.12732	0.22107
B	0.04848	-0.10237	-0.01602	0.0774	0.12097	-0.14806	-0.14171	-0.04829
D	0.13483	-0.01602	-0.10237	-0.00895	0.12732	-0.14171	-0.14806	-0.05464
C	0.22848	0.0774	-0.00895	-0.11214	0.22107	-0.04829	-0.05464	-0.16219

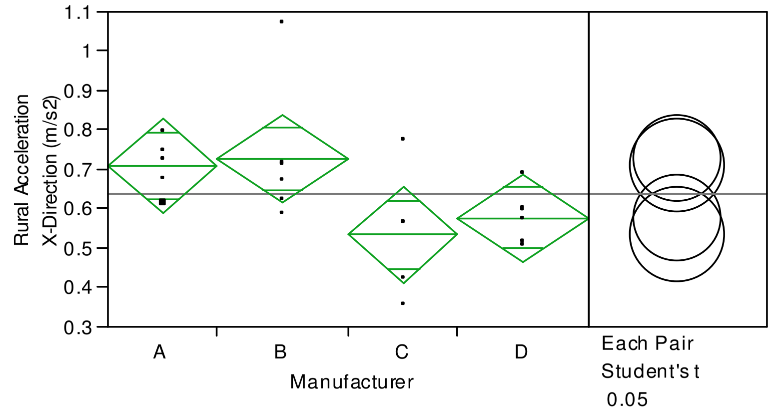

Figure 4-3 Analysis of variance and t-test of five mile rural X direction with trailer

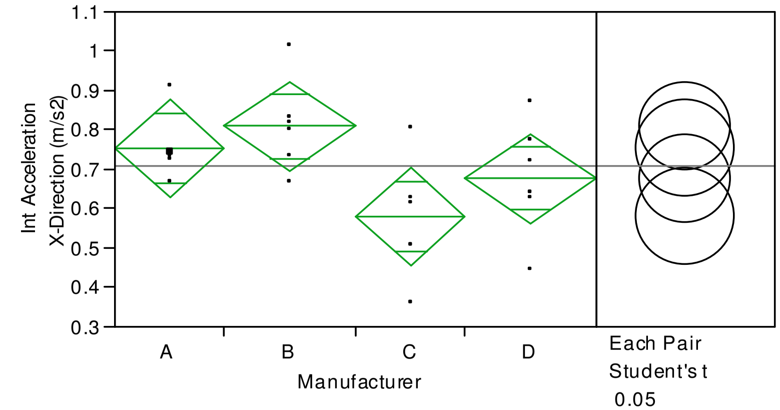

Figure 4-4 Analysis of variance and t-test of five mile interstate X direction with trailer

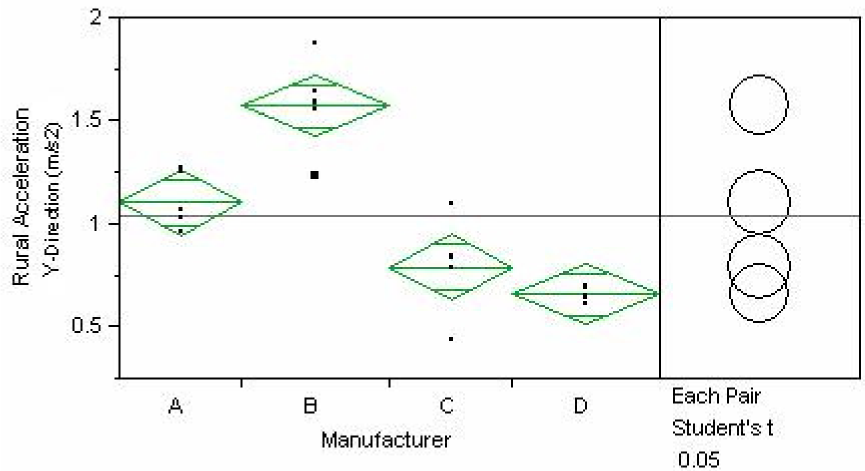

Figure 4-5 Analysis of variance and t-test of five mile rural Y direction with trailer

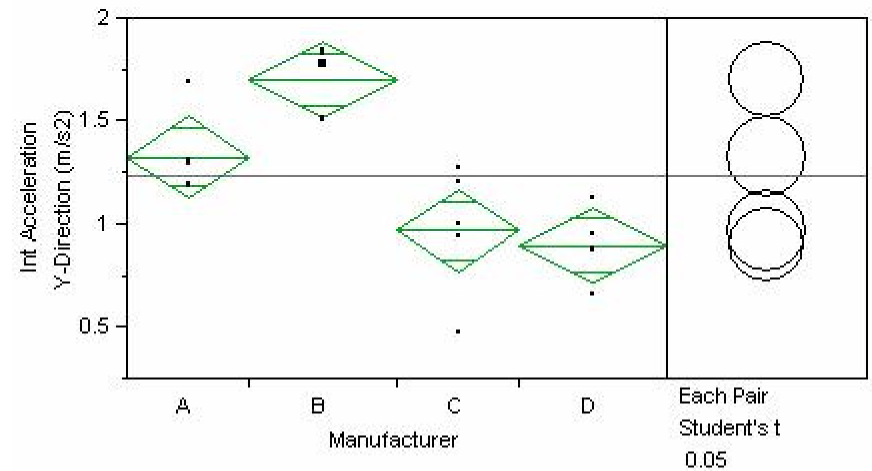

Figure 4-6 Analysis of variance and t-test of five mile interstate Y direction with trailer

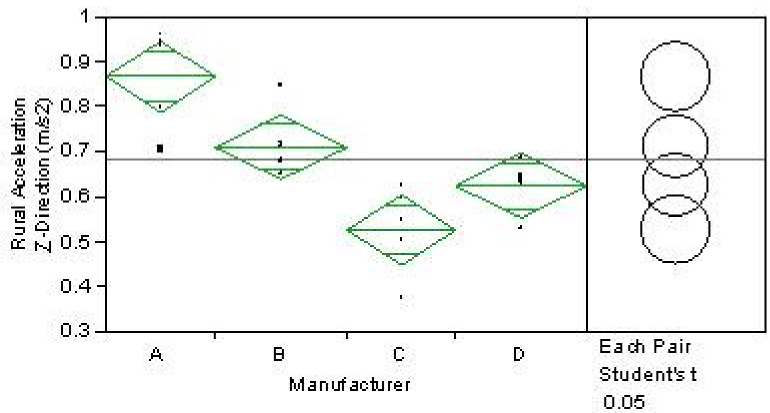

Figure 4-7 Analysis of variance and t-test of five mile rural Z direction with trailer

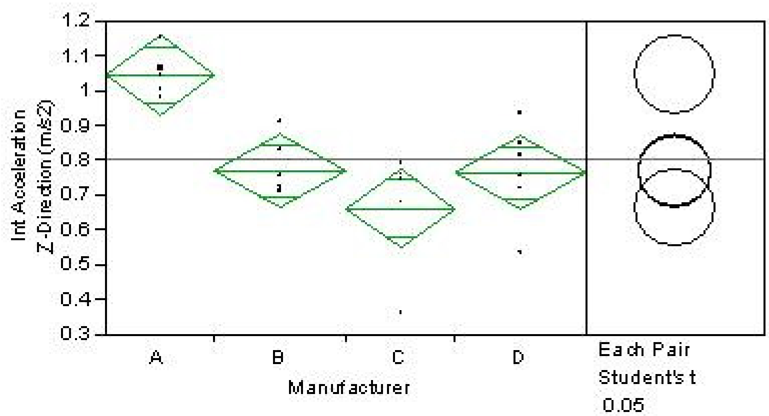

Figure 4-8 Analysis of variance and t-test of five mile interstate Z direction with trailer

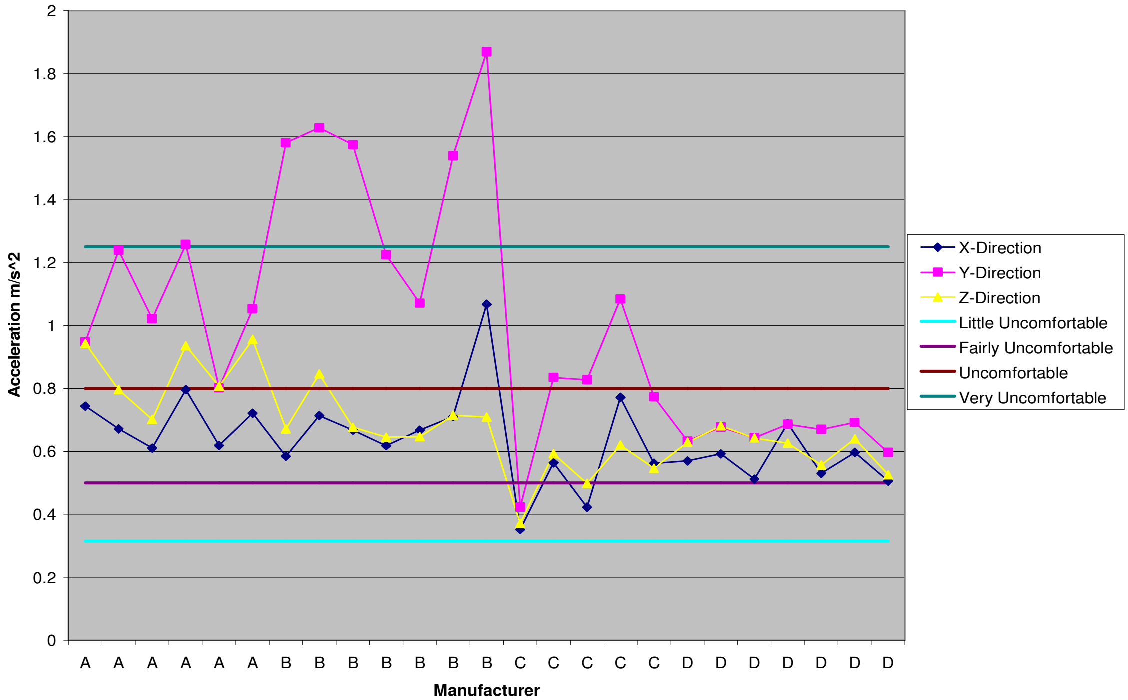

Figure 4-9 Vibration total value of comfort of trucks

4.2 Modeling results

One objective of this study was to develop a method for validating an Adams model of one of the tested trucks. The prerequisites for meeting this objective are an Adams model based on accurate mechanical specifications for one of the tested trucks and real data for that truck's vibration. Since real vibration data was generated by the accelerometers used in this study, it is available. Although specifications were requested from various sources, they have not been made available for any of the tested trucks.

The basic models were used to simulate and analyze five different HDDV, one from each of the four different manufacturers and one traveling without a weighted trailer attached. Each truck analyzed used the actual data from the accelerometers in the vertical direction, while the February 27, 2008 test used data from the X, Y, and Z directions. Simulations were completed consistently by analyzing all data at desired points for 2.5 seconds, with output recorded 500 times per second. The simulation time of 2.5 seconds was chosen to closely analyze the vibration at a particular point. Simulations that last much longer than 2.5 seconds do not show clear results on plots that are reduced to fit the screen size. The data that collected on the road was recorded at 5,120 points per second. This gives extremely accurate results and is useful for vibration analysis of a vehicle because of the road imperfections causing outliers. However, at 5,120 points per second, 2.5 seconds takes a significant amount of time to simulate. A recording frequency of 500 Hz was chosen due to the time constraints, but still produces very accurate results.

4.2.1 Frame predicting cab vibrations

A simulation using the basic model and the data collected on the rural highway of US-27 on April 25, 2008, was performed to compare actual data at transducer, T6, located on the frame, and transducer, T1, located underneath the driver seat in the cab. The exact location of each transducer can be seen in Figure 3-1.

The collected data from T6 was imported into Adams, fitted to a spline, and then added to the motion sensor that replicates T6. The 2.5 second simulation, recording at 500 Hz, was then carried out, “driven” by the acceleration data collected at T6. Figure 4-10 shows the acceleration data at T6 recorded by Adams, which is the same as the actual data collected. Figures 4-11 and 4-12 show the velocities and displacements of T6 calculated by Adams in the 2.5 second time period. Figure 4-12 shows a peak of about .03 meters of movement in the frame at T6. Figures 4-13, 4-14 and 4-15 show the acceleration, velocity and displacement, respectively, at T1 that Adams calculated, given the actual data from T6. Figure 4-16 is a comparison of the actual data collected at T1, blue, and the calculated data at T1, red. The comparison of actual data and the calculated data show inaccurate results, but the calculated data does predict the data in the same range as the data that was collected. The inaccuracy is not surprising, since the model did not incorporate specifications of the truck on which the data were collected.

Each truck was simulated at each of the transducers to predict the vibrations underneath the seat of the driver. Also, combinations of transducers were used to predict the vibrations at T1. Using the interstate data from February 27, 2008 test, each T1 prediction by other transducers can be seen Figures 4-17, 4-18, 4-19, 4-20, 4-21, 4-22, 4-23 and 4-24. The same simulations were carried out for each of the five HDDV and can be seen in Appendices I, II, III, IV and V. The accuracy of the data predictions is significantly higher when data from the same body of interested is used to help predict the vibration. In contrast, the data from just the frame produces inaccurate results, but estimates the vibration in the same range.

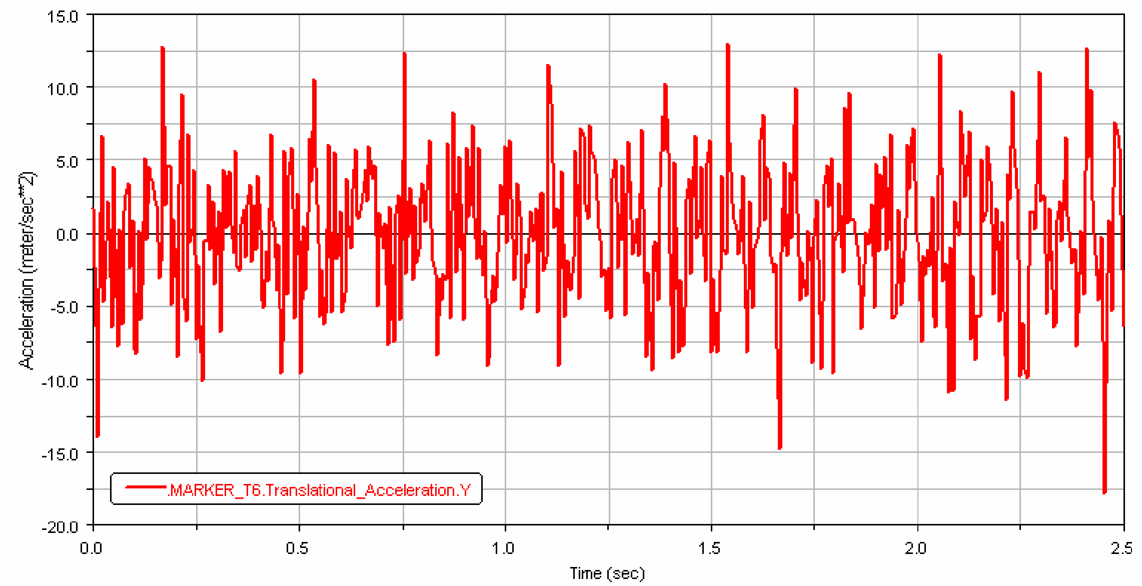

Figure 4-10 Actual acceleration at transducer T6 in Y-direction

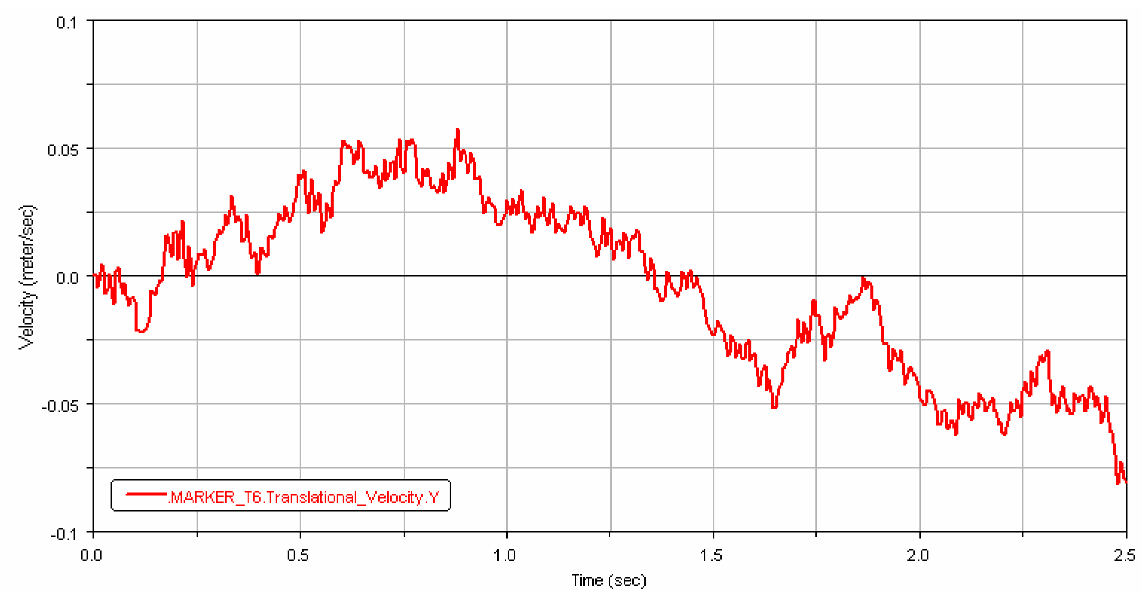

Figure 4-11 Actual velocity at transducer T6 in Y-direction

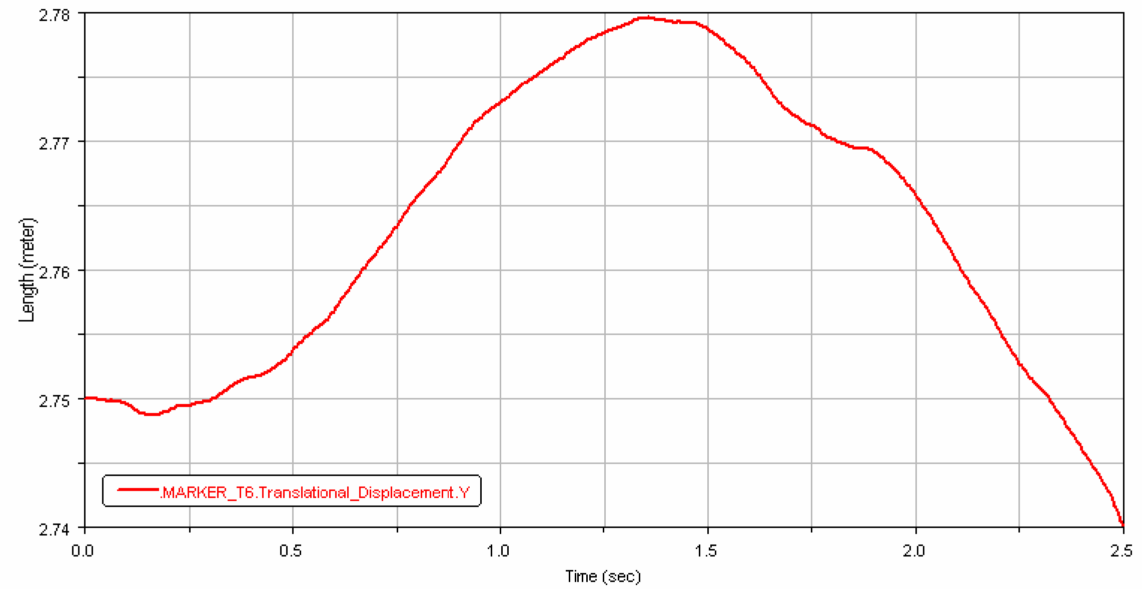

Figure 4-12 Actual displacement in the Y-direction at transducer T6 in Y-direction

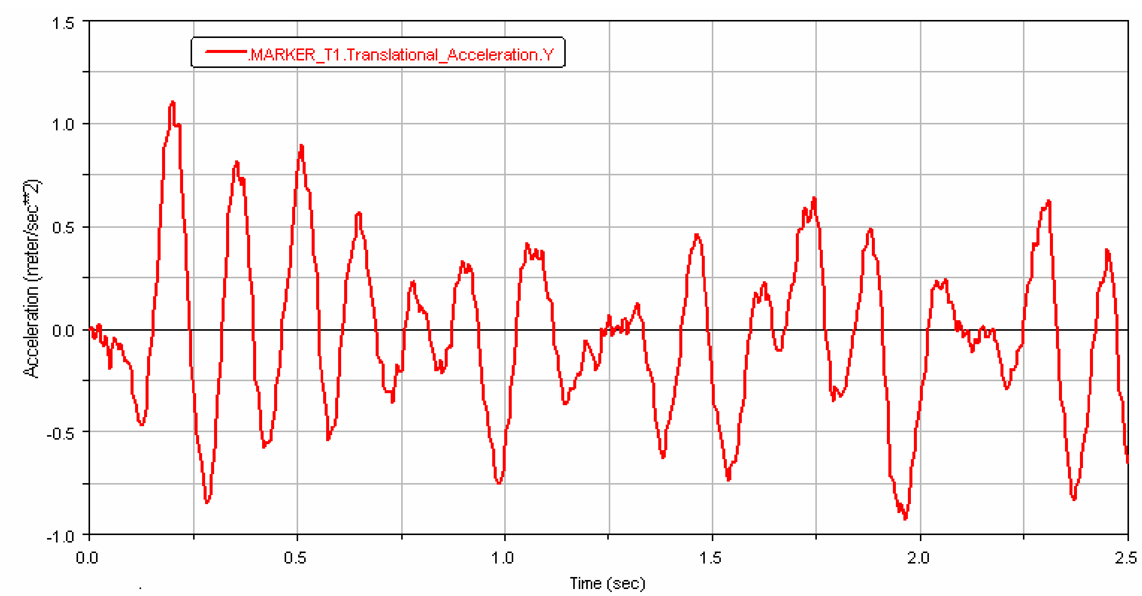

Figure 4-13 Acceleration predicted by T6 at transducer T1 in Y-direction

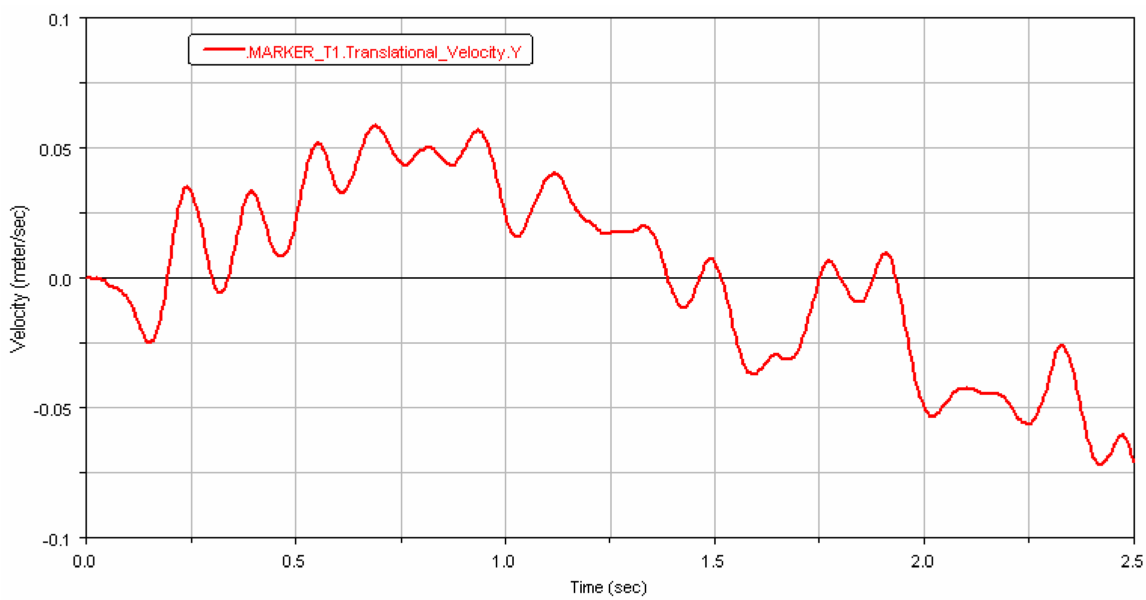

Figure 4-14 Velocity predicted by T6 at transducer T1 in Y-direction

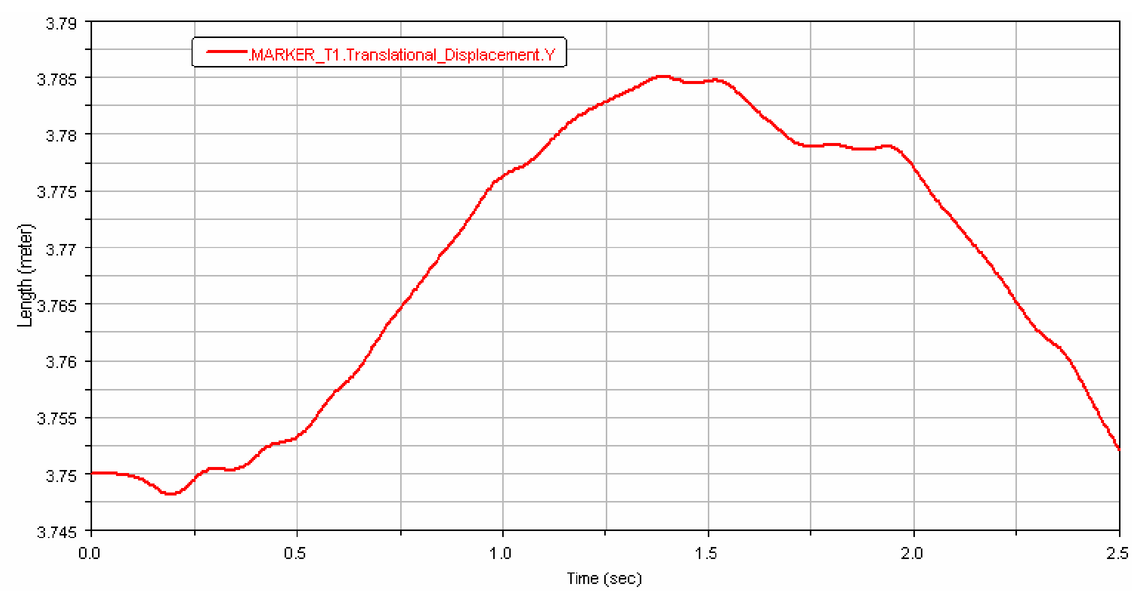

Figure 4-15 Displacement predicted by T6 at transducer T1 in Y-direction

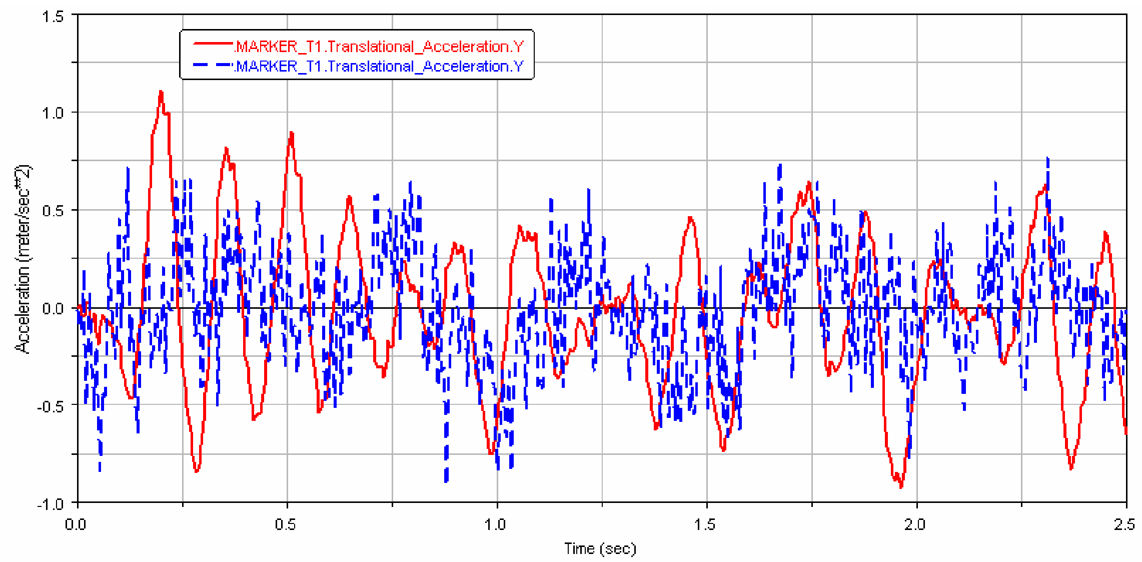

Figure 4-16 Comparison of Actual T1 data (blue) versus modeled T1 data (red)

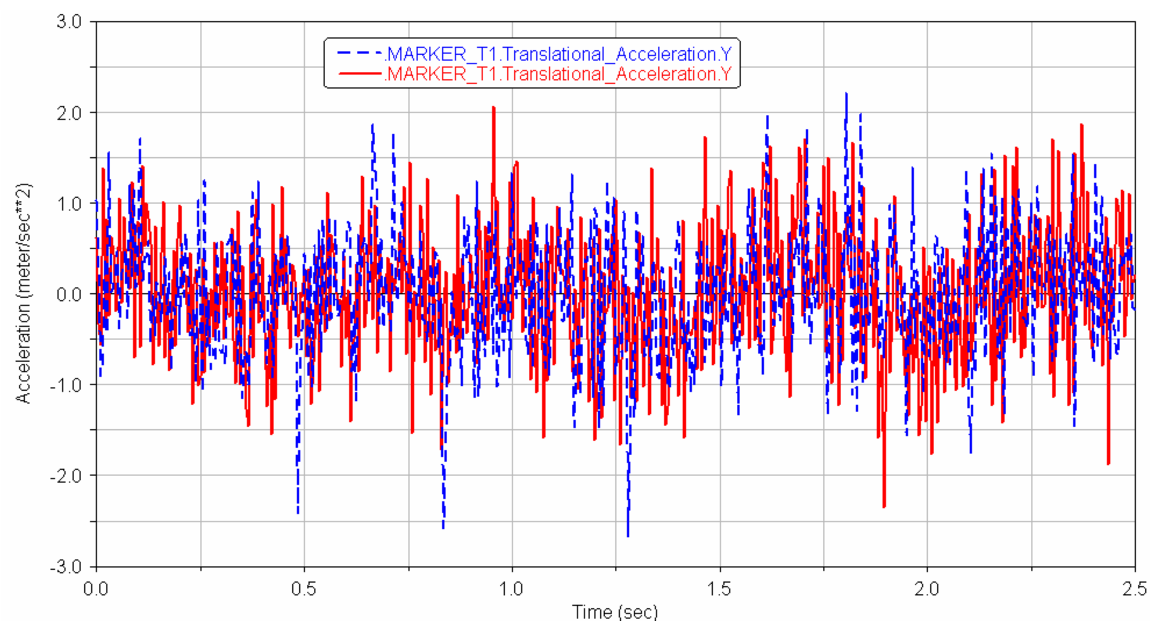

Figure 4-17 T2 predicts T1 (red) compared to actual T1 (blue)

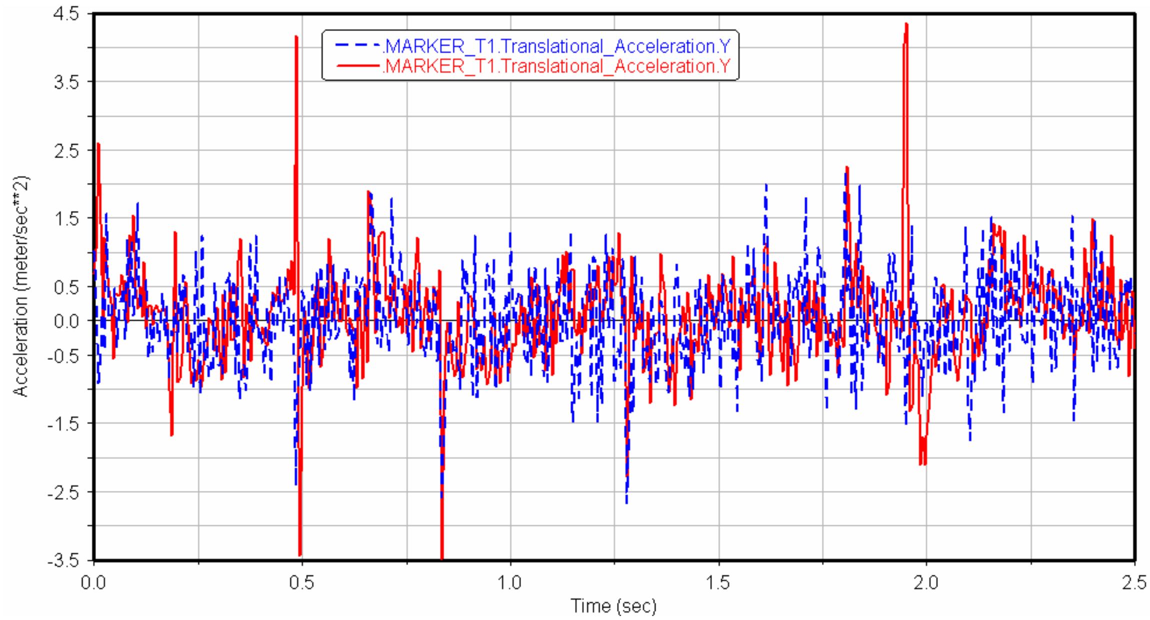

Figure 4-18 T3 predicts T1 (red) compared to actual T1 (blue)

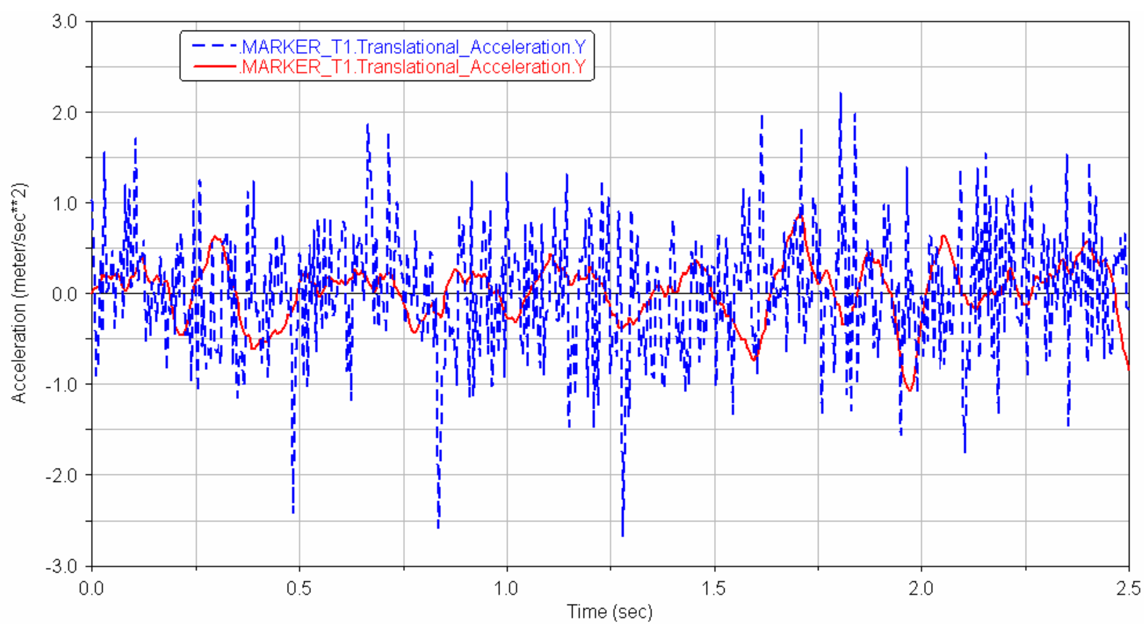

Figure 4-19 T6 predicts T1 (red) compared to actual T1 (blue)

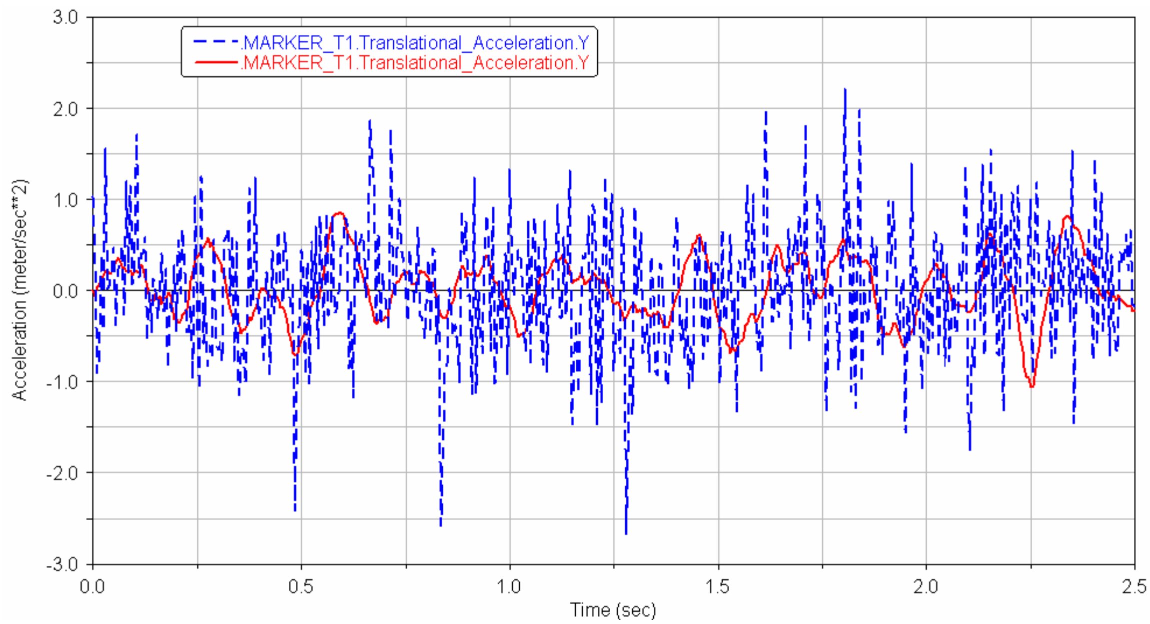

Figure 4-20 T7 predicts T1 (red) compared to actual T1 (blue)

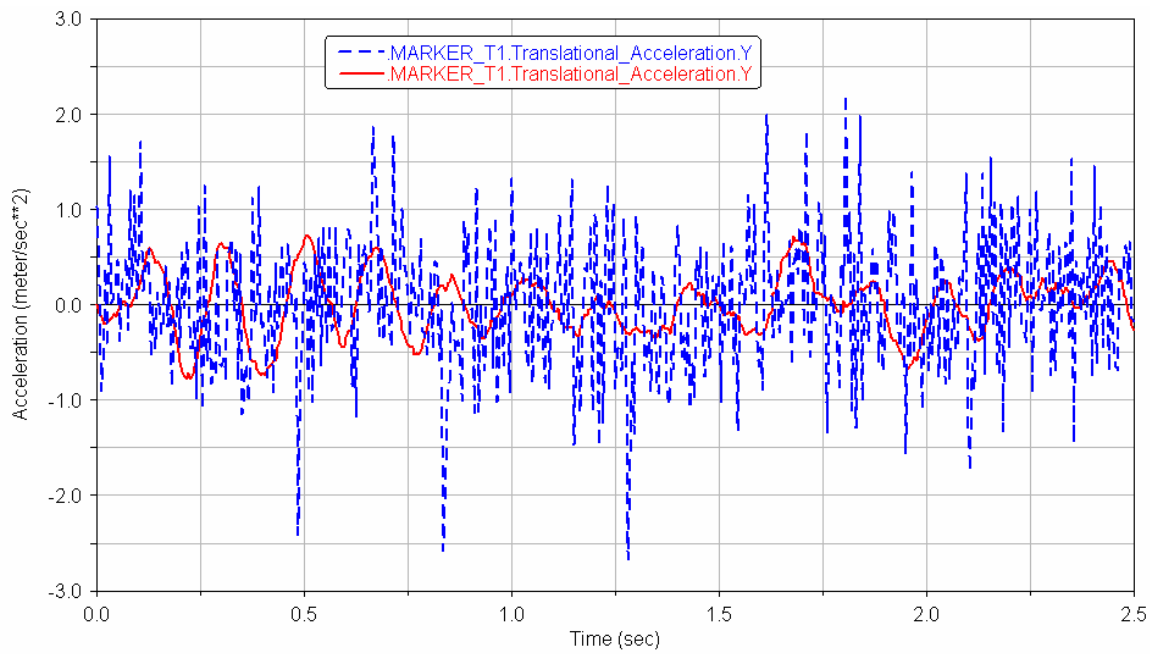

Figure 4-21 T8 predicts T1 (red) compared to actual T1 (blue)

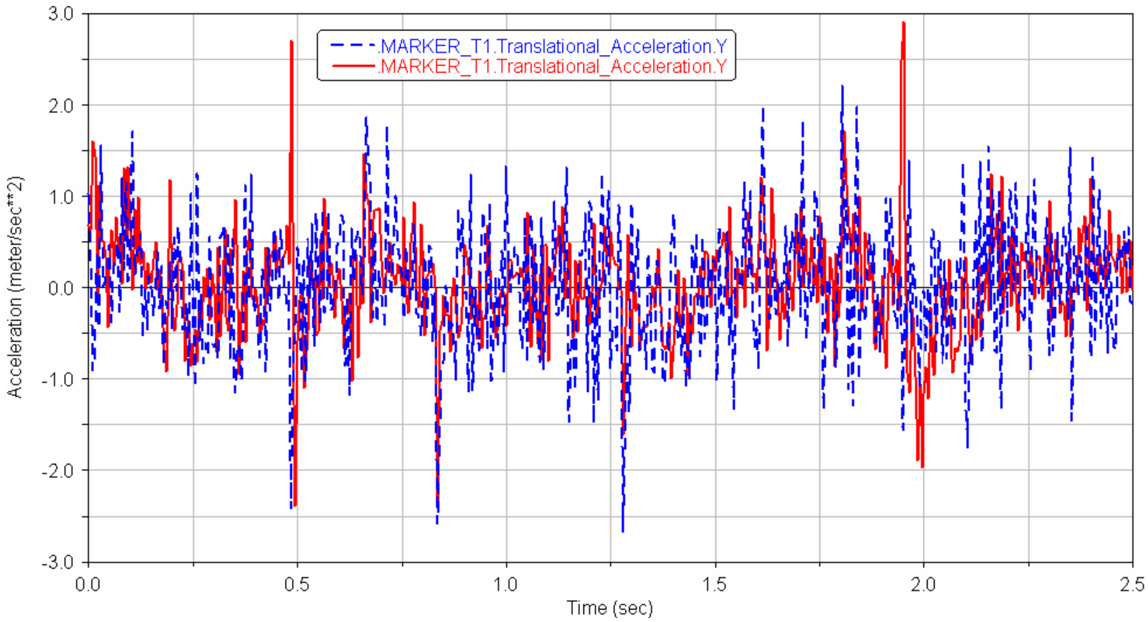

Figure 4-22 T2 and T3 predict T1 (red) compared to actual T1 (blue)

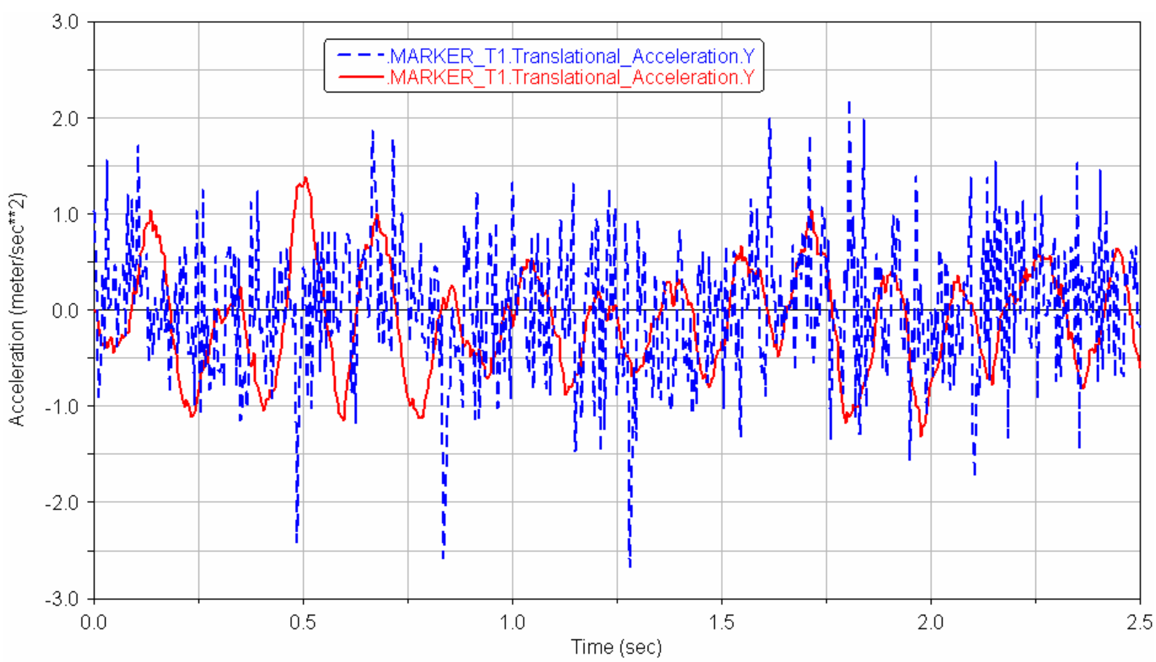

Figure 4-23 T6 and T7 predict T1 (red) compared to actual T1 (blue)

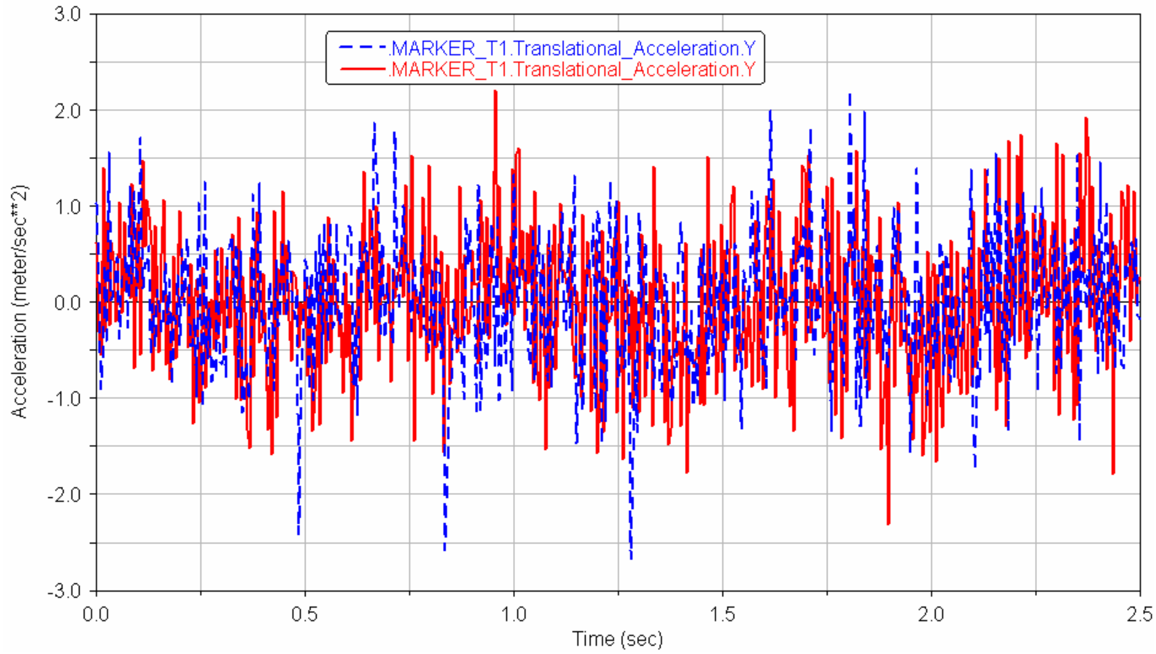

Figure 4-24 T2, T6 and T7 predict T1 (red) compared to actual T1 (blue)

4.2.2 Cab predicting frame vibration

Other simulations were completed by using collected transducer data at T1 to analyze accelerations, velocities and displacement of the cab, and also to predict vibrations on the frame at T6. Figures 4-25, 4-26 and 4-27 show the actual acceleration, velocity and displacement, respectively, at T1 in the vertical direction from the November 5, 2008, tests, while on rural roads. Figure 4-28, 4-29 and 4-30 show the acceleration, velocity and displacement, respectively, predicted at T6 by the model using T1 as the driving force of the simulation. The actual data from T6 was then compared to the predicted results of T6 using T1 to “drive” the model and can be seen in Figure 4-31. The transducer, T3, which is located in the back of the cab, was then used with T1 to predict the vibration on the frame. Figure 4-32 shows the results from the combination of T1 and T3 to predict T6 and is compared to the actual T6 data. Finally, the transducer T8, which is located around the middle of the frame, was combined with T1 and T3 to predict T6 and can be seen in Figure 4-33. Using the cab data to estimate the vibration of the frame gives very inaccurate results. The data collected show that the vibration at the frame is much higher than at the cab. The results from the cab show the frame to be vibrating magnitudes less than the actual vibration at the frame. However, when vibration data from the frame were added to the cab data, the results became significantly more accurate.

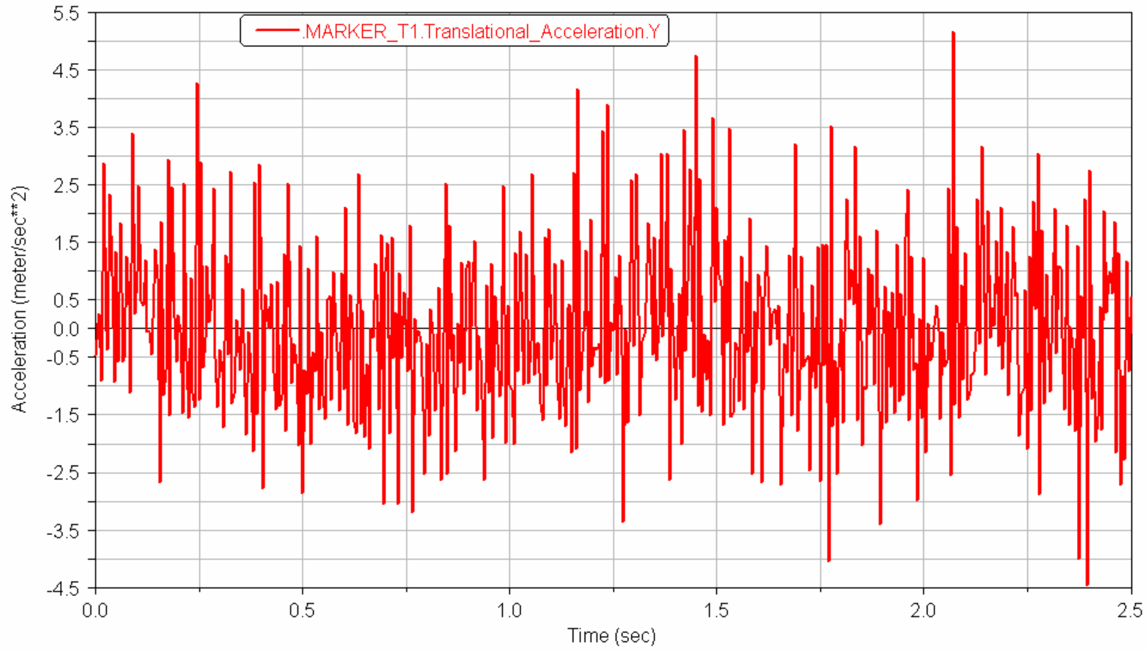

Figure 4-25 Actual acceleration at transducer T1 in Y-direction

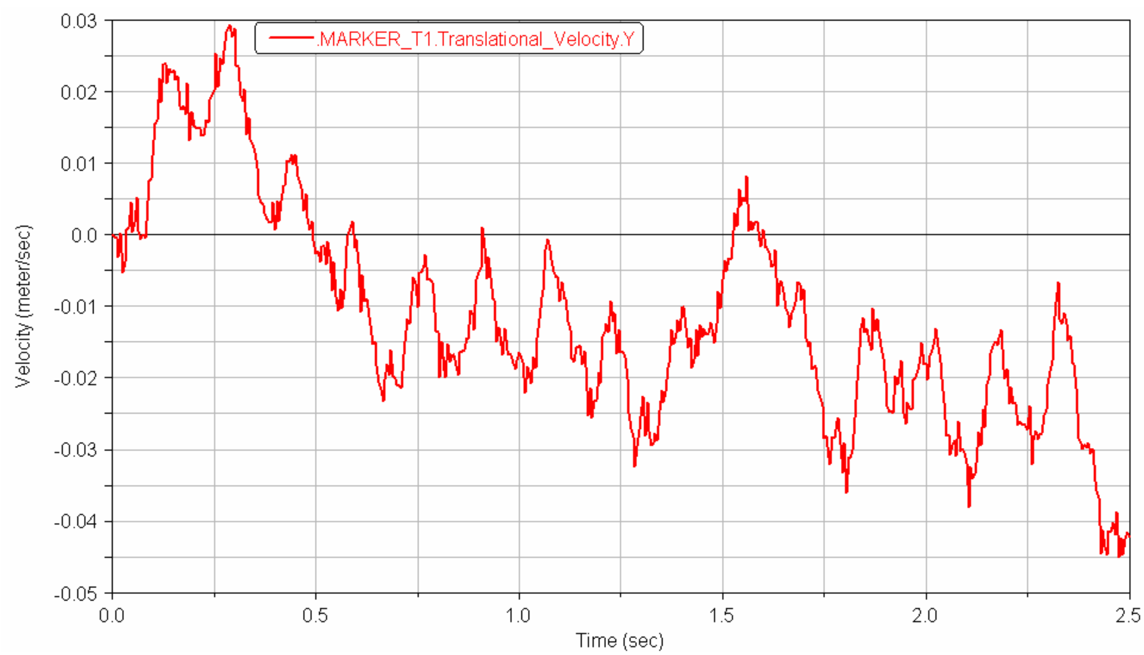

Figure 4-26 Actual velocity at transducer T1 in Y-direction

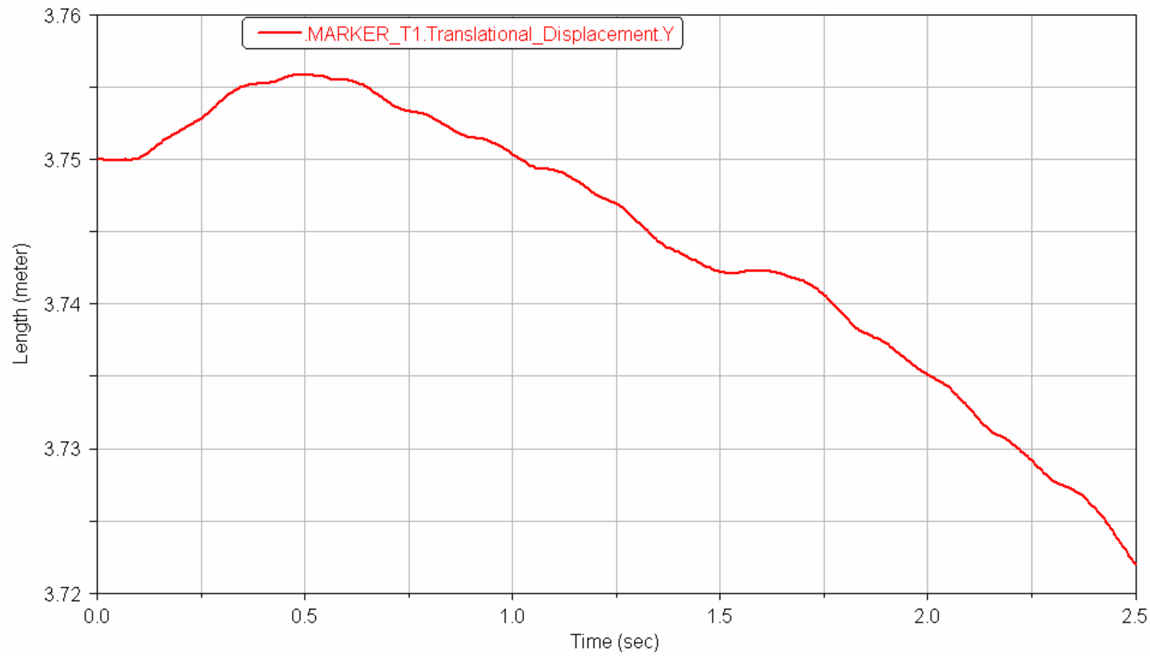

Figure 4-27 Actual displacement at transducer T1 in Y-direction

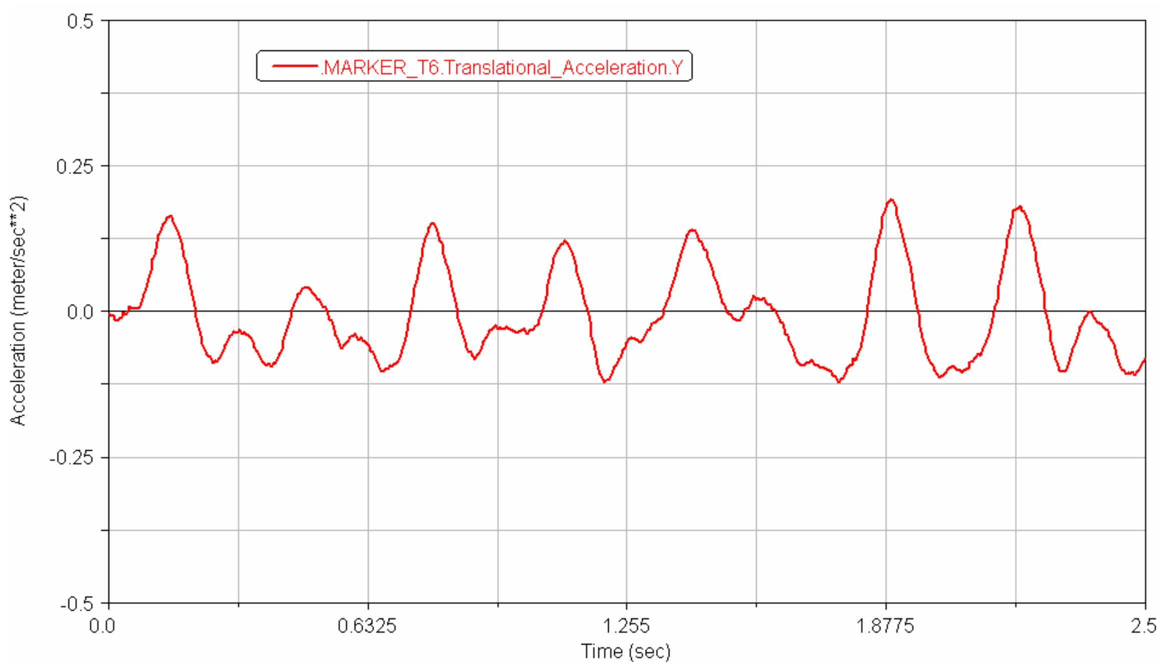

Figure 4-28 Acceleration predicted by T1 at transducer T6 in Y-direction

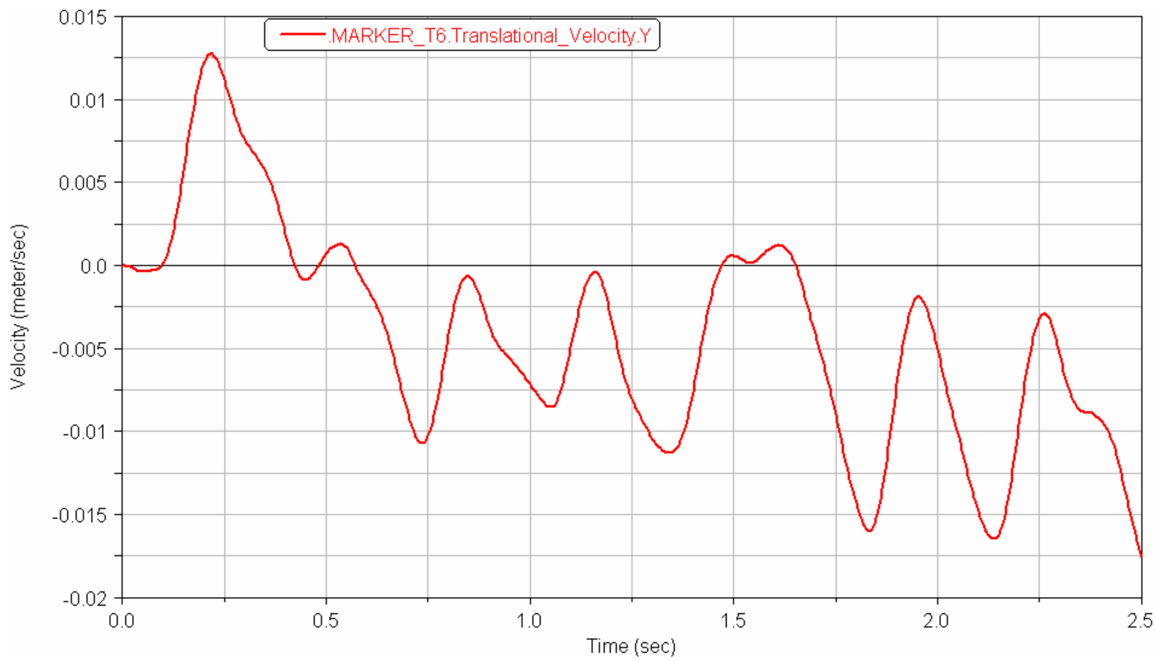

Figure 4-29 Velocity predicted by T1 at transducer T6 in Y-direction

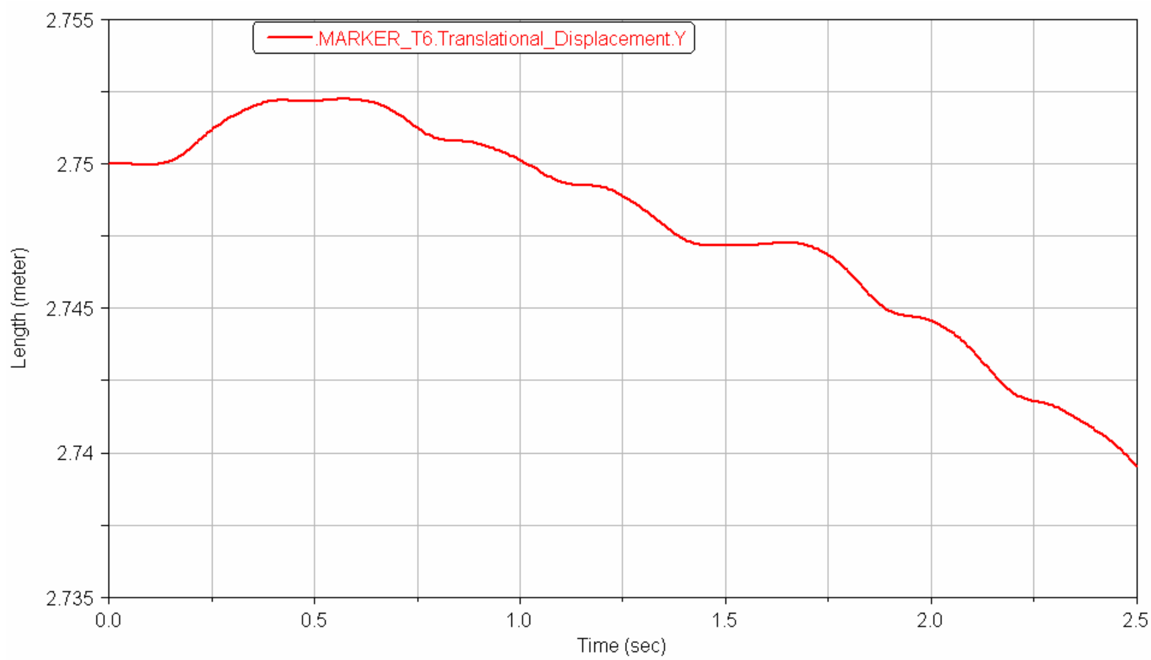

Figure 4-30 Displacement predicted at transducer T6 in Y-direction

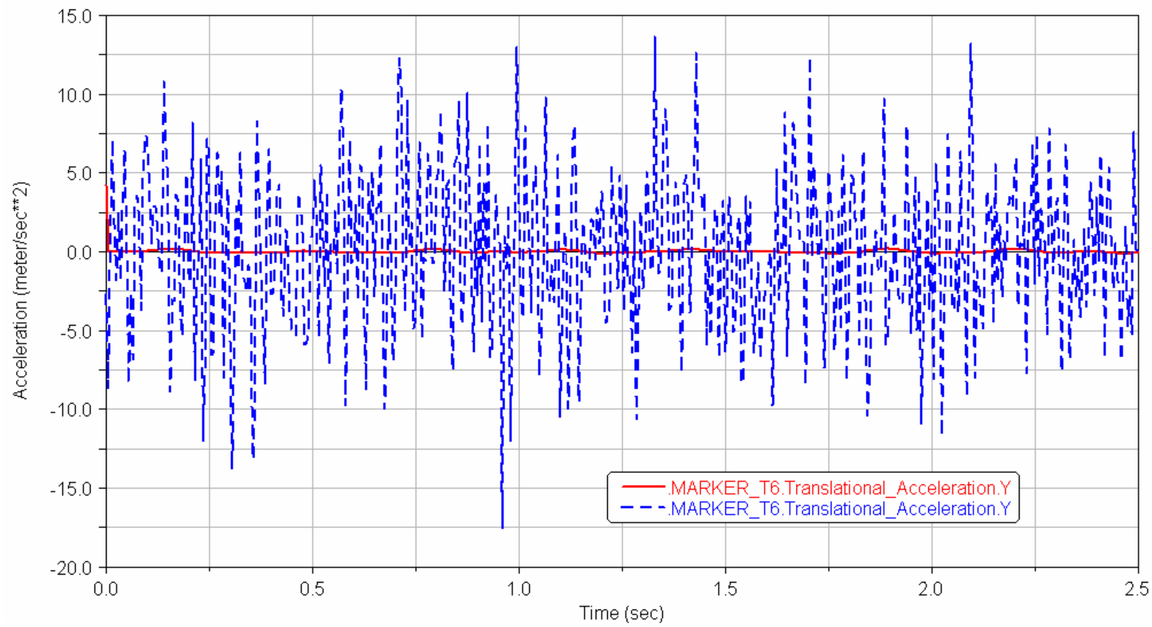

Figure 4-31 T1 as input predicts T6 (red) vs. Actual T6 data collected (blue)

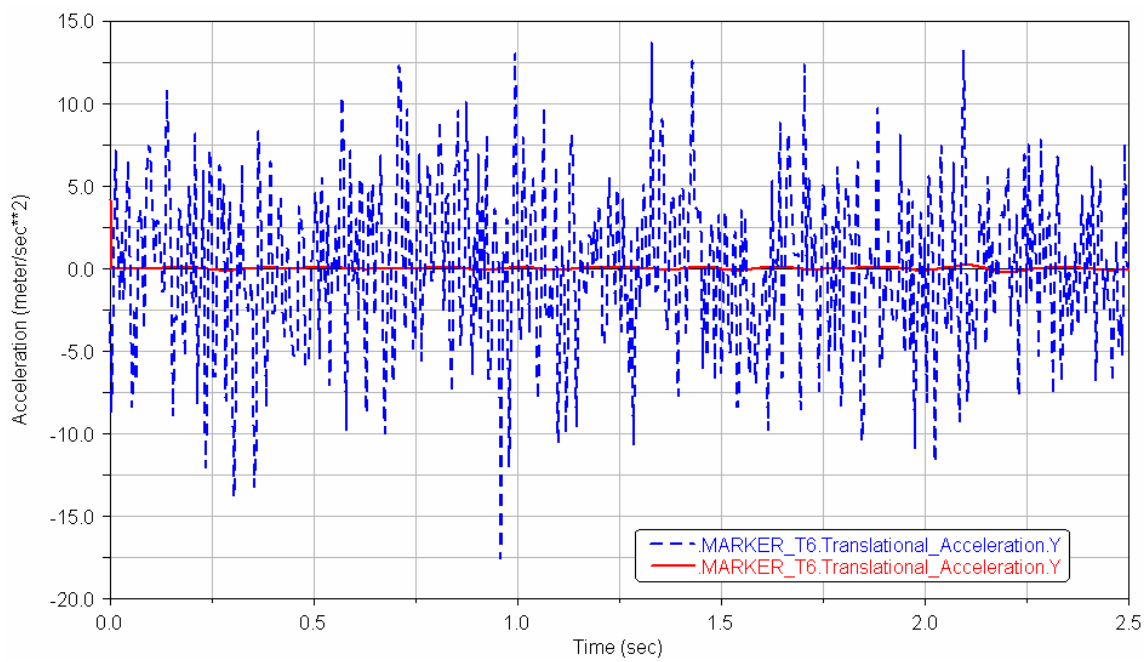

Figure 4-32 T1 and T3 predict T6, red vs. Actual T6 data collected, blue

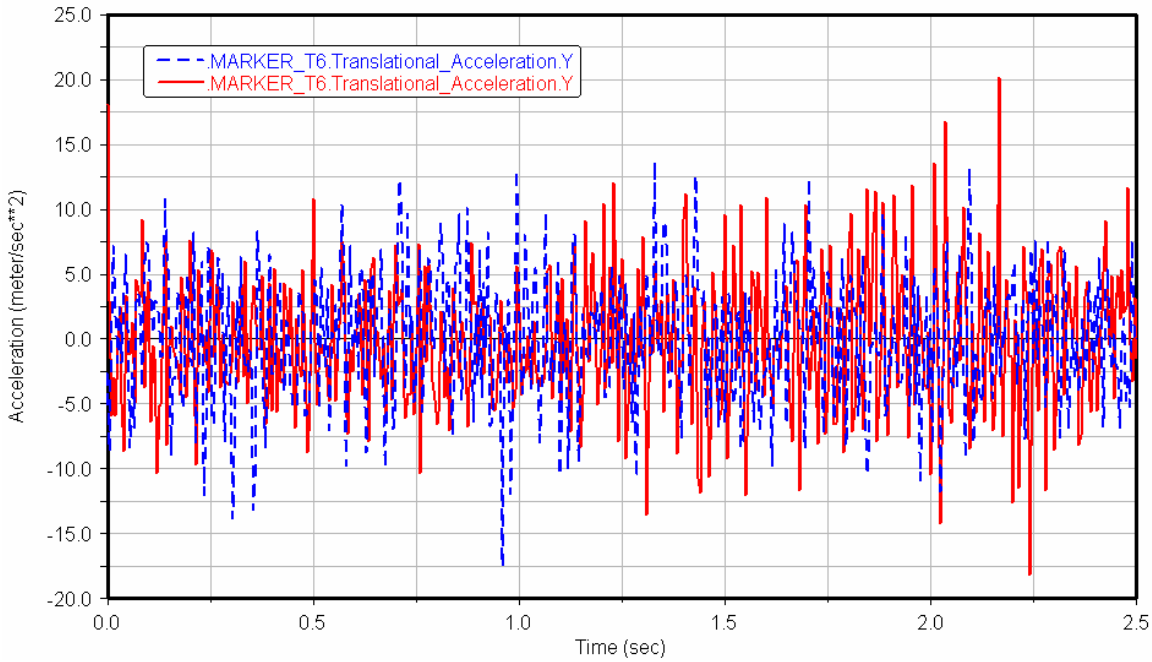

Figure 4-33 T1, T3 and T8 predict T6 (red) vs. Actual T6 data collected (blue)

4.2.3 Cab and frame predict tire vibration

Two simulations were completed using February 27, 2008, interstate data to analyze the response of the center of mass of the front driver tire when the transducers from the frame or the cab were "driving" the model. The data collected from T7, located on the frame, was used to "drive" the model to predict the acceleration of the front driver tire. Figure 4-34 shows the comparison. Also, the acceleration data of T2, located on the cab, was used to simulation the model and estimate the vibration at the front driver tire. Results can be seen in Figure 4-35.

4.2.4 Three-dimensional results

The data from February 27, 2008, were used to produce three-dimensional results. The basic model with a trailer was used for simulation. Since the motion sensors that were used previously only solve for one direction, two more motion sensors were added to each transducer in the X and Z direction, giving 18 total motion sensors. X, Y and Z data were recorded while in transit and imported separately to create 18 different splines. The data could then be simulated using any direction at any sensor desired. The results in the X and Z directions were similar to the results in Y direction, but with different magnitudes. These results can be seen in Appendix V. There are many different scenarios that could be analyzed using all of the data in the future with a more accurate model.

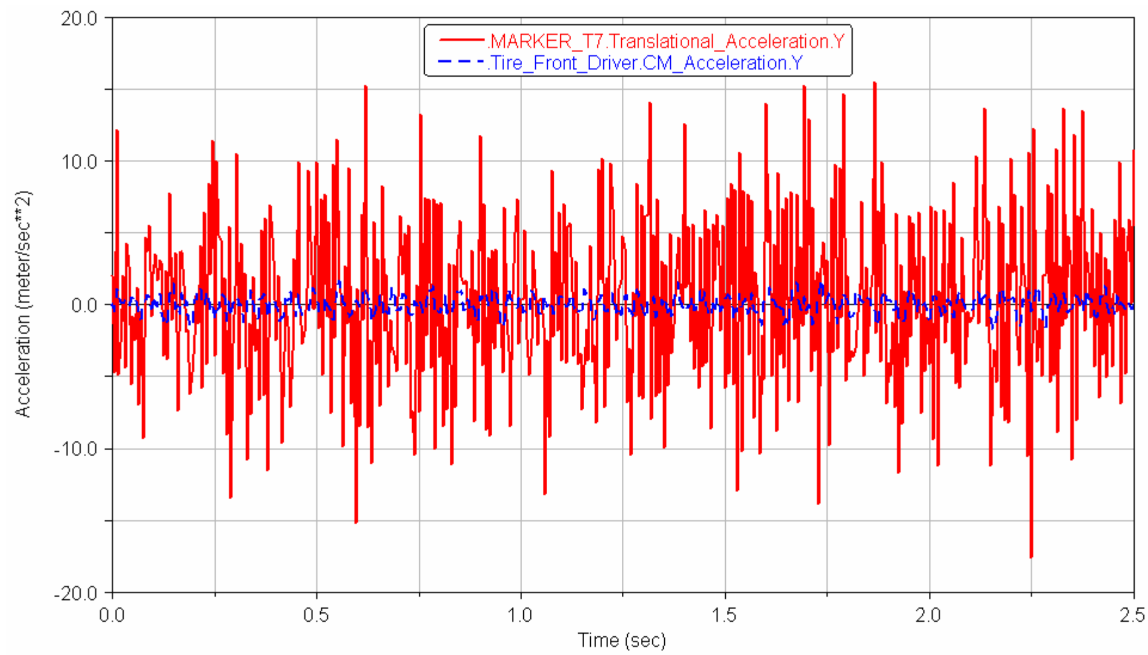

Figure 4-34 T7 actual acceleration (red) vs. Predicted front tire acceleration by T7 (blue)

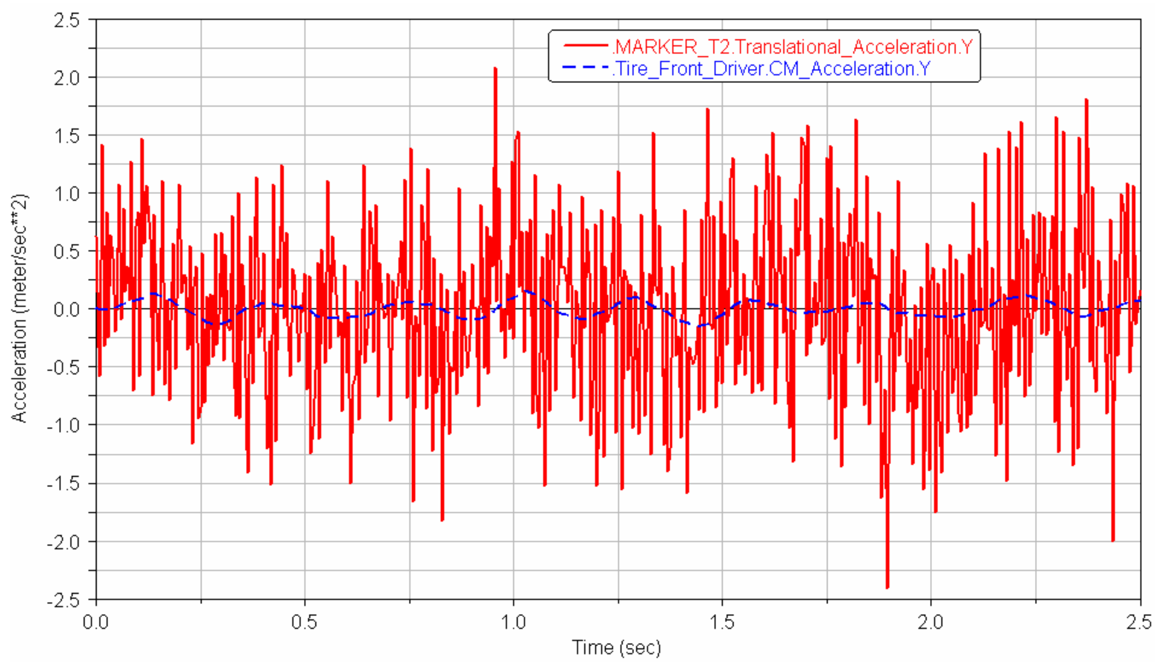

Figure 4-35 T2 actual acceleration (red) vs. Predicted front tire acceleration by T2 (blue)

4.2.4 Improvements

During the simulation of the November 20, 2008, test, using the basic HDDV model without a trailer, unusually high vibration predictions were noticed. The simulations were predicting vibration to be about three times the actual data measured. The displacement values were oscillating considerably more than the actual data collected. These high results of the acceleration and displacement of T1 predicted by T6 and compared to the actual data of T1 can be seen in Figures 4-36 and 4-38. The spring and damping coefficients were obtained by literature review. Both coefficients were then changed separately to gain improvement of the simulation. The spring coefficient was then decreased to improve the simulations. This, however, produced very similar results and did not improve the model. The damping coefficient was then increased to try to improve results. The damping coefficient was changed from six kNs/m to twenty kNs/m and the results improved significantly. The improved results can be seen in Figures 4-37 and 4-39.

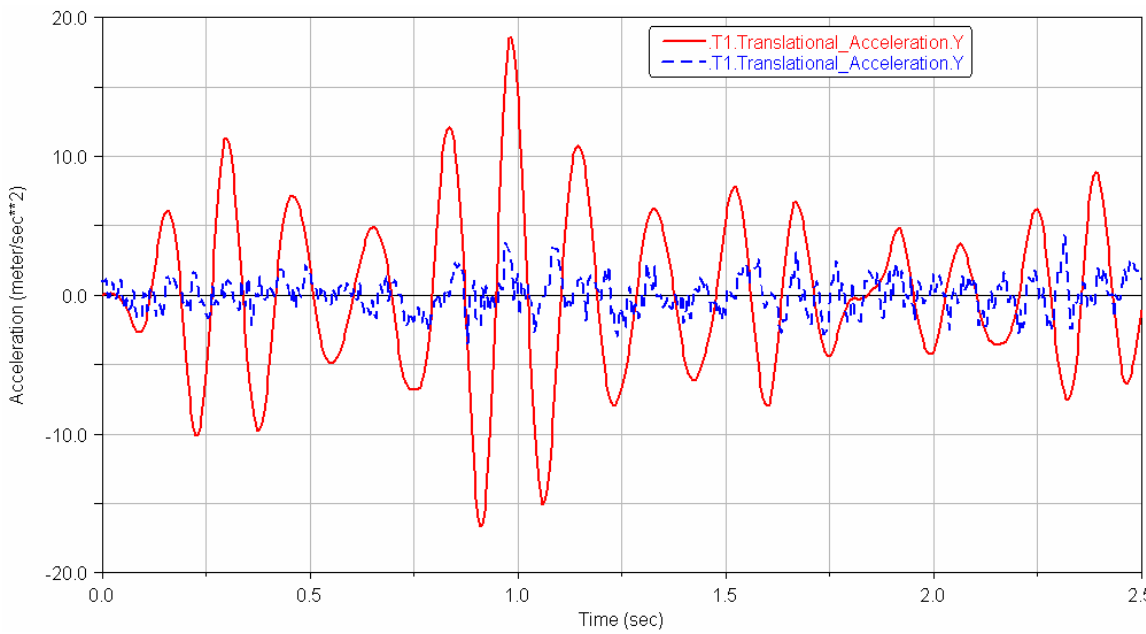

Figure 4-36 Actual acceleration at T1 (blue) vs. Predicted acceleration at T1 by T6 (red)

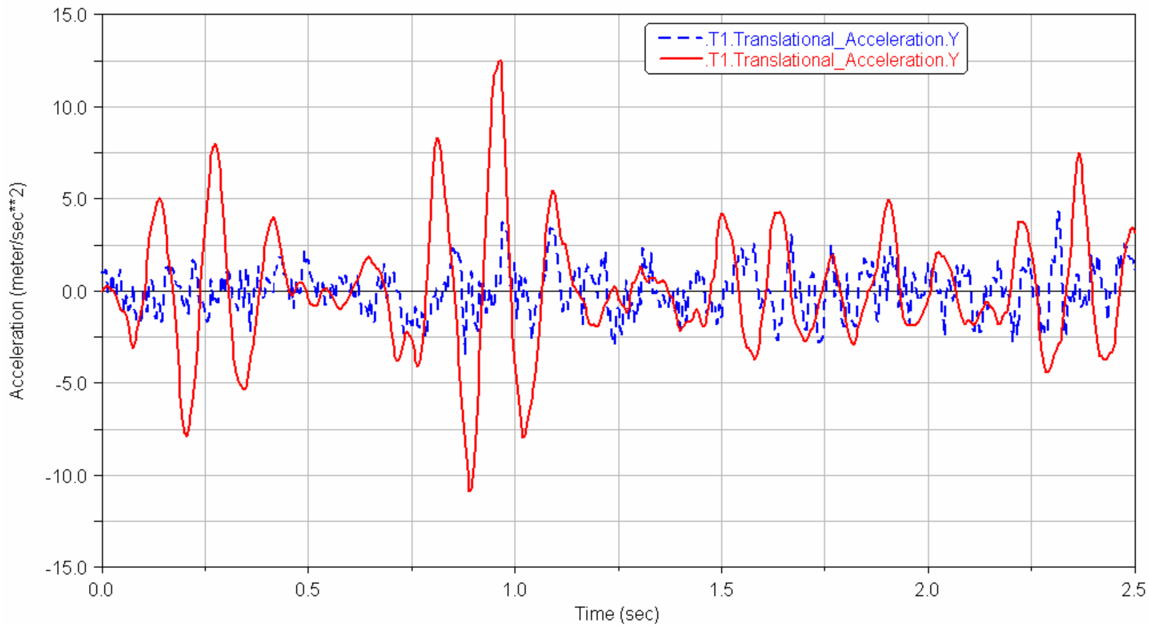

Figure 4-37 Actual acceleration at T1 (blue) vs. Predicted improved acceleration at T1 by T6 (red)

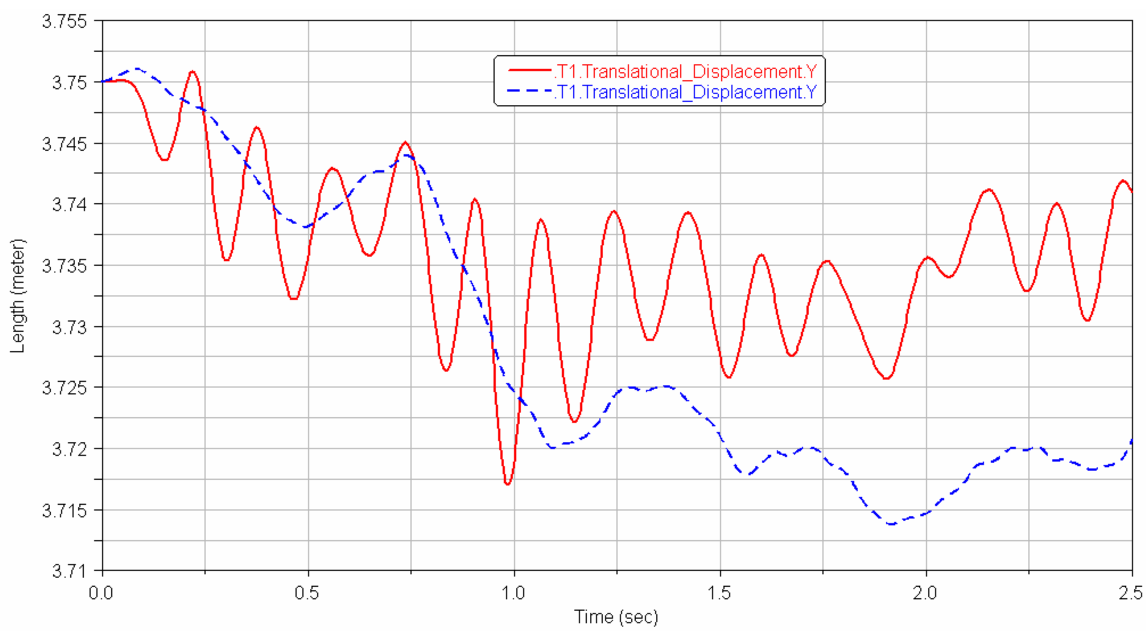

Figure 4-38 Actual displacement at T1 (blue) vs. Predicted displacement at T1 by T6 (red)

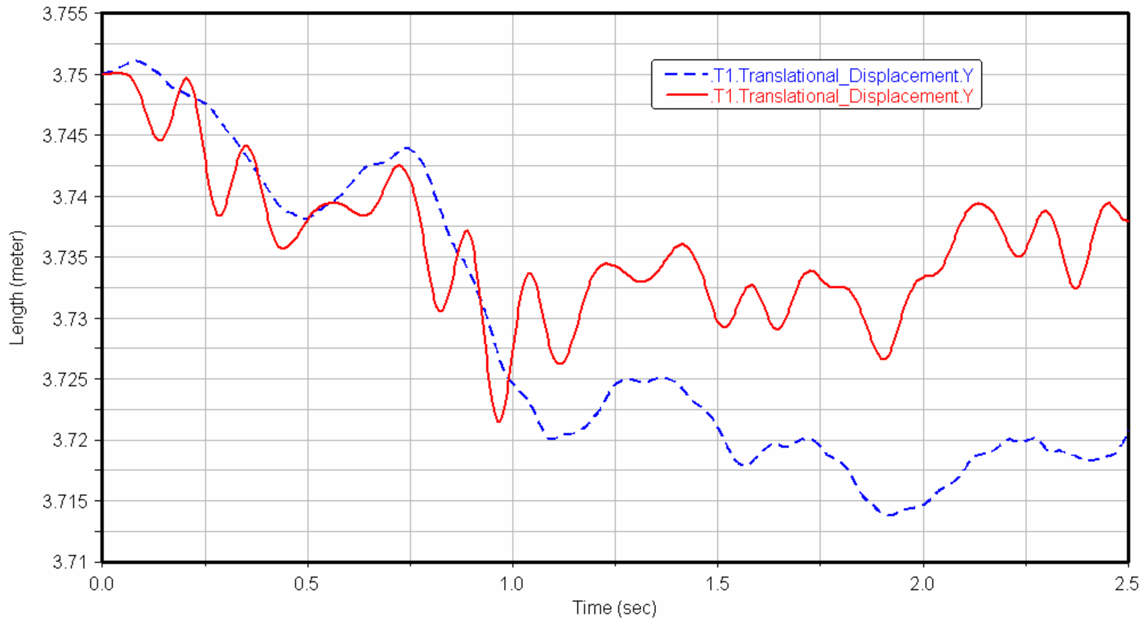

Figure 4-39 Actual displacement at T1 (blue) vs. Predicted improved displacement at T1 by T6 (red)

4.2.5 Sensor Placement

T6, T7 and T8 are each located on the frame. T6 and T7 are located equal distances on each side the frame, closer to the back of the truck, while T8 is located on the same side as T7, but closer to the middle of the truck. All three transducers were used separately to "drive" the model to predict the vibration at T1. These results can be seen in Figures 4-40, 4-41 and 4-42. The results show very similar predictions, which is desired, and lead to comparing each prediction at T1 to one another. The results can be seen in Figure 4-43. The predictions by each transducer give a calculated ninety-one percent correlation with one another. The transducers were then used to predict the vibrations at T2, which is located underneath the passenger seat. These estimations made by each transducer were compared and can be seen in Figure 4-44. These results showed the same high correlation and were very similar to one another. The results show that only one transducer on a body of interest is sufficient to model results using an extremely accurate model in a MBS/FEA simulation package.

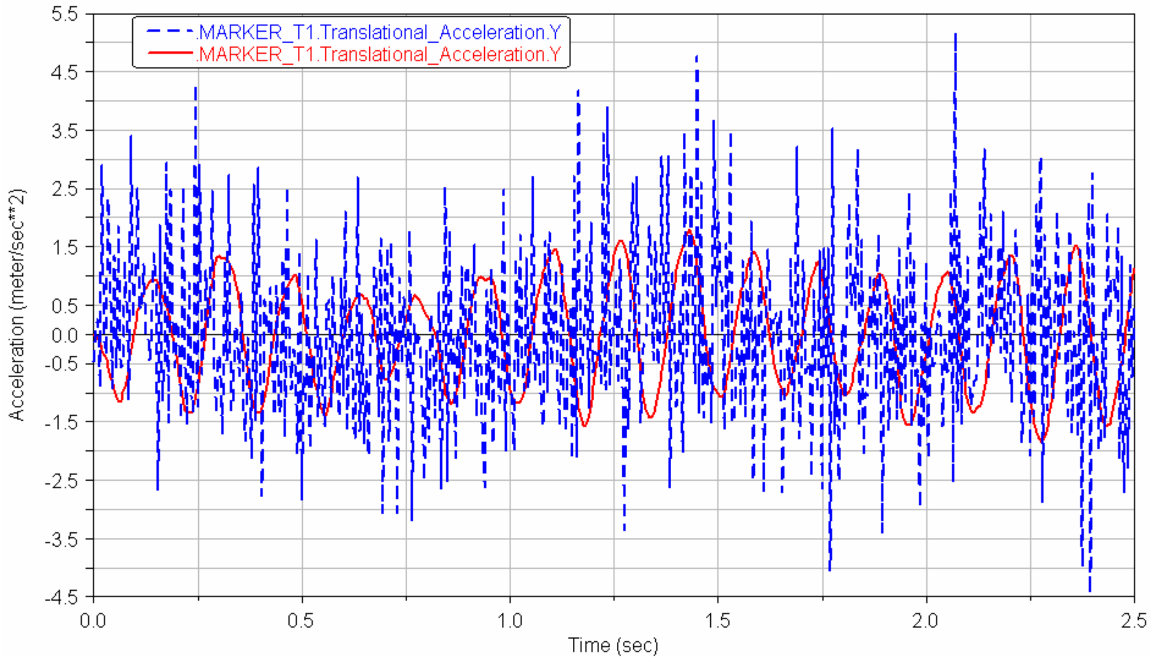

Figure 4-40 T6 predicts acceleration T1 (red) vs. Actual acceleration at T1 (blue)

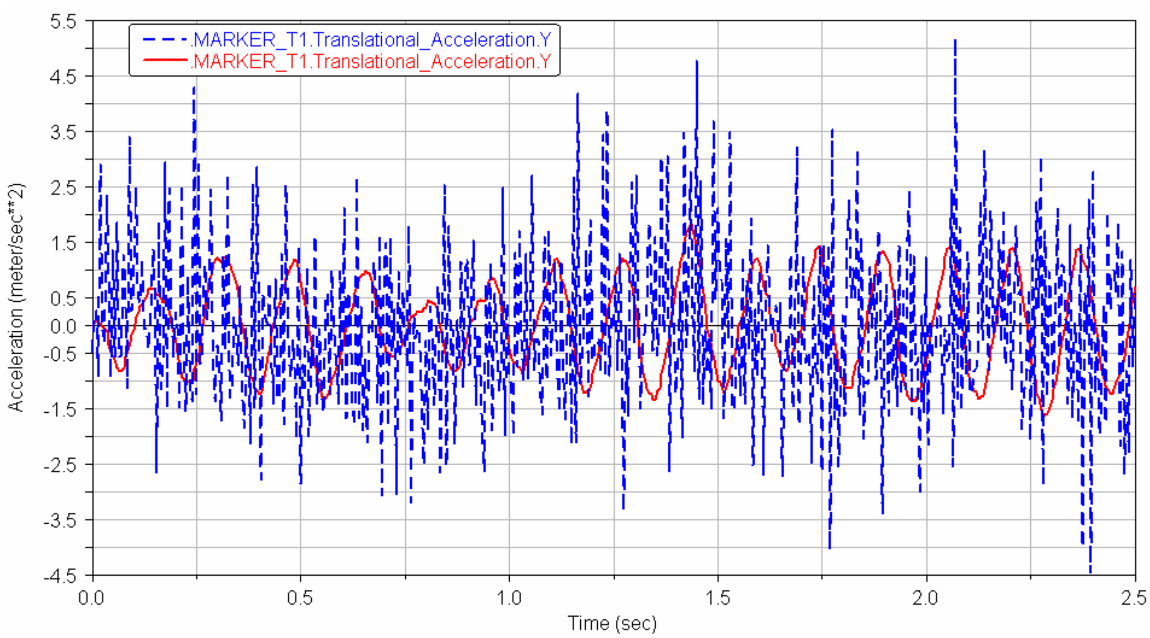

Figure 4-41 T7 predicts acceleration T1 (red) vs. Actual acceleration at T1 (blue)

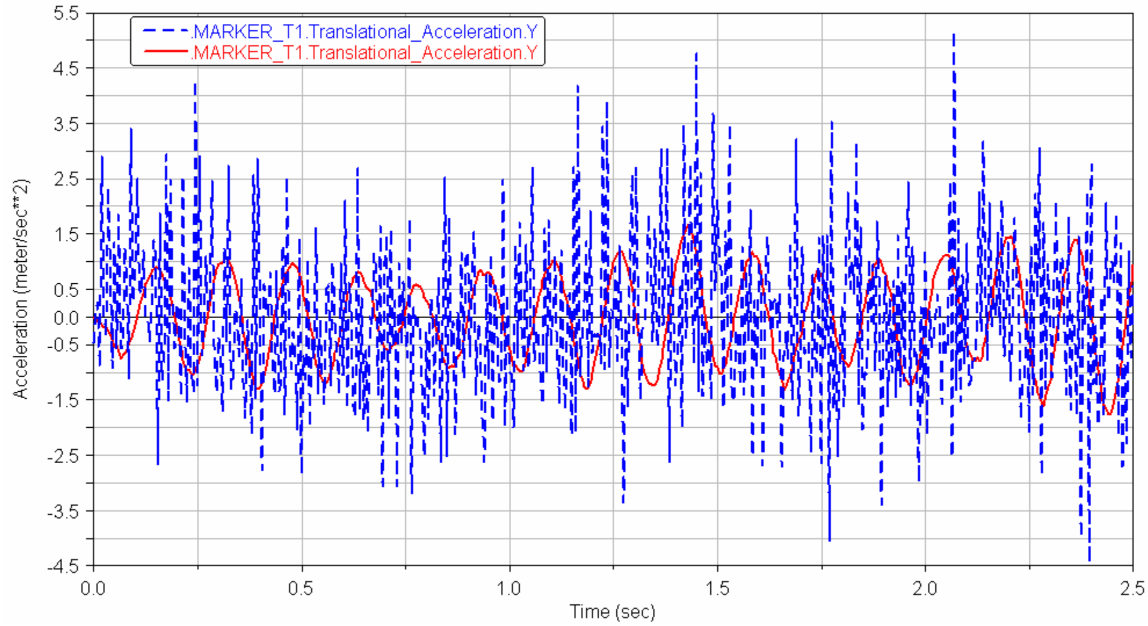

Figure 4-42 T8 predicts acceleration T1 (red) vs. Actual acceleration at T1 (blue)

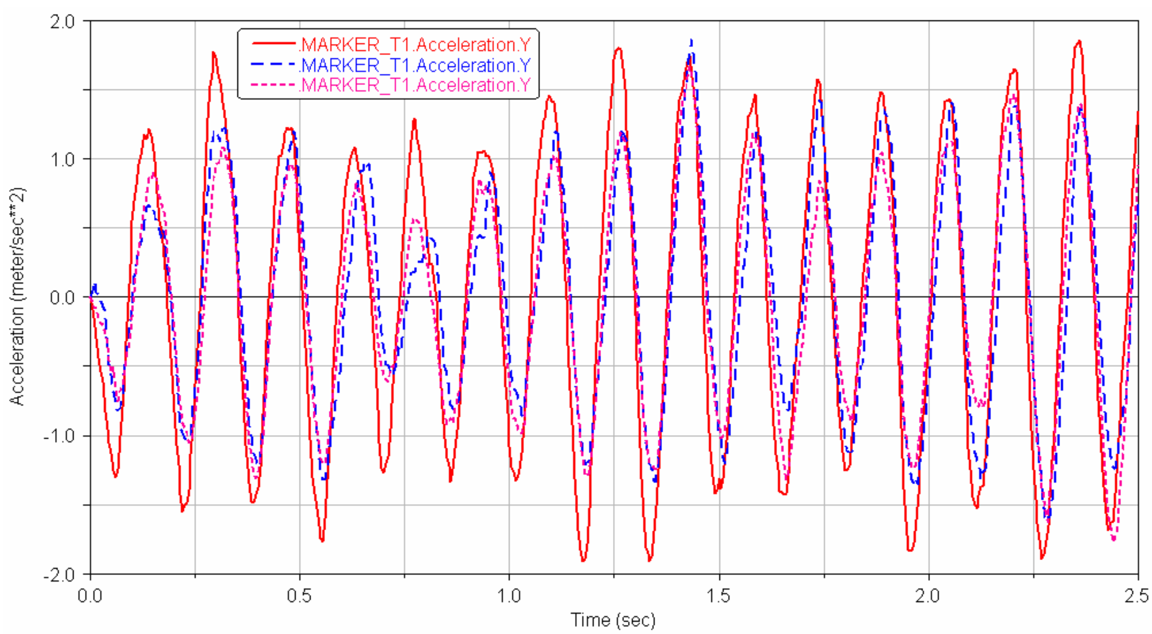

Figure 4-43 T6 (red) vs. T7 (blue) vs. T8 (pink) predicting acceleration at T1

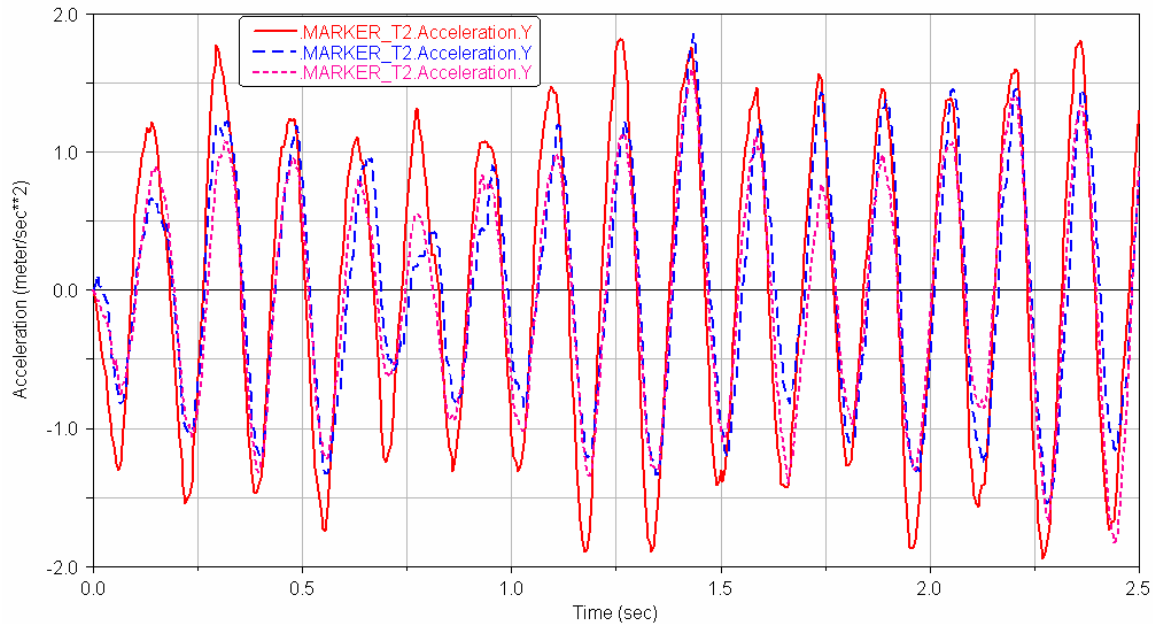

Figure 4-44 Figure 4 32 T6 (red) vs. T7 (blue) vs. T8 (pink) predicting acceleration at T2

Chapter 5 Conclusions and recommendations

Twenty-two trucks were compared on the same interstate and rural roads, while five of the trucks were modeled and analyzed using Adams software. The results were analyzed to compare each manufacturer at the source of vibrations directed at the driver and to help give an understanding of how the vibration is transferred to the cab. Also, models were designed to be able to simulate responses and predict vibrations anywhere on the HDDV. The following conclusions can be drawn from the present study.

1. US-27 and I-75 N show similar vibration results.

The analysis of the rural roads of US-27 and the interstate roads of I-75 showed very similar results for each road type. As mentioned above, this was expected because the total vibrations of the two road types were not considered significantly different, while vibrations on the interstate roads of I-40 were considered significantly lower than US-27 and I-75. The road condition of I-75 was considered very rutted, which could explain the reason for the higher vibration levels and the similar results as US-27. The roadway is a major contributor to the vibrations experienced in the cab.

2. At the floor underneath the driver seat, there were significant differences in the levels of vibration experienced by trucks from different manufacturers.

Manufacturers A and B showed significantly higher vibrations underneath the driver seat in the Z direction than Manufacturers C and D. Also, Manufacturer A demonstrated higher vibration results in the Y direction than all of the tested manufacturers. Manufacturers C and D showed the lowest amount of vibration measured on each road type. If the mechanical properties of each truck tested have been available, the models could have been used to develop recommendations for reducing the vibrations for each type of truck. However, during the data collection phase, it was noticed that Manufacturers A and B had several features that probably increased the vibration in the cab. Figure 5-1 shows a spring-damper used to dampen vibrations of the cab used by Manufacturer A, while Figure 5-2 shows a typical spring-damper used with Manufacturers C and D. The spring-damper used with manufacturer A is probably one of the reasons why there are higher vibrations vertically and side to side. Figure 5-3 shows the frame of one of the Manufacturers B tested. It was recorded that Manufacturer B was the only vehicle maker tested that had the braces connect to the frame and the axle. The brace probably stiffens the frame and could be the reason that manufacturer showed the highest vertical vibrations.

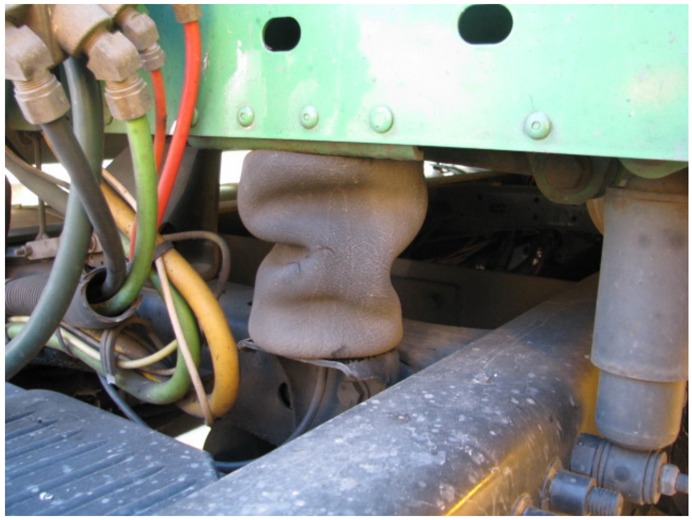

Figure 5-1 Cab spring-damper from manufacturer producing significantly higher vibrations

Figure 5-2 Cab spring-damper from manufacturer producing significantly lower vibrations

Figure 5-3 Frame of manufacturer producing significantly higher vibrations

3. Adams can be used to model detailed dynamic behavior and make improvements of HDDV.

Animations, plots and tables were made using the simulations performed in Adams. Adams is capable of measuring accelerations, velocities, displacements, forces, deformations and torques. Also, changes can be made on existing models, by changing stiffness or damping coefficients, adding or removing parts or changing the material in Adams to improve design of HDDV, which can reduce the exposure of WBV to the driver.

4. Vehicular models created in Adams can be “driven” by acceleration data taken from tests of real trucks.

Importing acceleration data in tab delimited text files into Adams allows the data to be used with motion sensors or actuators to “drive” the model. This is the source of motion that oscillates the desired body and can be simulated.

5. Vehicular models created in Adams were not shown to produce valid simulations of tested trucks.

Because the mechanical properties of the components of the tested truck were not available, the basic model does not simulate the tested truck. Hence, one should not draw conclusions from either the similarities or the differences between the comparison curves of actual data and predicted data. But the process by which comparisons were created could be used to validate an Adams model of a tested truck, if such a model were available.

6. Tire data is needed to “drive” the whole model.

Although not accurate, the transducers of the frame predicted acceleration, velocities and displacements using the basic model in the same range of the actual data collected at the cab. However, the transducers from the cab predicted very inaccurate results of the frame compared to the actual data from the frame, and the same with the frame and the cab predicting the tires. The reason for the inaccuracy is that the vibrations recorded at the cab have been dampened. The frame also has been dampened by the suspension, which results in inaccurate results at the tires. The frame can be used to “drive” the model to predict the frame, but tire transducers are needed to “drive” the whole model.

7. Only one transducer for each body of interest is needed for modeling.

The transducers that were located on the frame of the basic models predicted similar vibration at the cab during simulation. These results had high correlations and predicted the same accuracy at two different locations in the cab. Each transducer used different data that was collected to simulate the model and predict the vibrations. These results indicate that only one transducer is necessary for modeling and simulating each body of interest.

8. Modeling results are more accurate using transducer data on the body of interest.

The predictions of vibrations were inaccurate, but significantly improved if the prediction used data from the same body of interest. The frame predicting cab results were most accurate when cab data was combined with frame data. The cab was unable to predict frame vibrations unless data from the frame were used.

The following are recommendations for future work from this study.

1. Transducers should be placed on each axle.

It is recommended that if the test were repeated to put ten transducers on the tested HDDV, two on each axle on the passenger and driver side. The reason for two on the axles is because of the contact points of the tires and the changes in the road. Figure 5-4 shows the recommended transducer placement. The transducers recording at the axle will give road data and also all produce more accurate modeling results. If the model has very accurate mechanical properties, the transducer data from the axles is probably the only data needed to “drive” the model.

Figure 5-4 Recommended transducer placement on axle

2. Transducer should be placed on the sleeping bed while idling.

Transducer placement is very important for the accuracy of the model. However, it could also be important for other studies in the future. There has not been research conducted on the vibration exposure to the truck driver while sleeping in the cab of the HDDV. So it is recommended that a transducer be placed on the bed inside the cab of a HDDV, especially while idling. The HOS regulation only allows limited amounts of driving to increase the safety of the drive. However, drivers tend to sleep in the truck while idling, which causes the drivers to be exposed to WBV while driving and sleeping. This may be a very important area that has yet to be studied, and could be potentially helpful to driver's safety.

3. Validate the model using Adams.

Given mechanical specifications for the tested trucks, it would be possible to validate computer-based models of those trucks. Those models could then be "driven" over any virtual terrain or roadway that is of interest, and be put through any maneuvers that are of interest, to assess the trucks' performance. This process would likely be far less expensive and time consuming than physical testing of trucks. In time, computer-based simulations of HDDV could become an efficient and effective tool in assessing and optimizing the design and performance of HDDV.

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Appendix I: November 5, 2008 road test modeling results

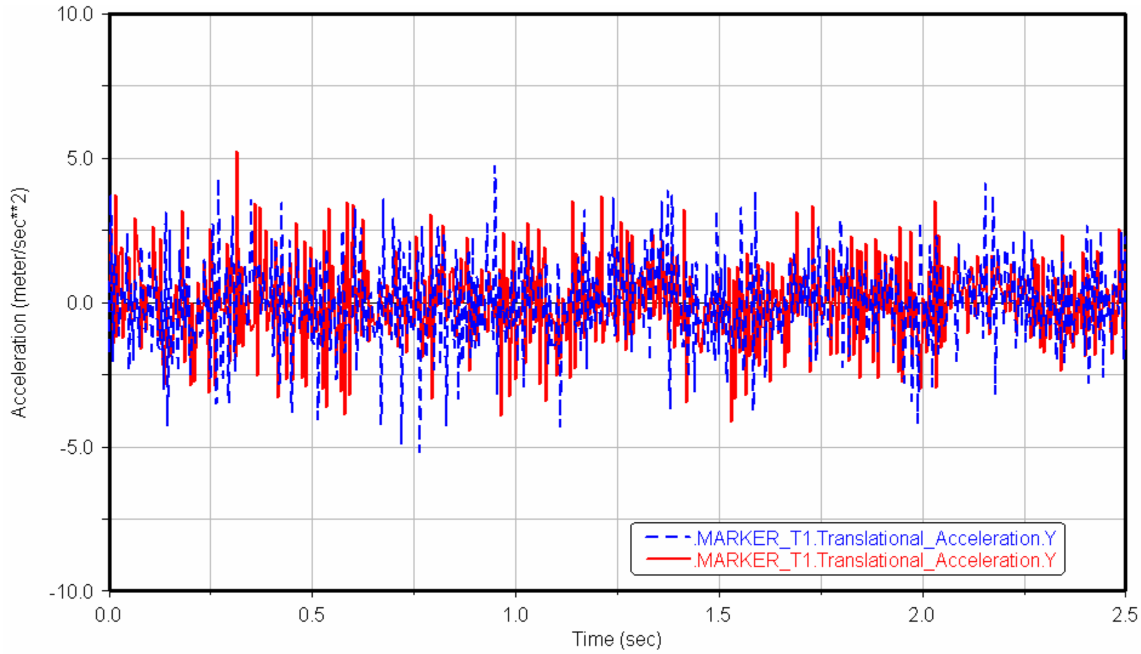
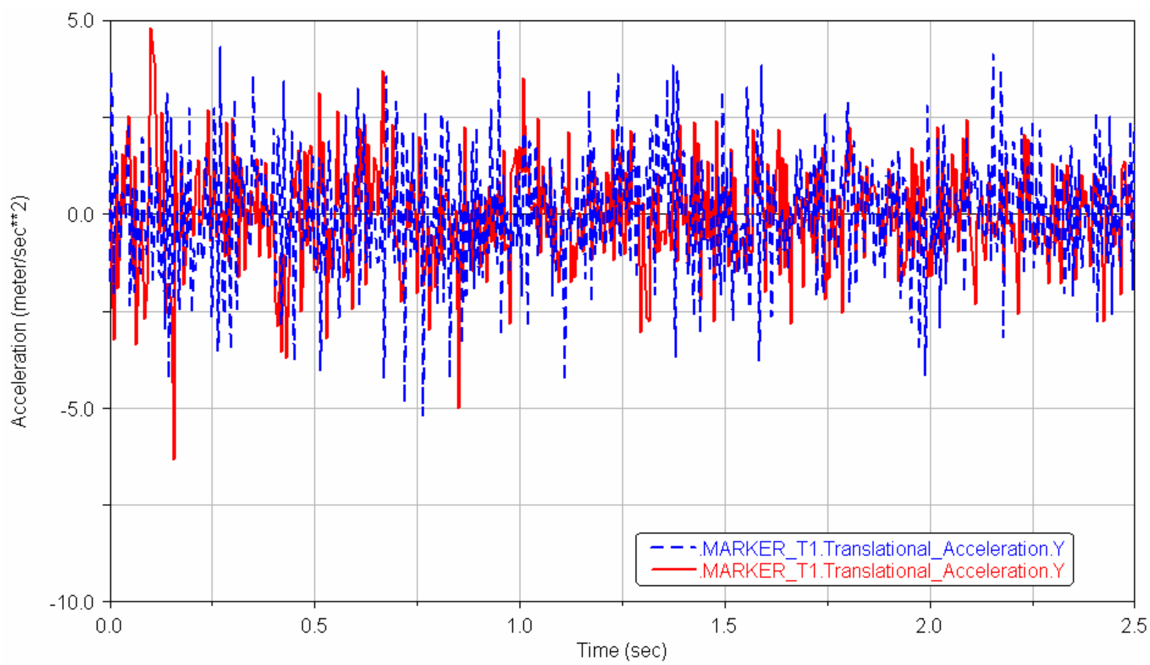


Figure A1-1 Interstate T2 predicts T1 Nov 5, 2008



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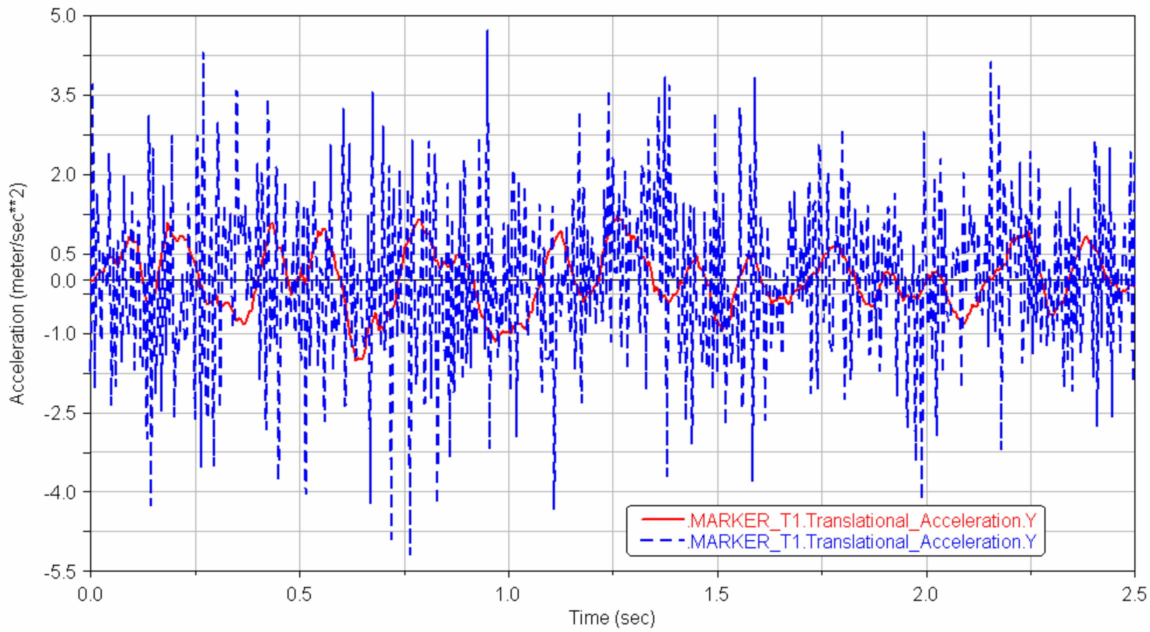

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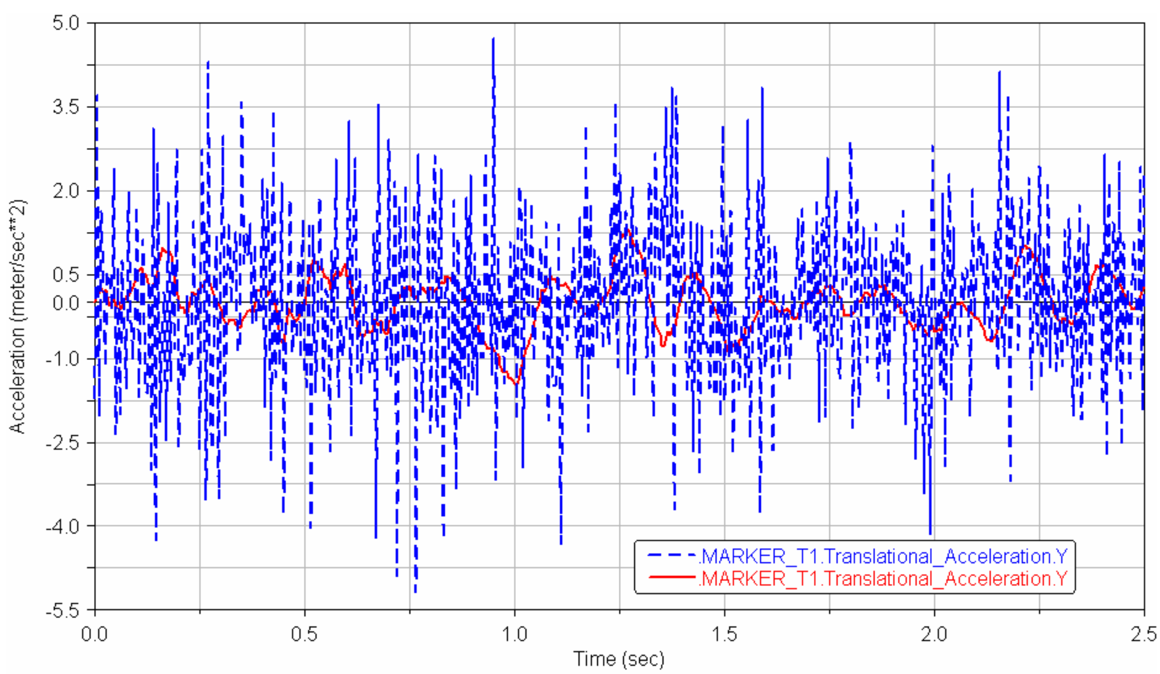

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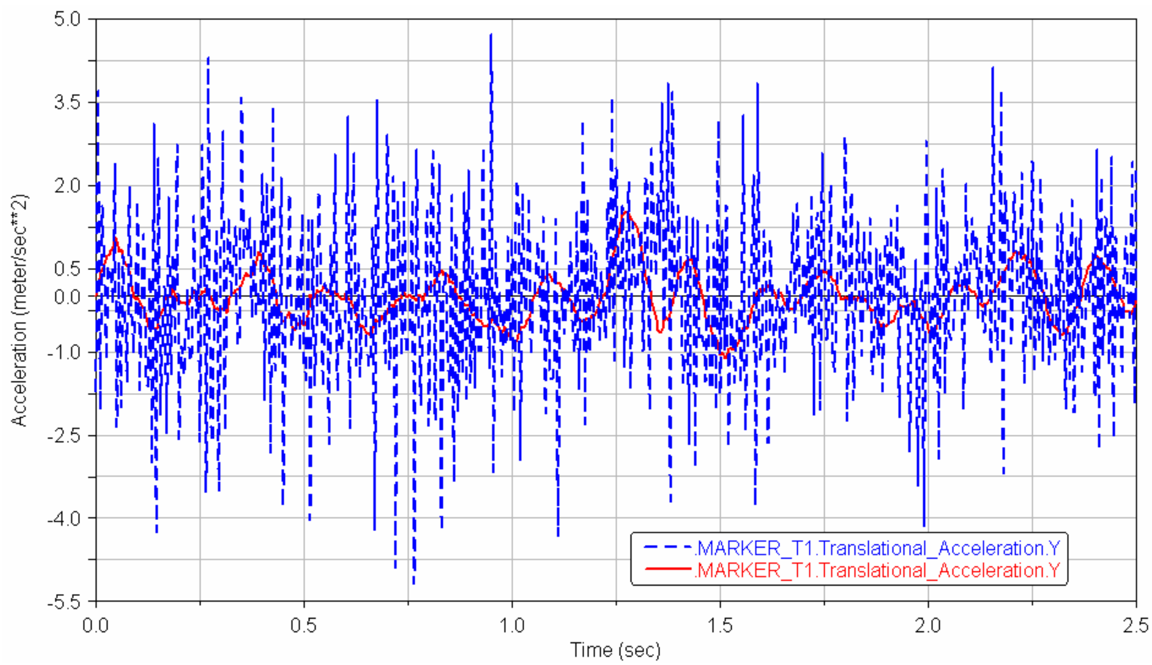

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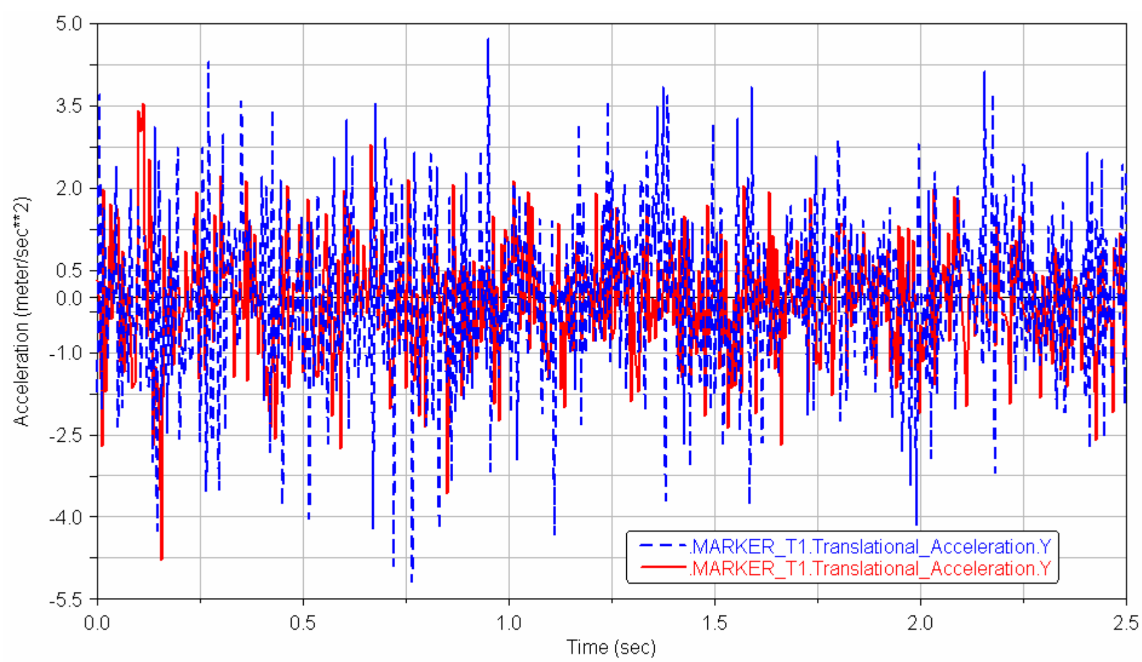

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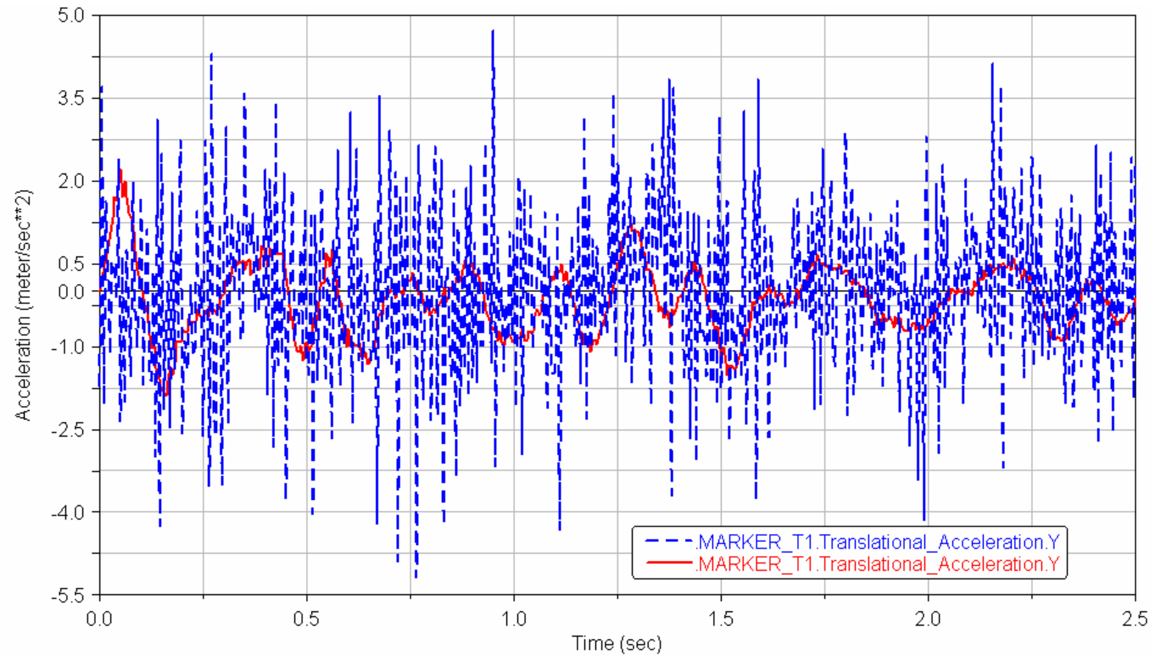

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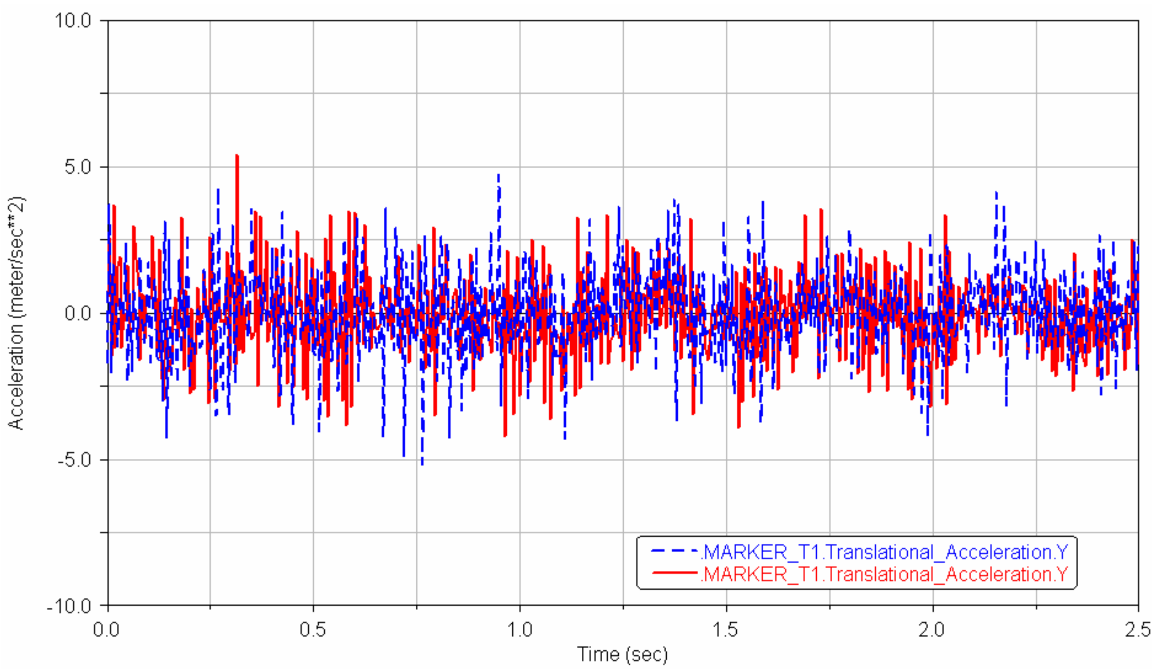

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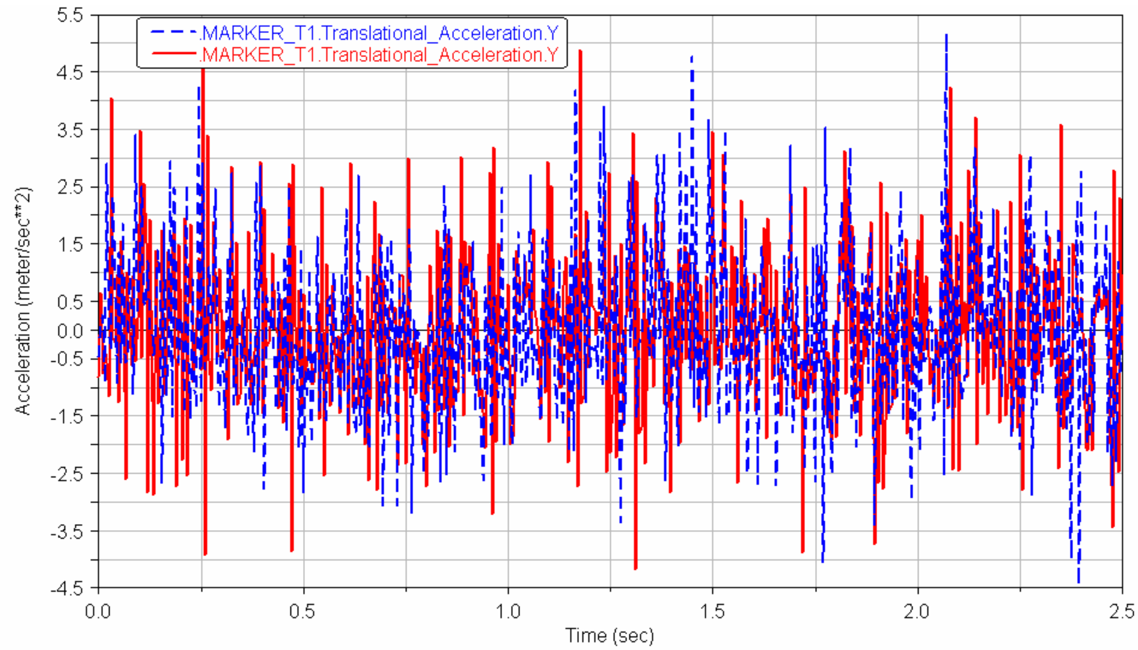

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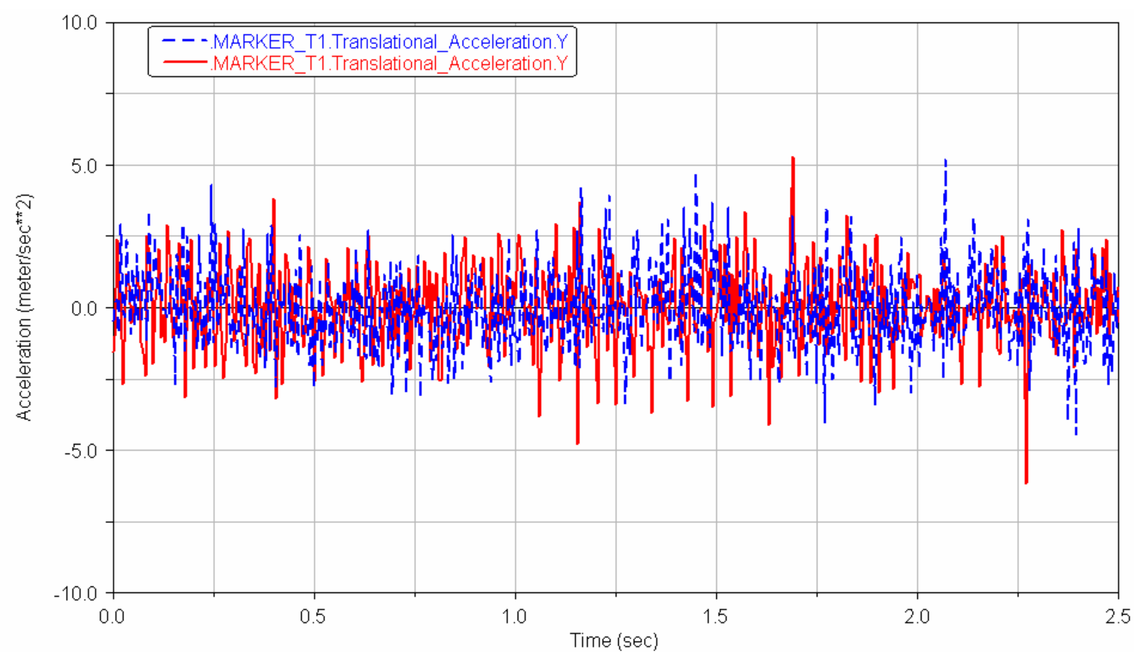

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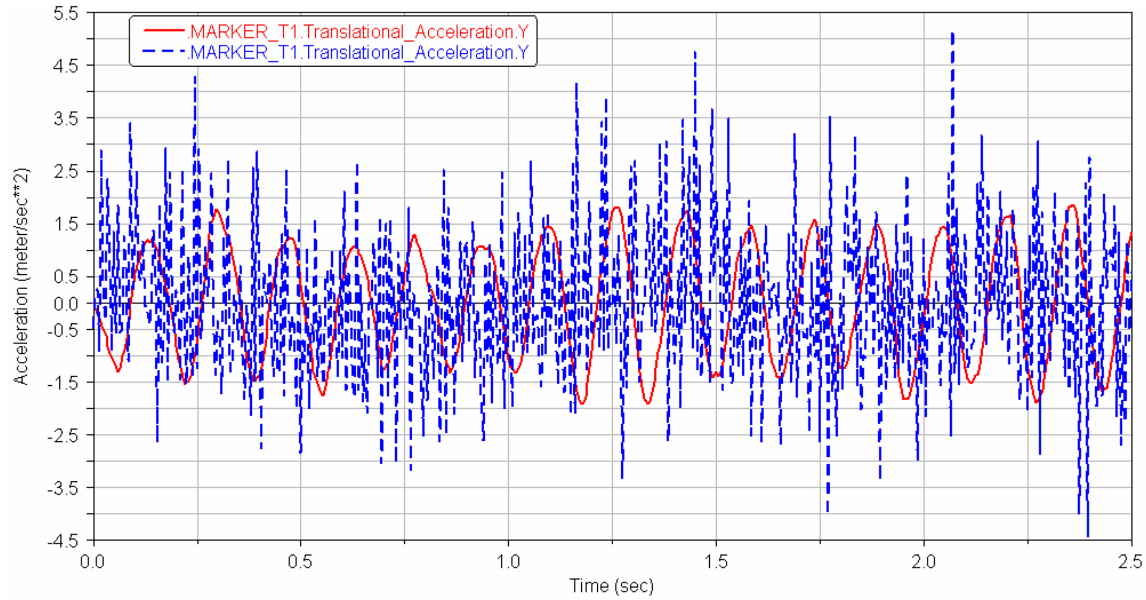

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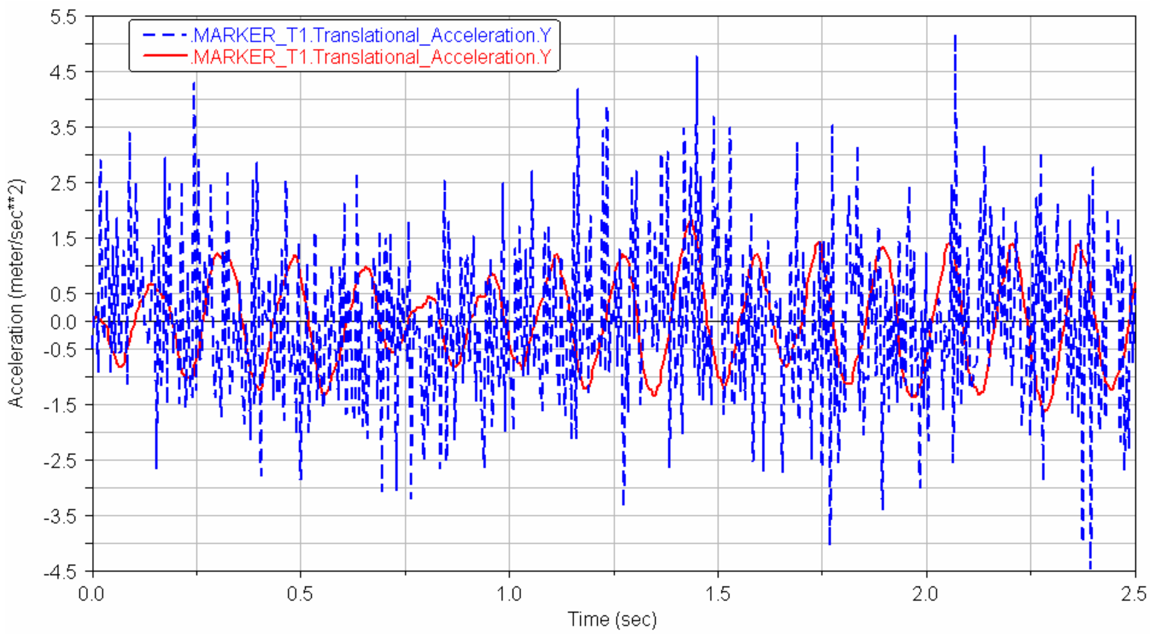

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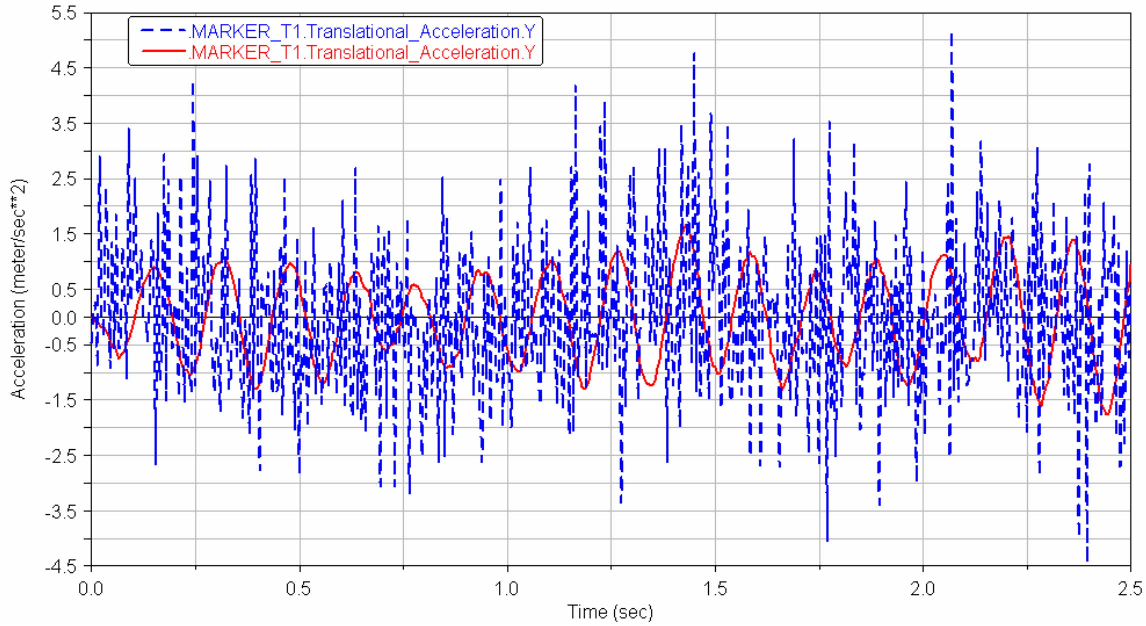

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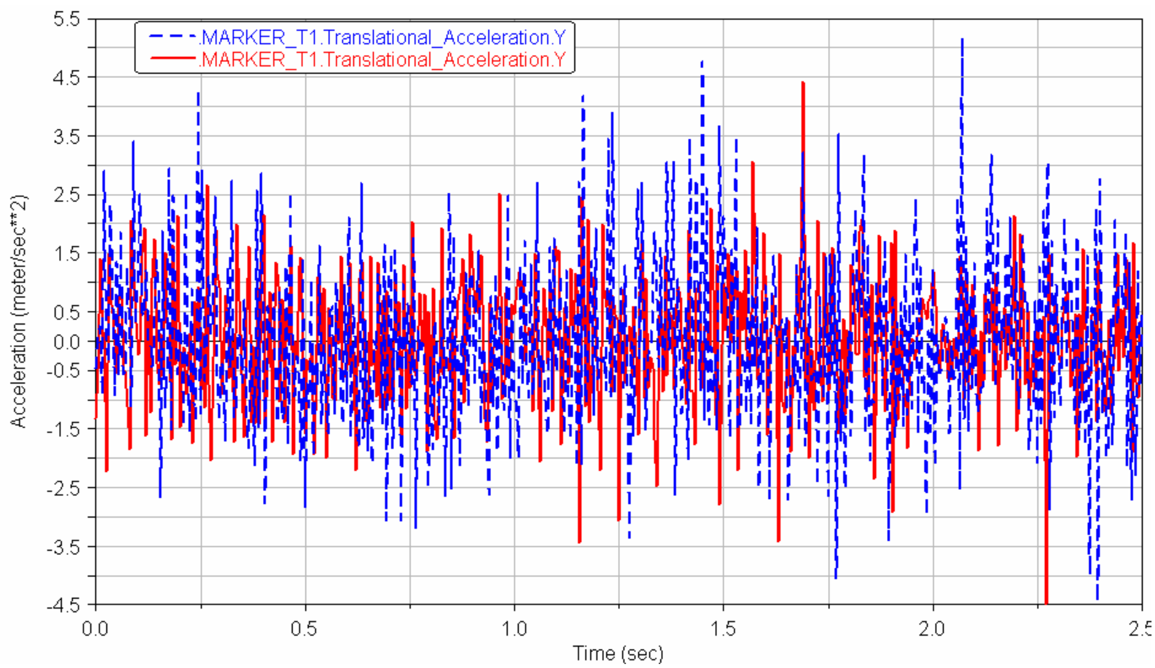

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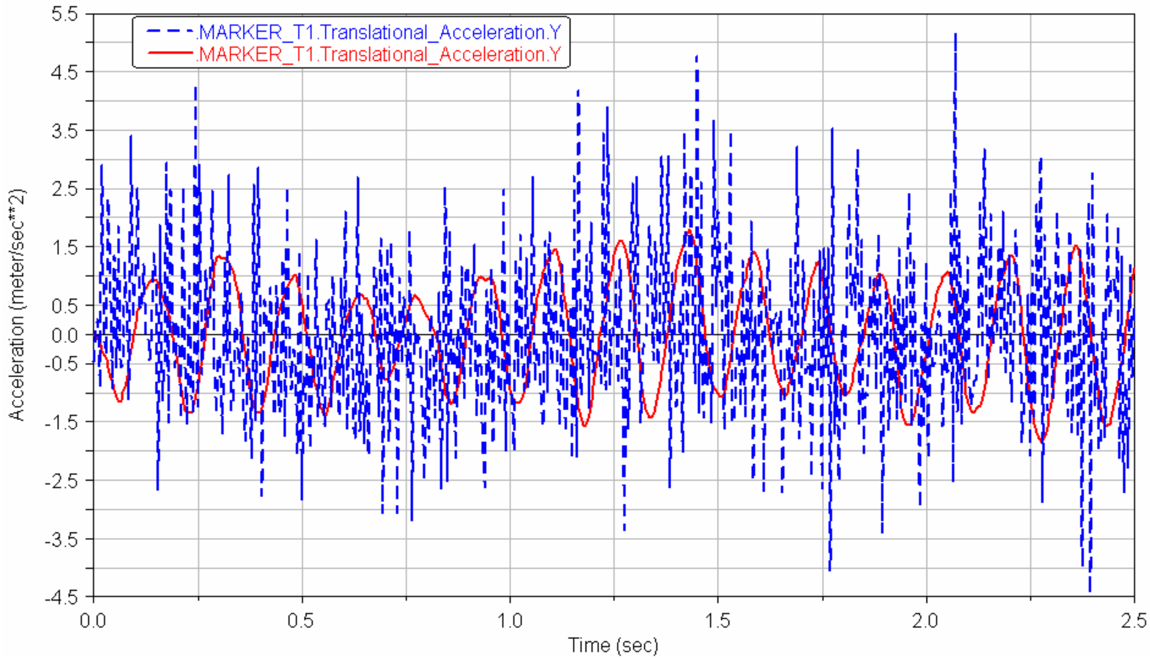

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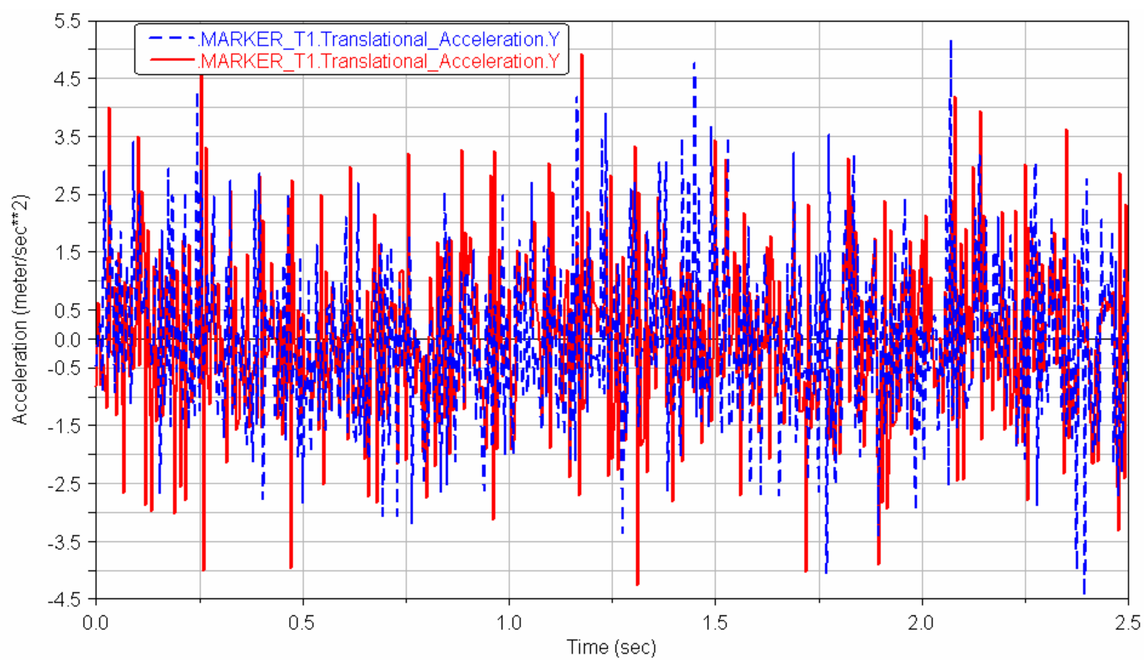
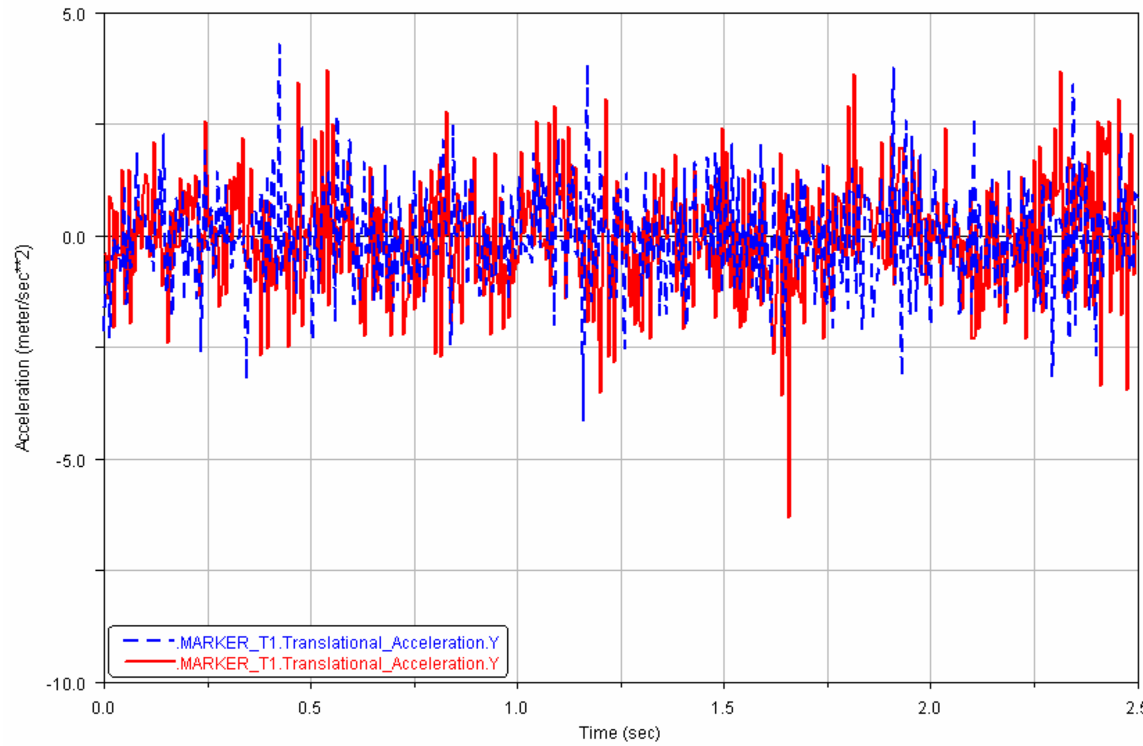


Figure A1-16 Rural T2, T6 and T7 predict T1 Nov 5, 2008

Appendix II: November 21, 2008 road test modeling results



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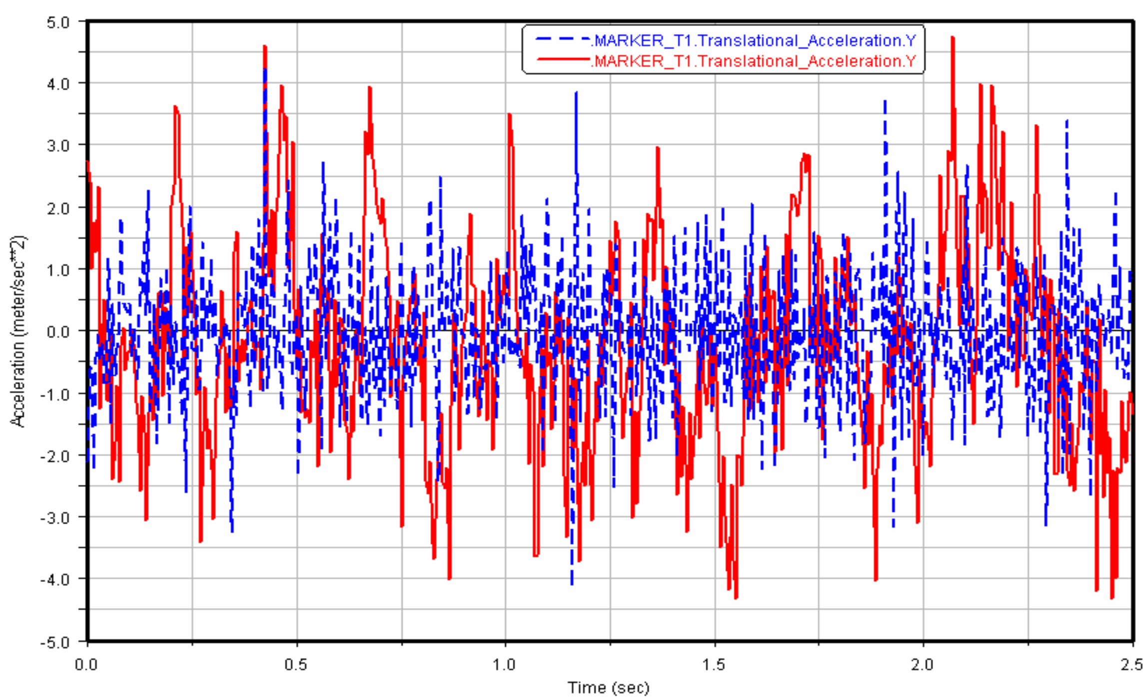

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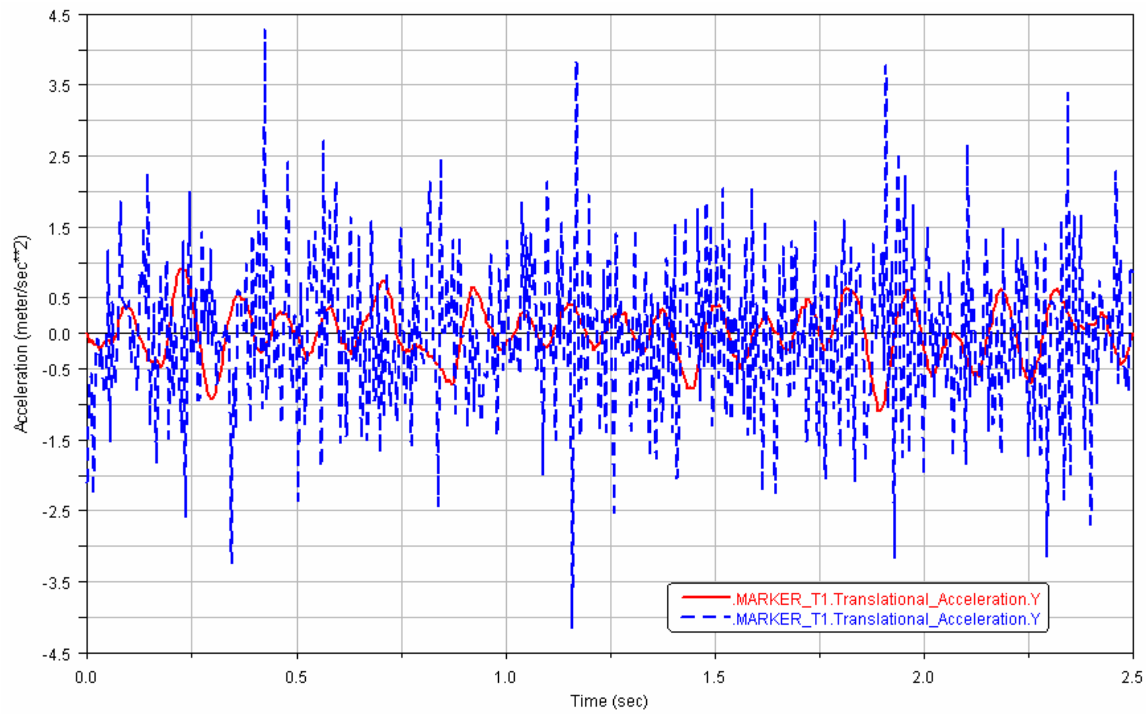

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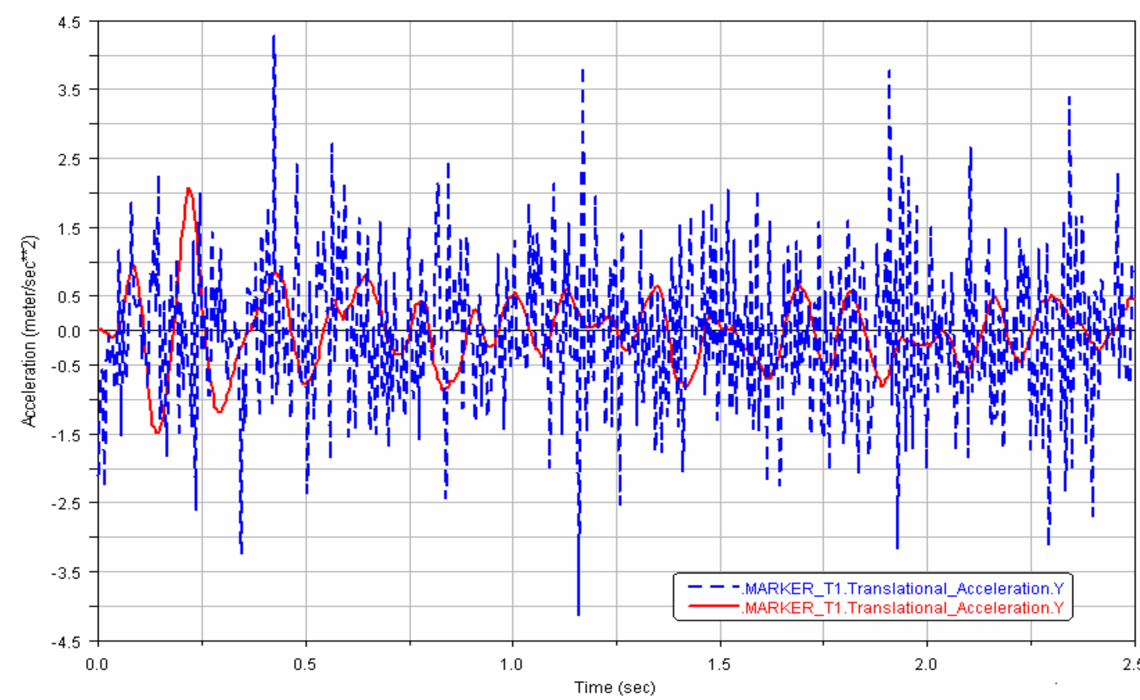

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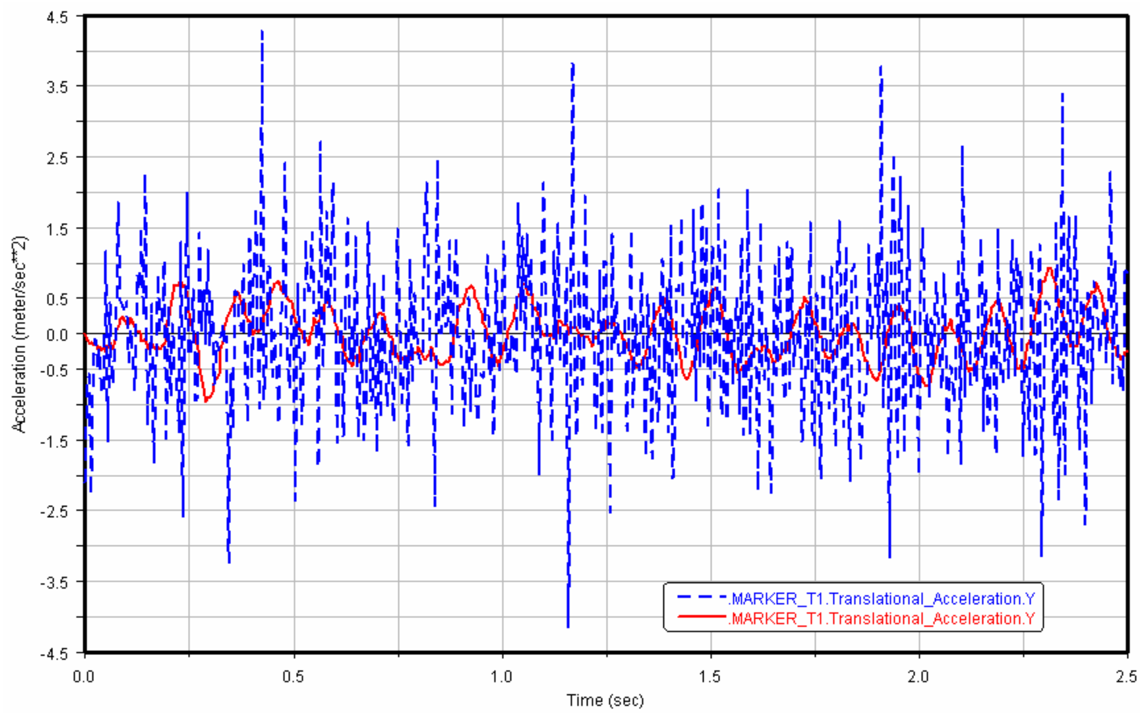

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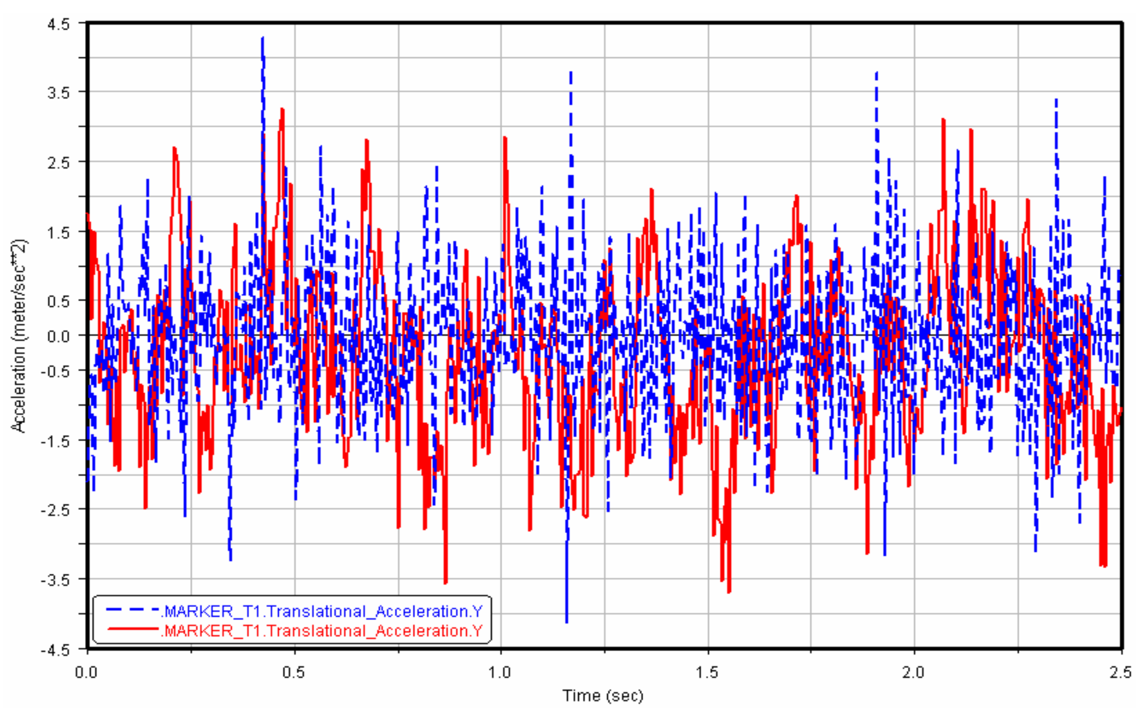

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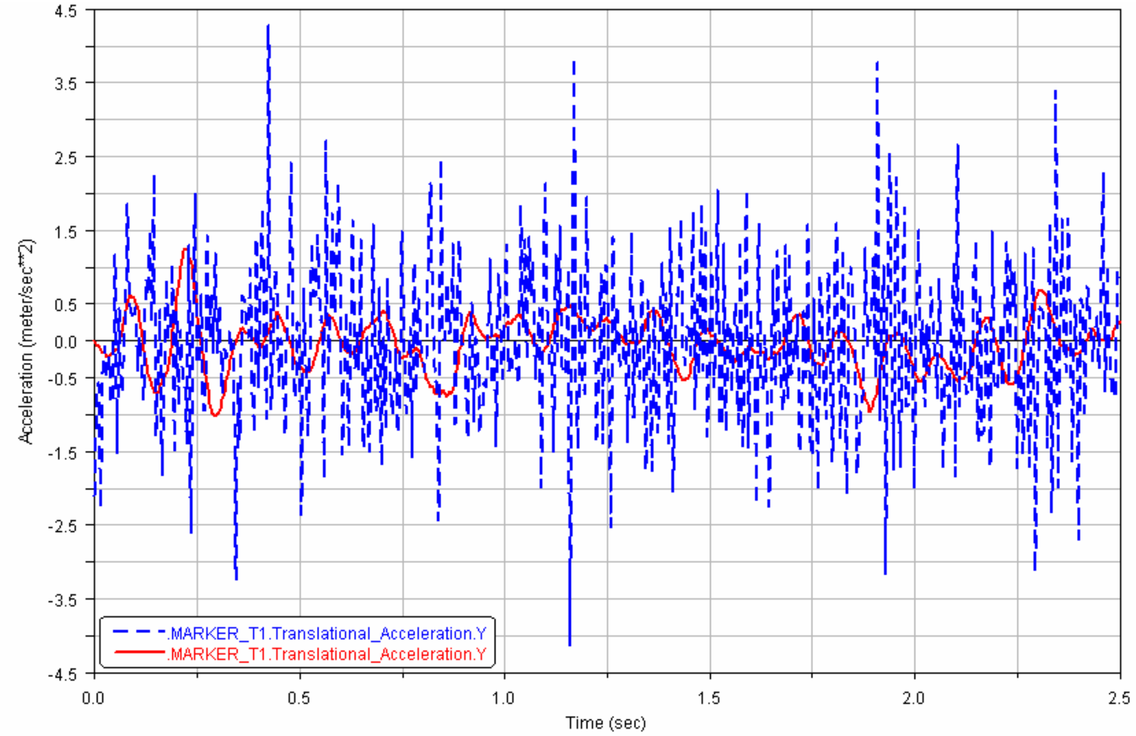

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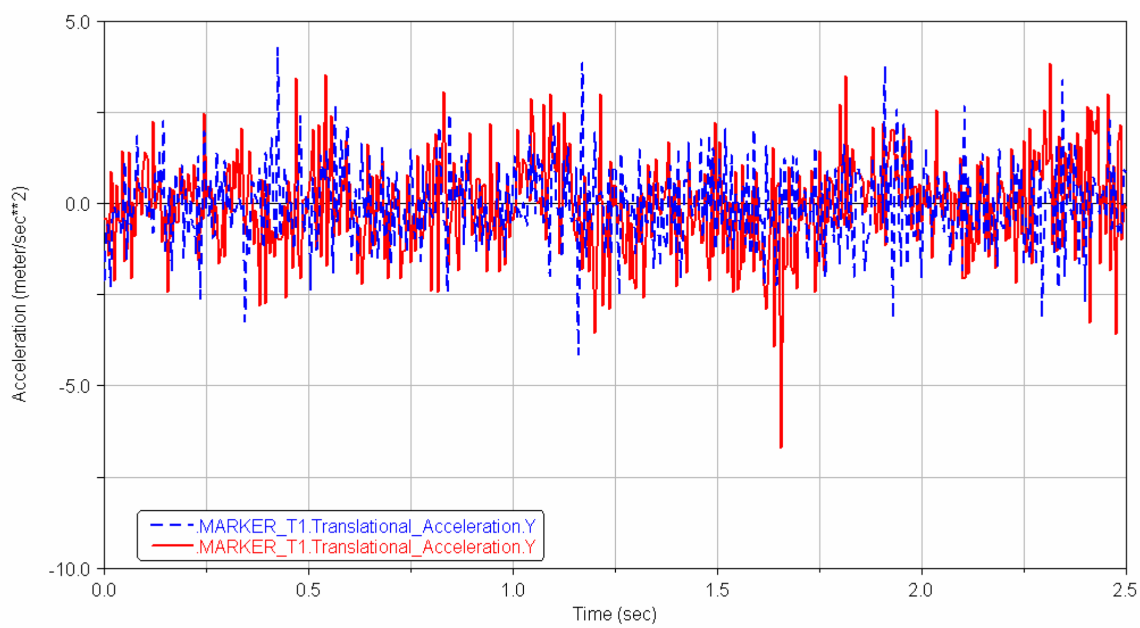

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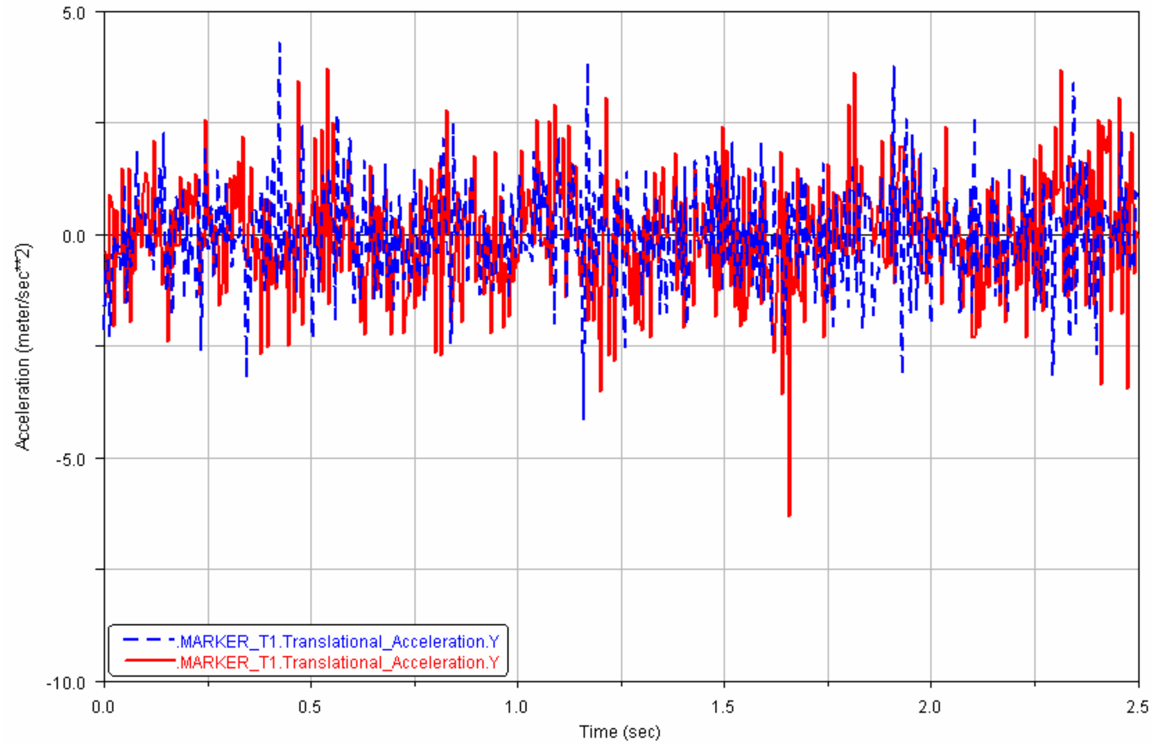

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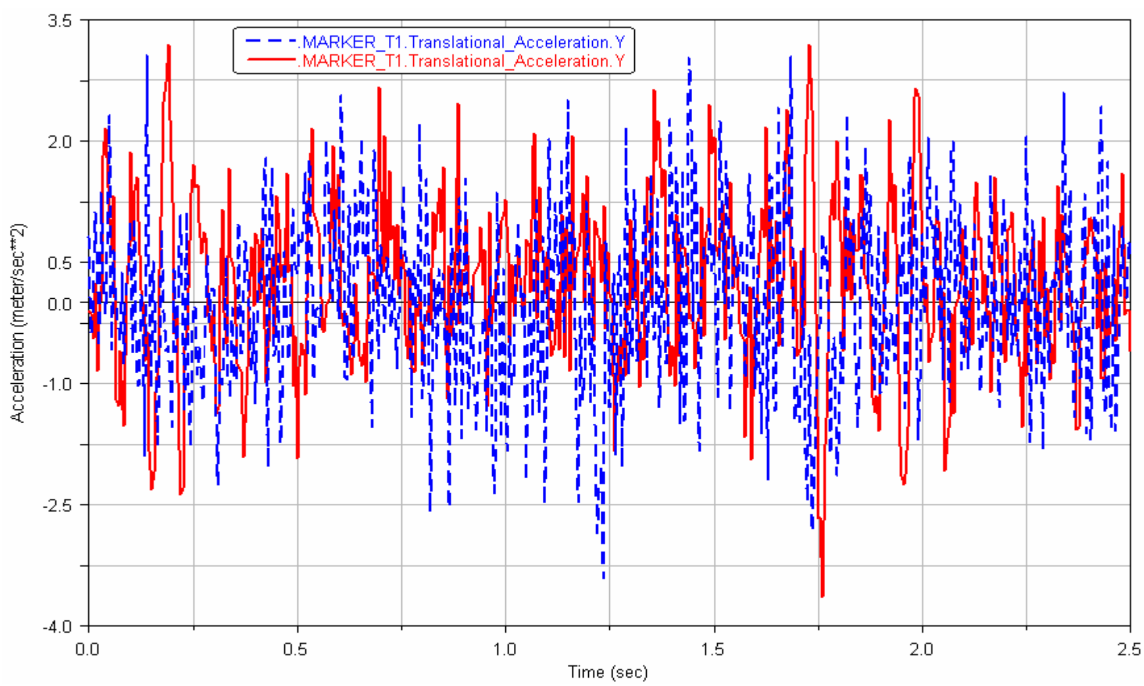

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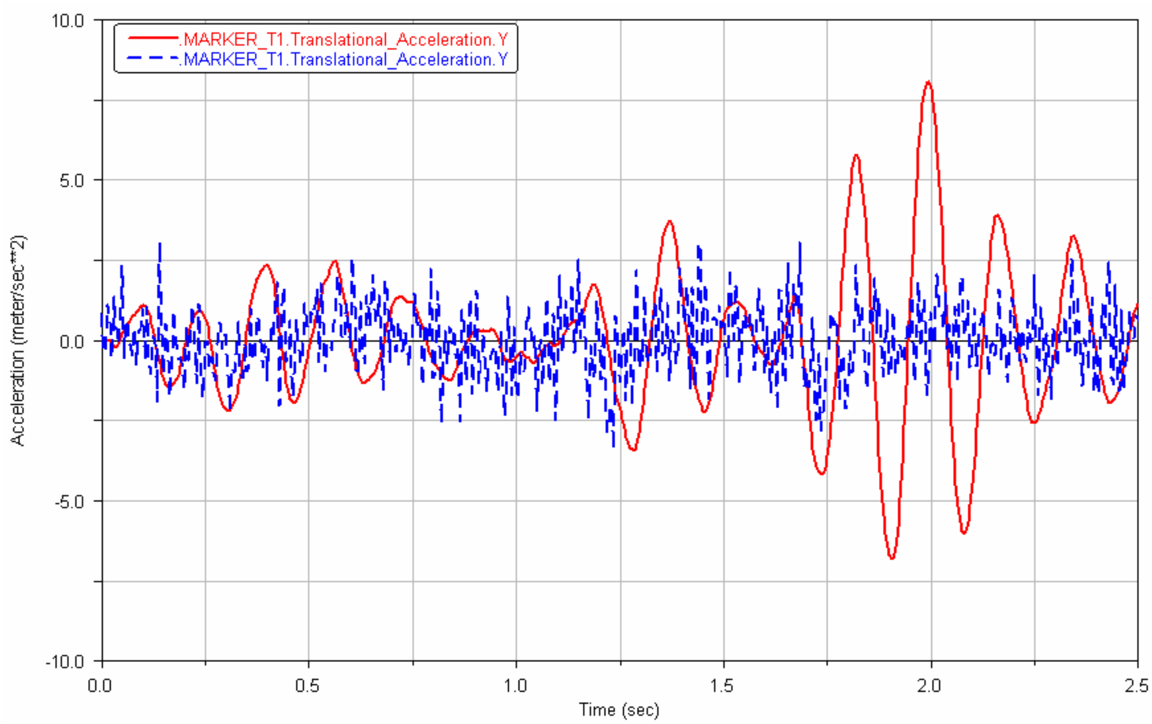

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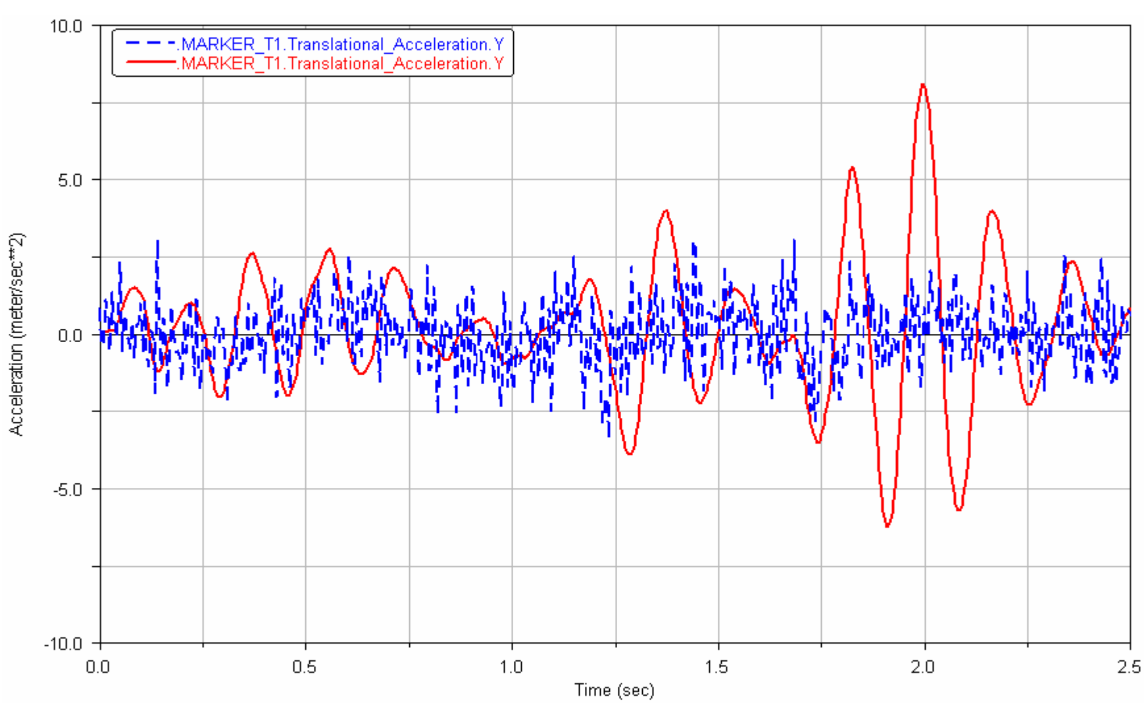

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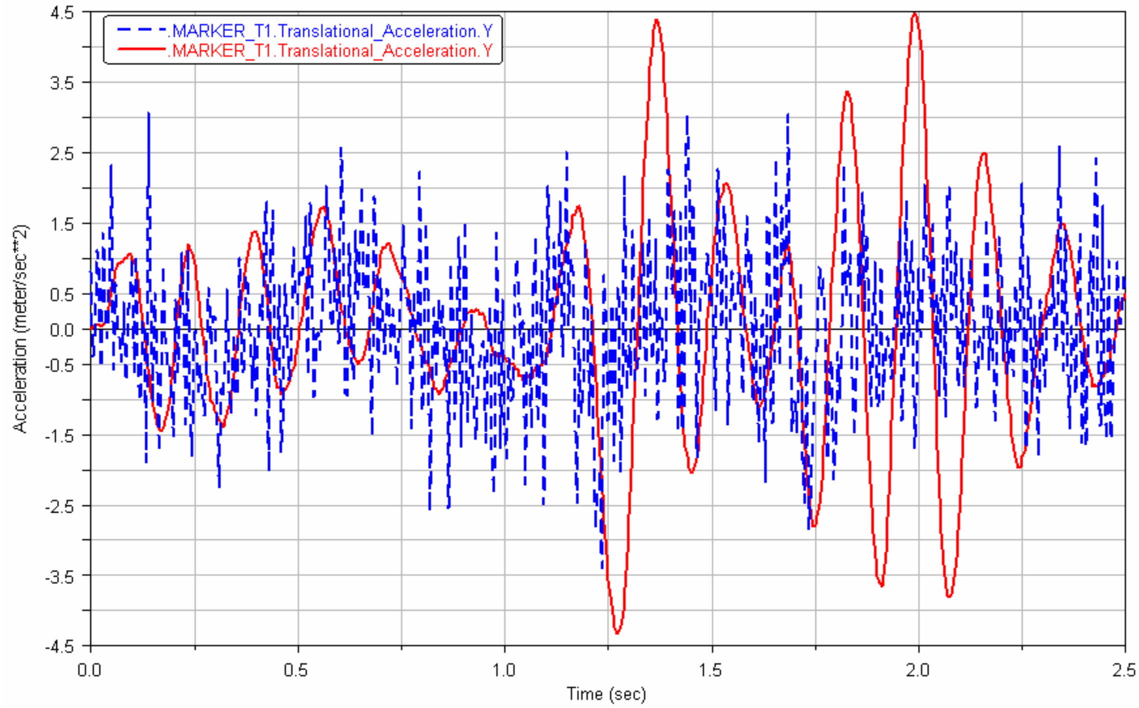

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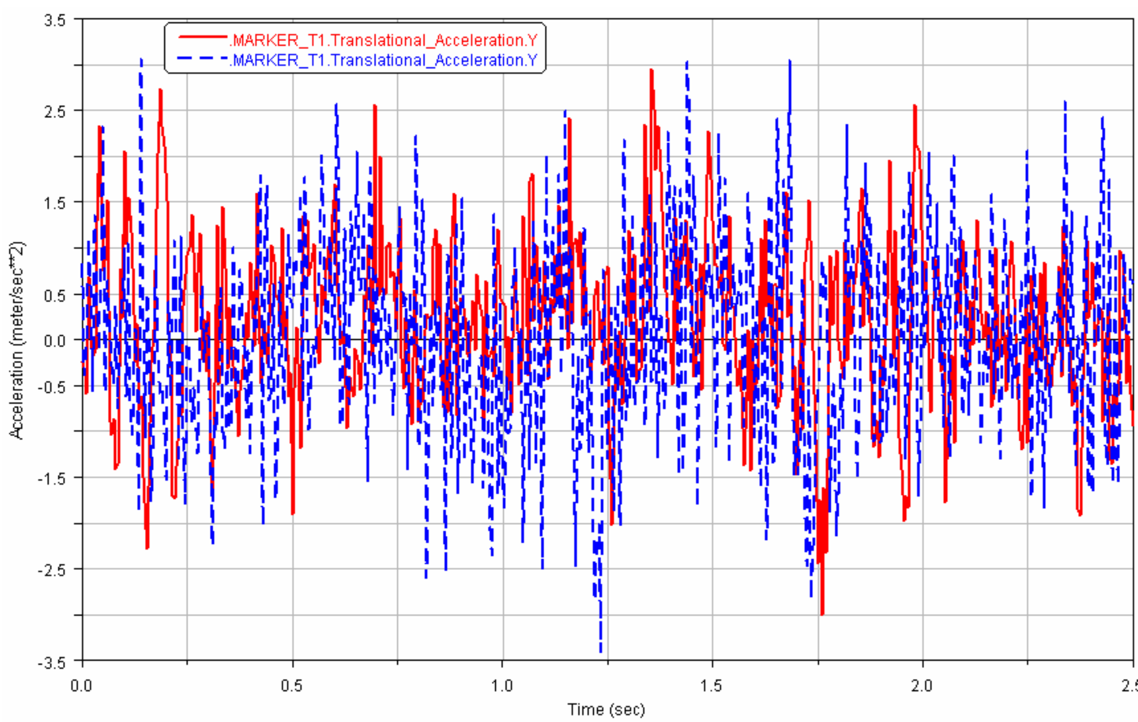
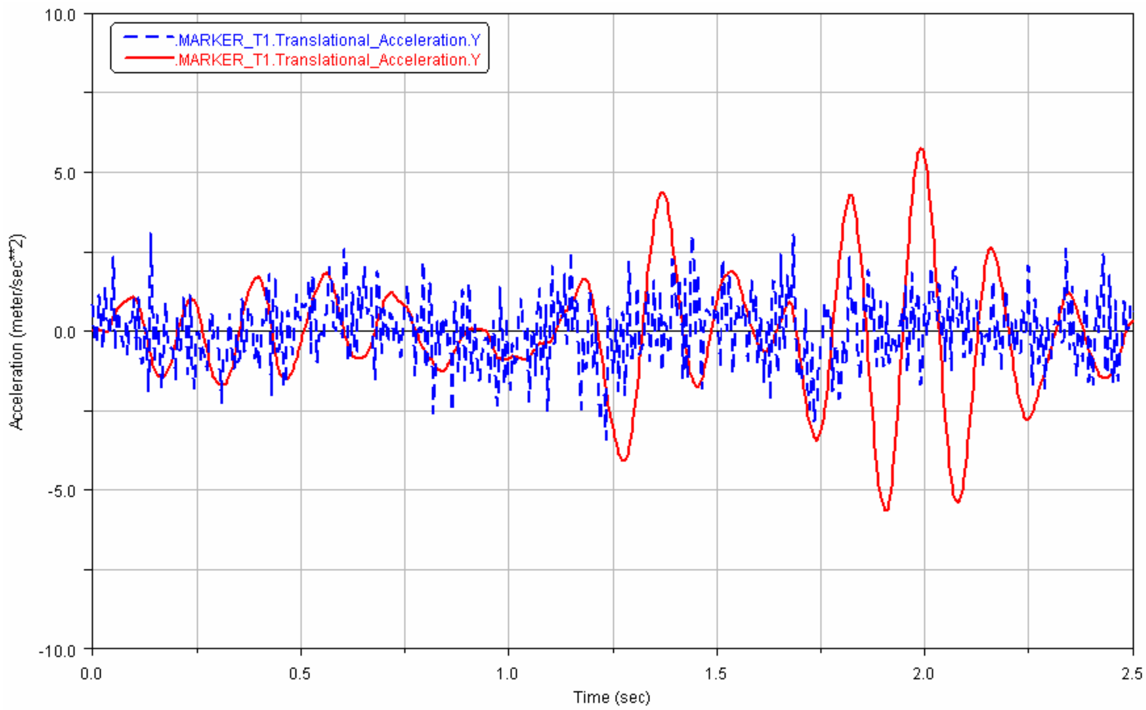


Figure A2-14 Rural T2 and T3 predict T1 Nov 21, 2008



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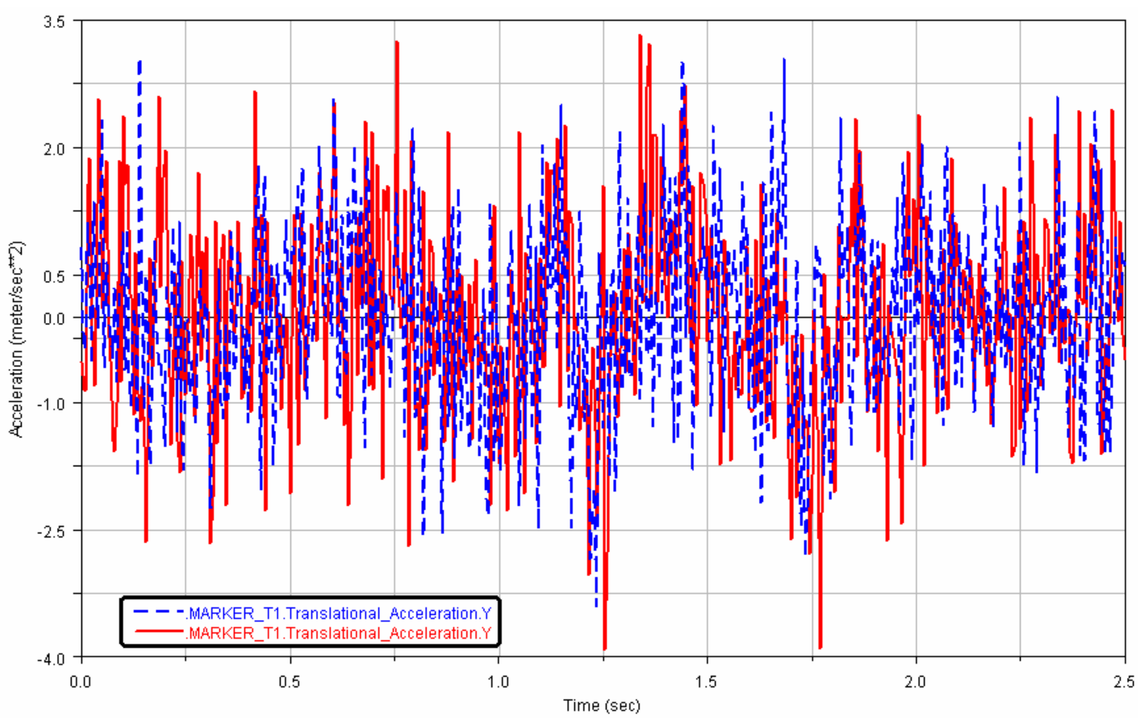


Figure A2-16 Rural T2, T6 and T7 predict T1 Nov 21, 2008

Appendix III: April 25, 2008 road test modeling results

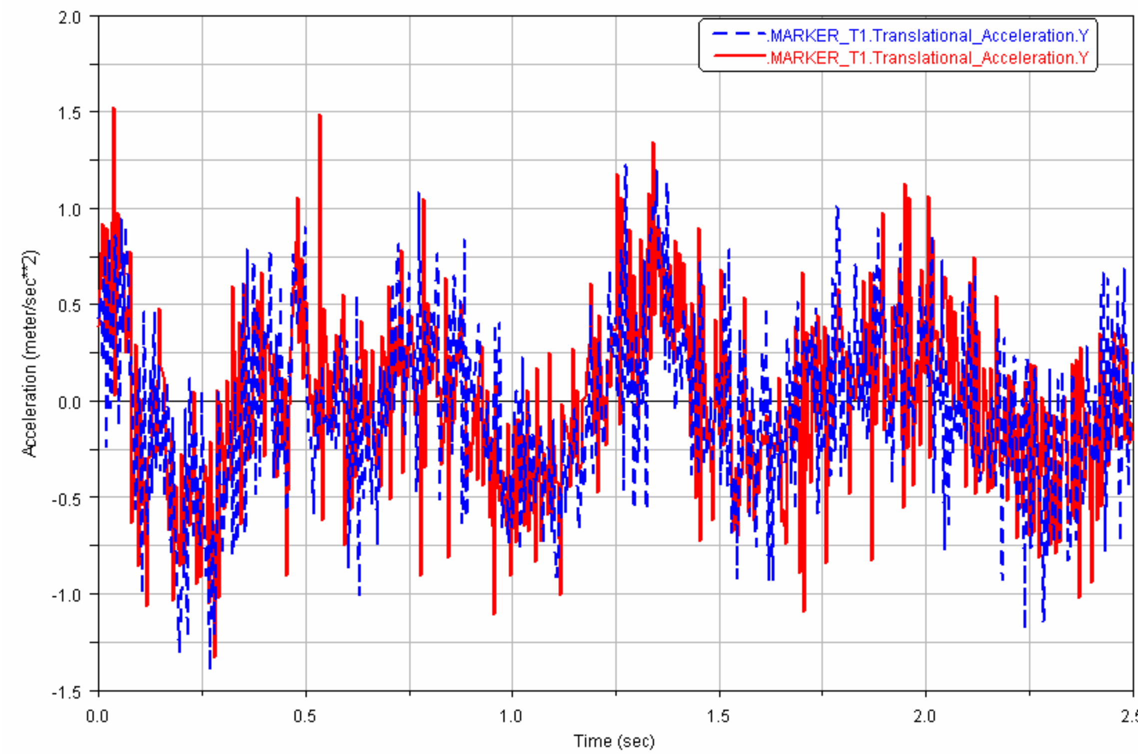
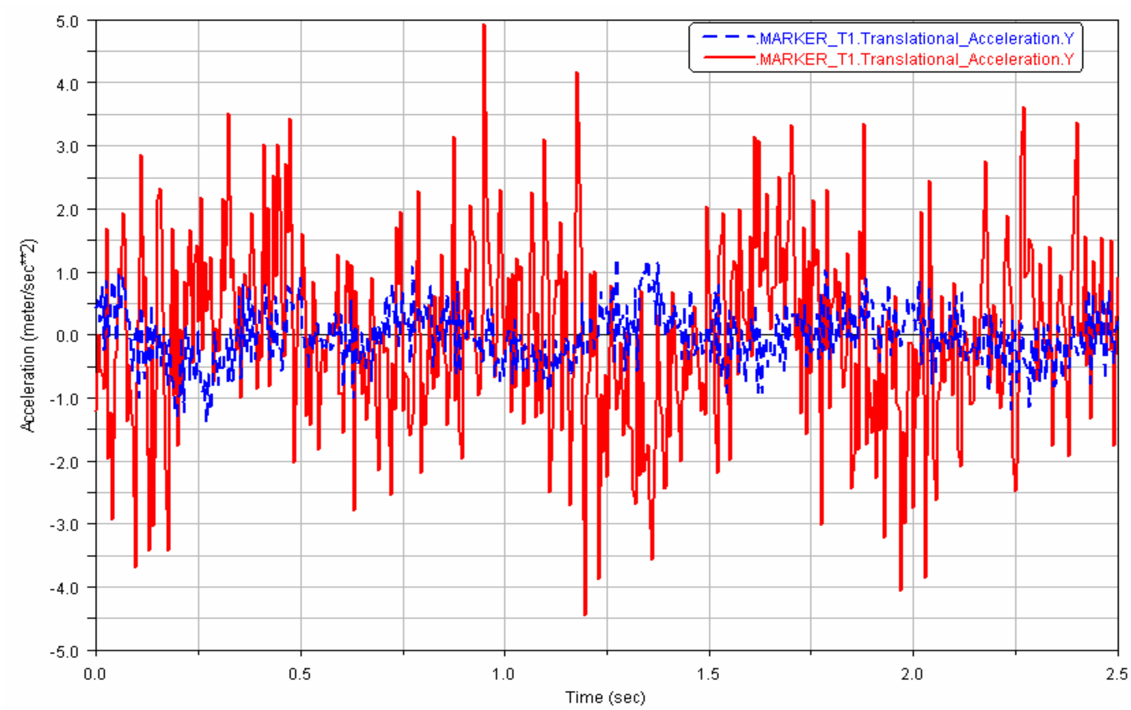


Figure A3-1 Interstate T2 predicts T1 April 25, 2008



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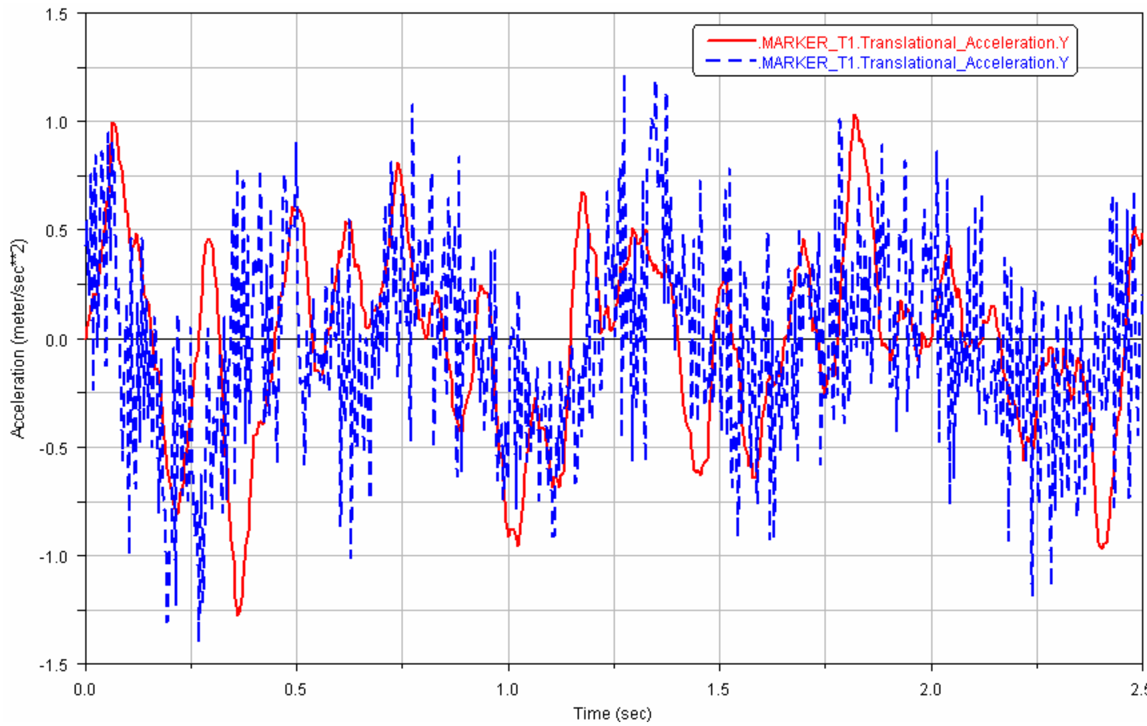

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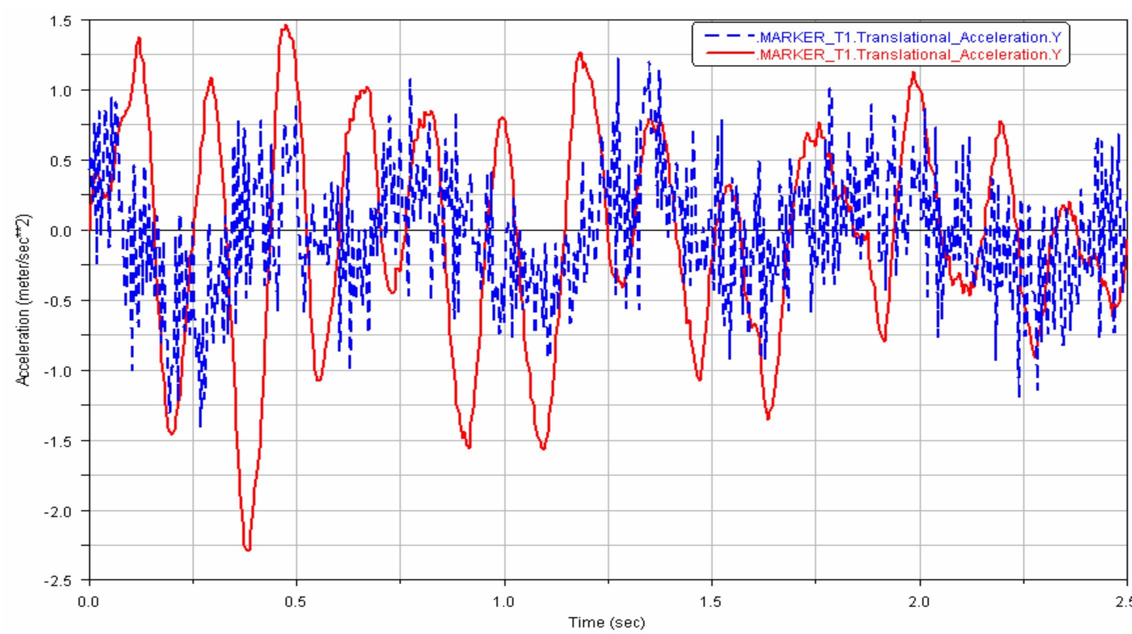


Figure A3-4 Interstate T7 predicts T1 April 25, 2008

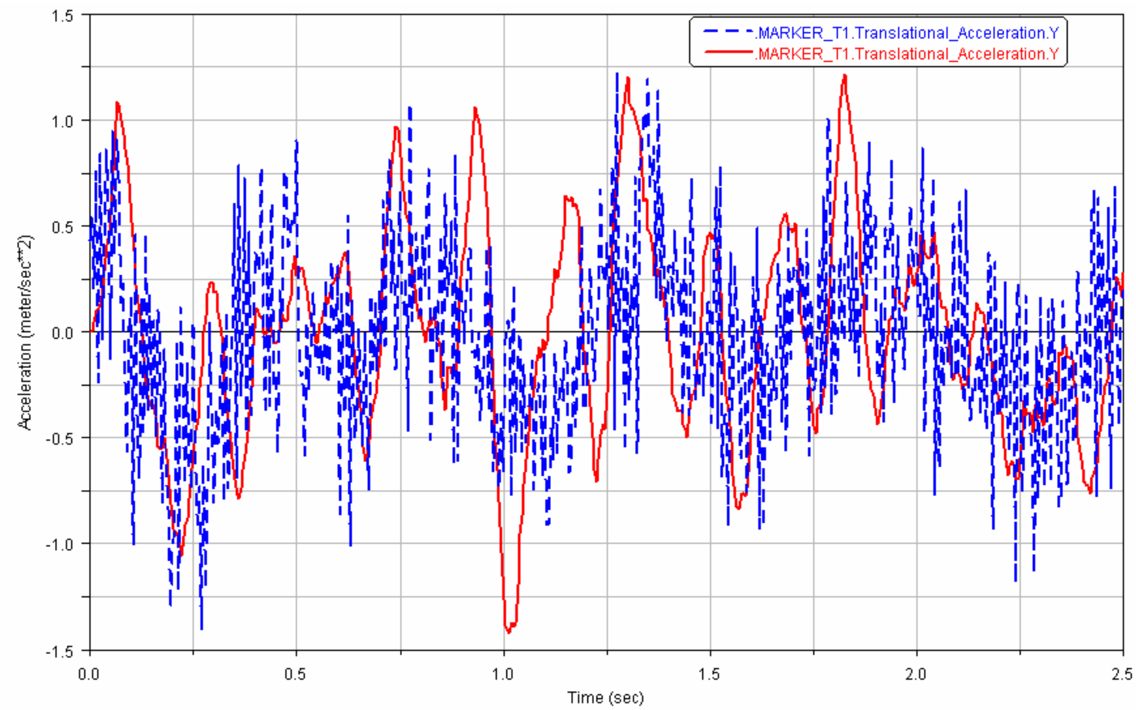
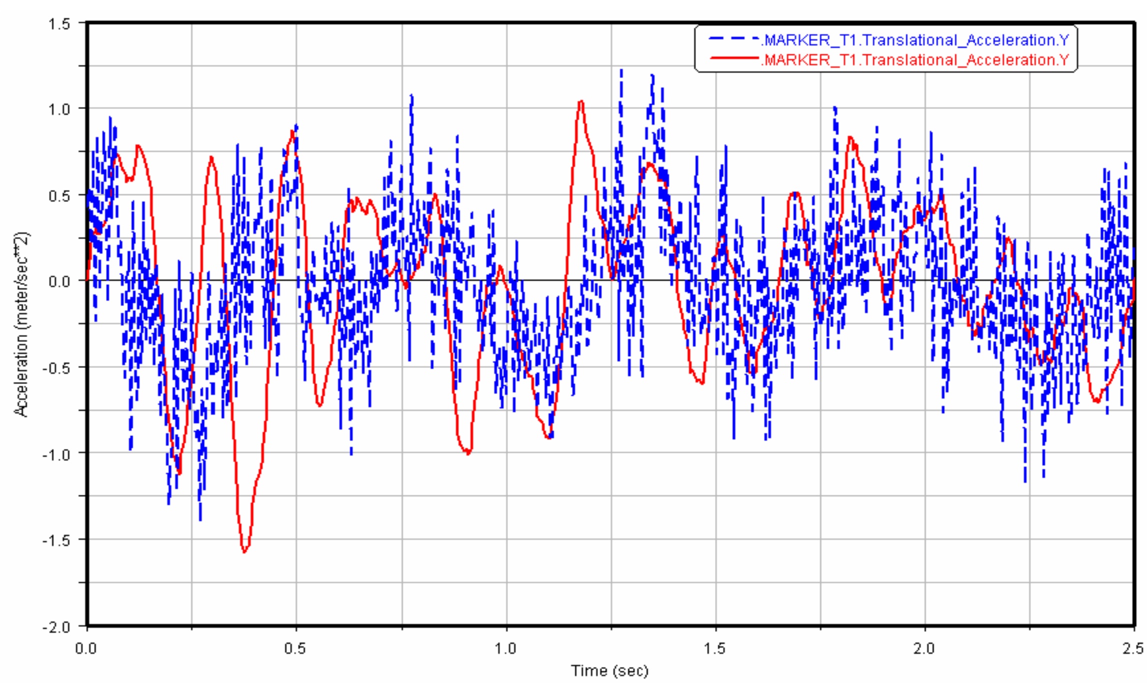


Figure A3-5 Interstate T8 predicts T1 April 25, 2008



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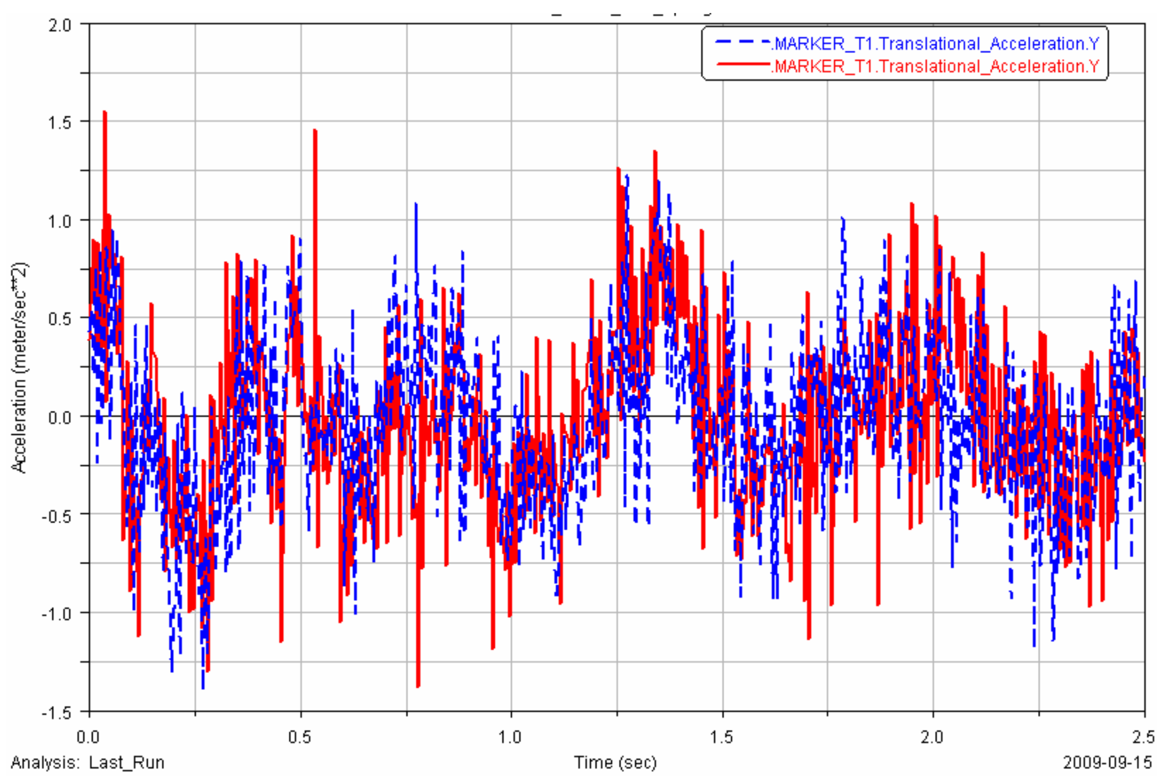

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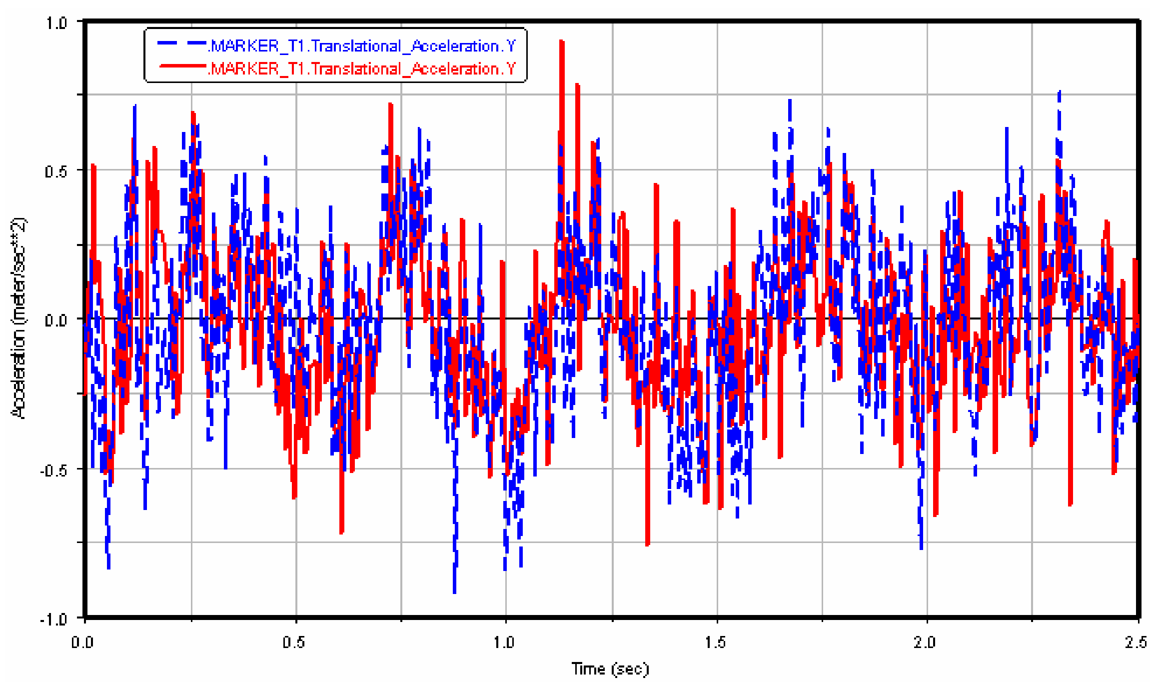

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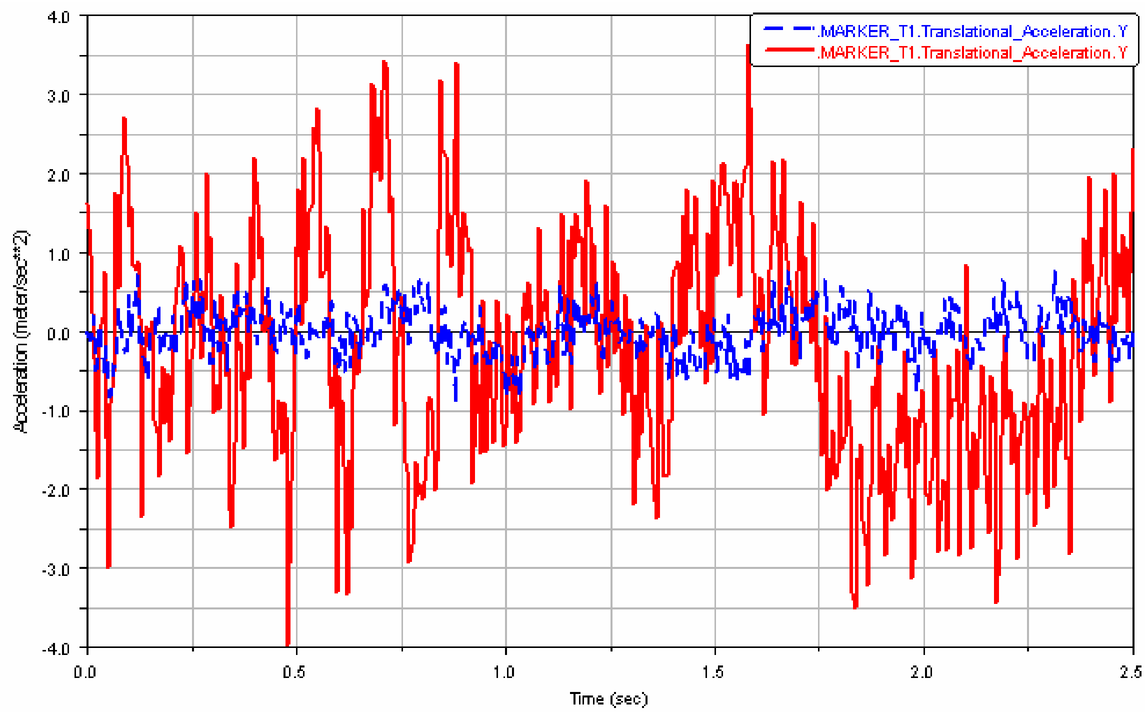

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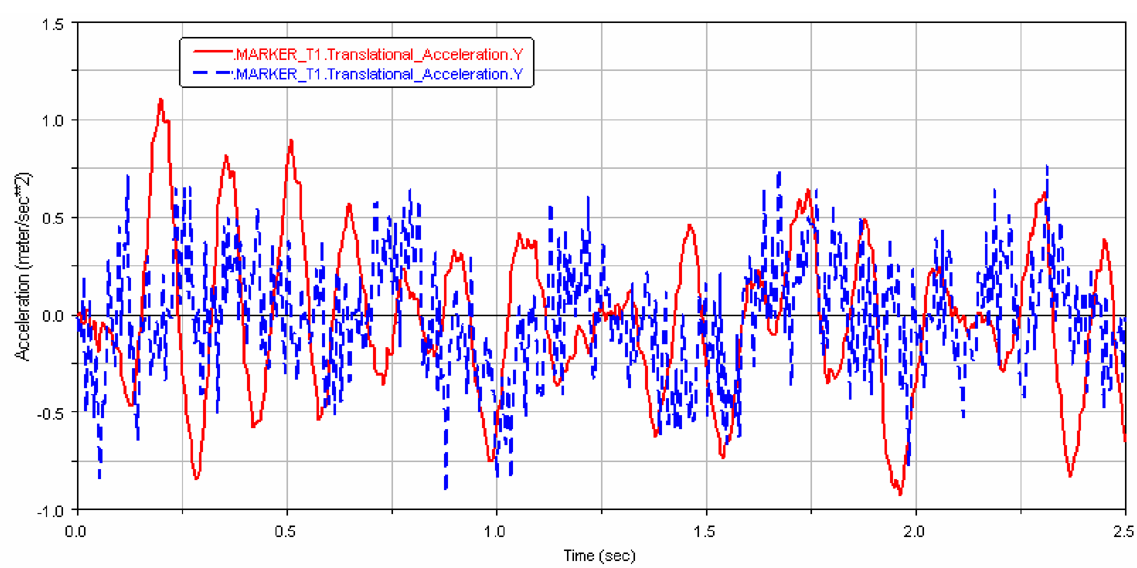

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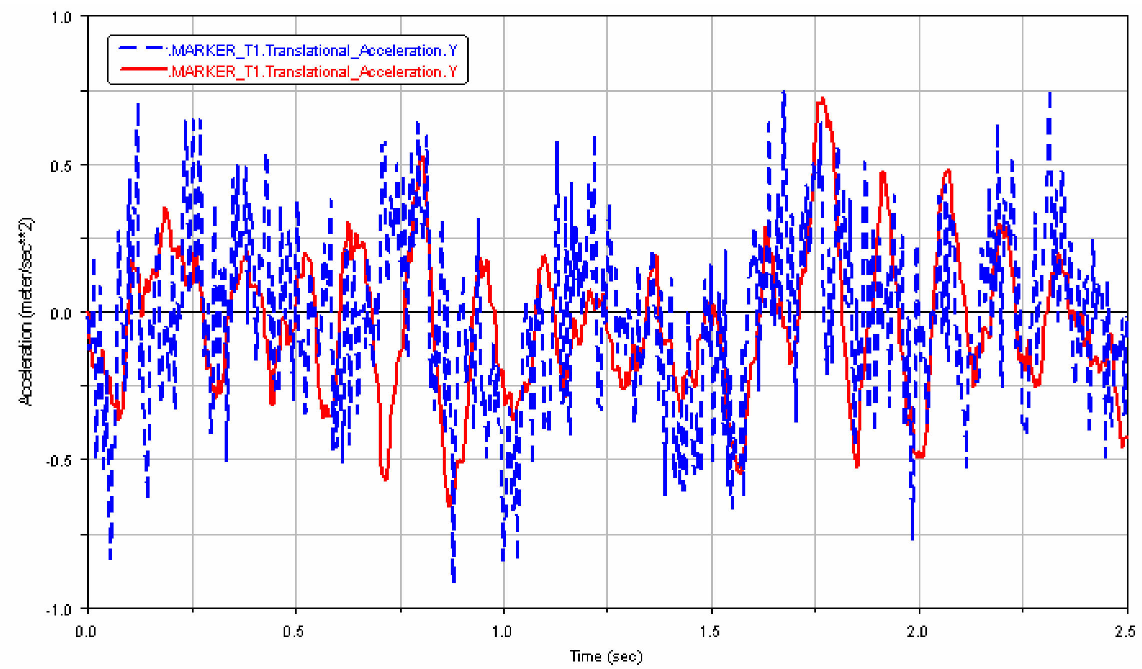

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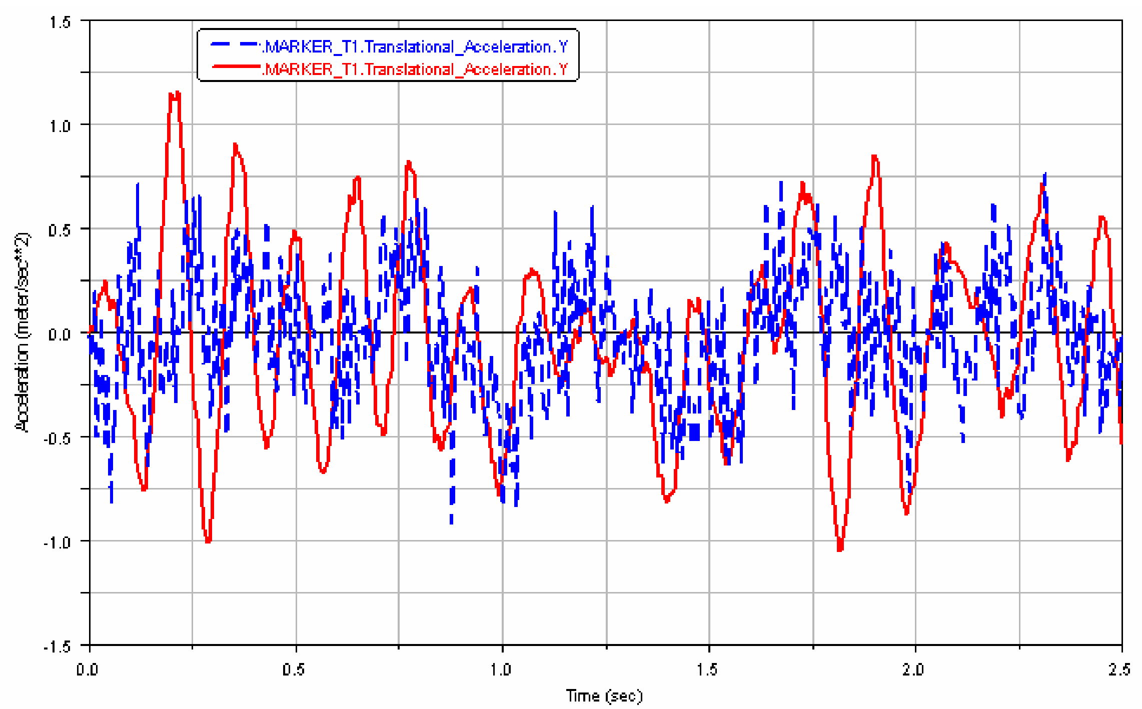

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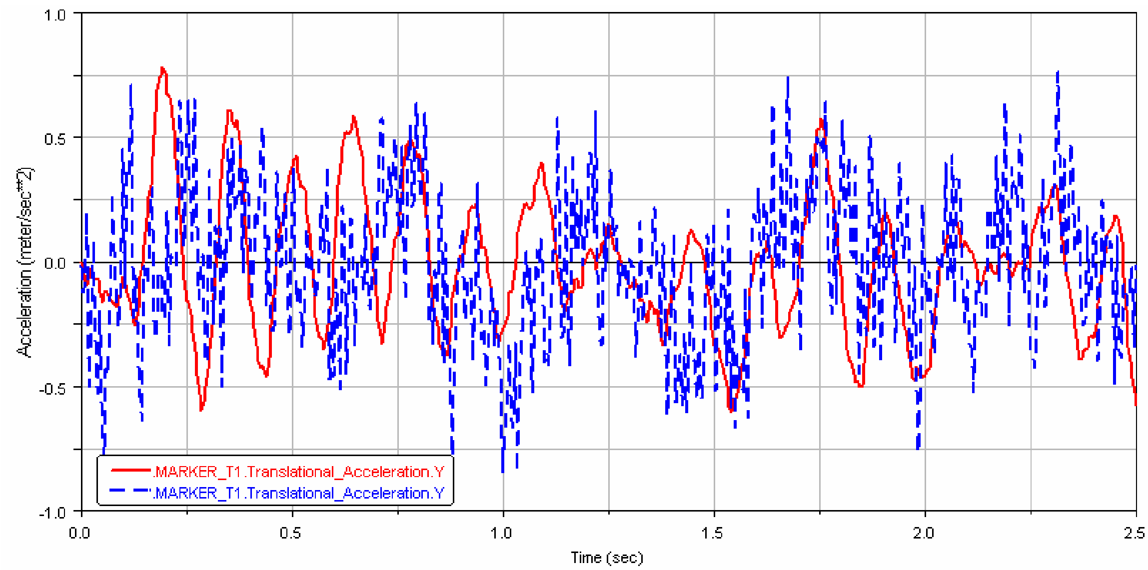


Figure A3-13 Rural T6 and T7 predict T1 April 25, 2008

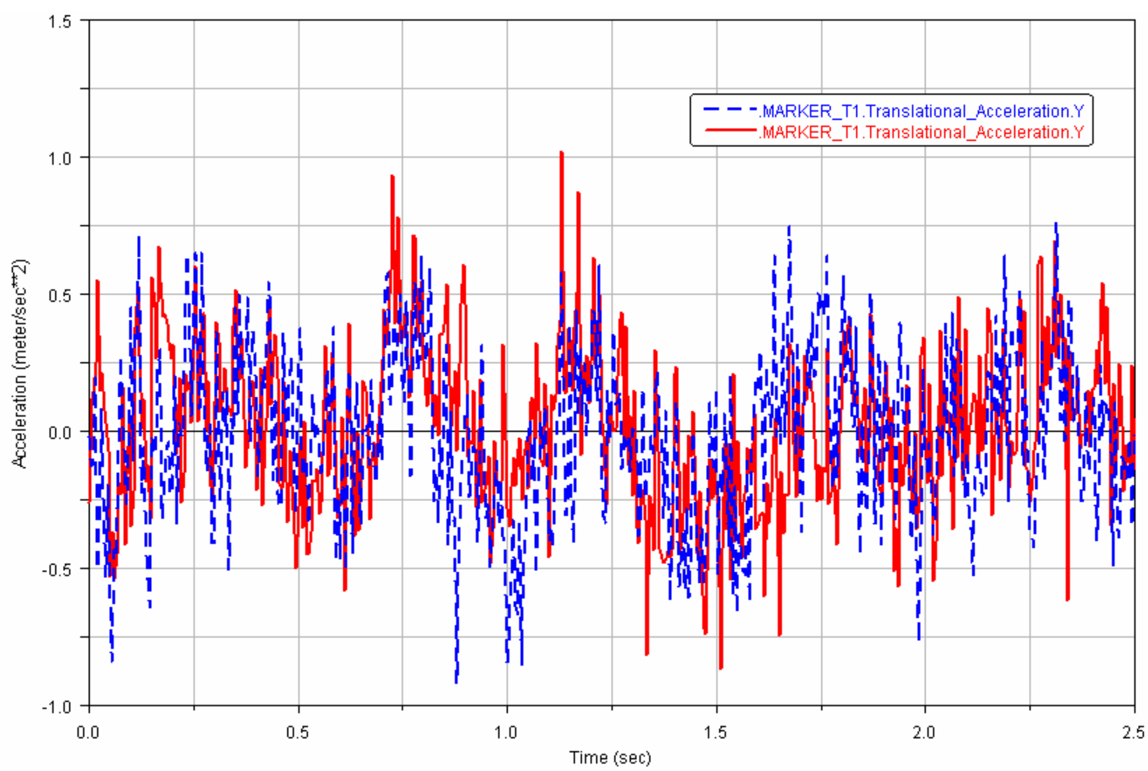
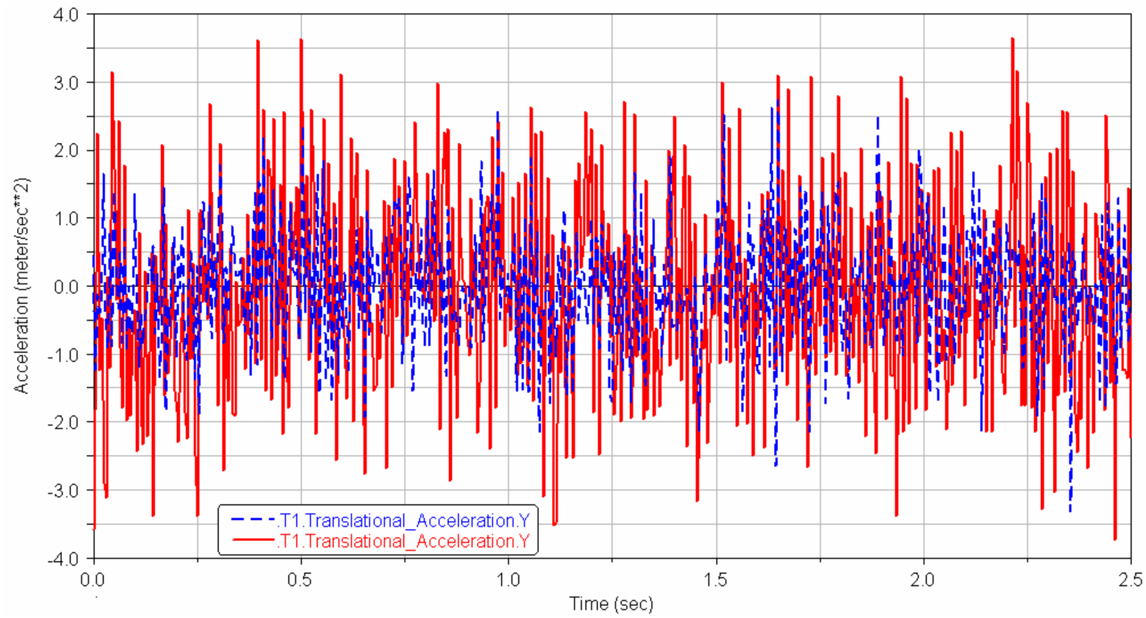


Figure A3-14 Rural T2, T6 and T7 predict T1 April 25, 2008

Appendix IV: November 20, 2008 road test modeling results



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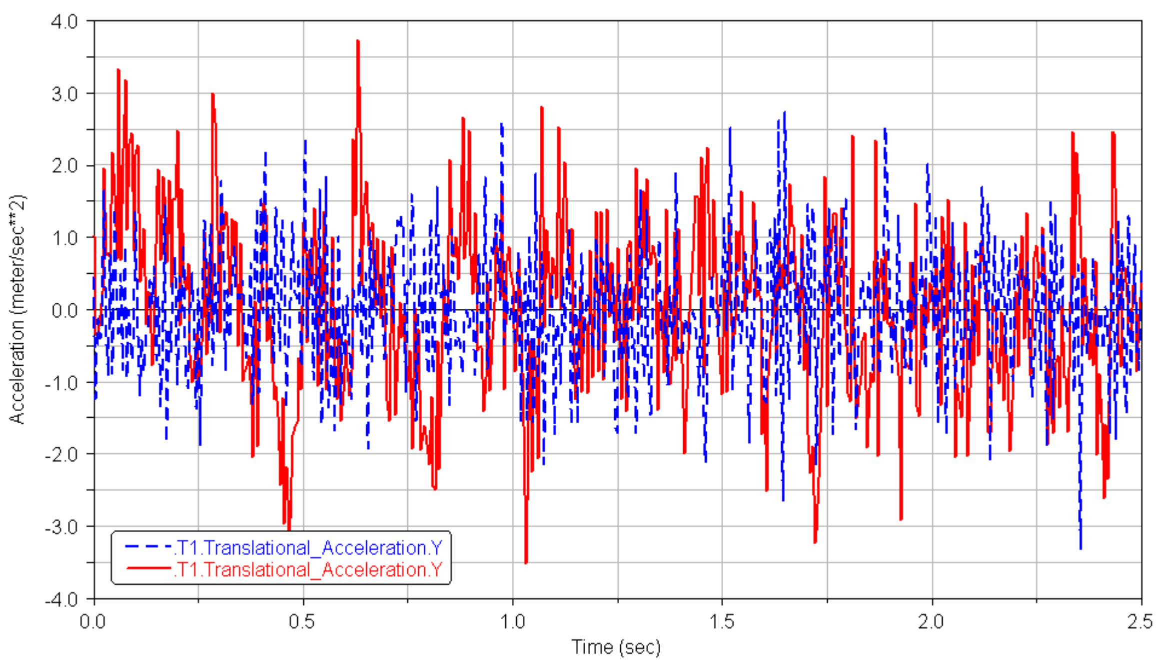

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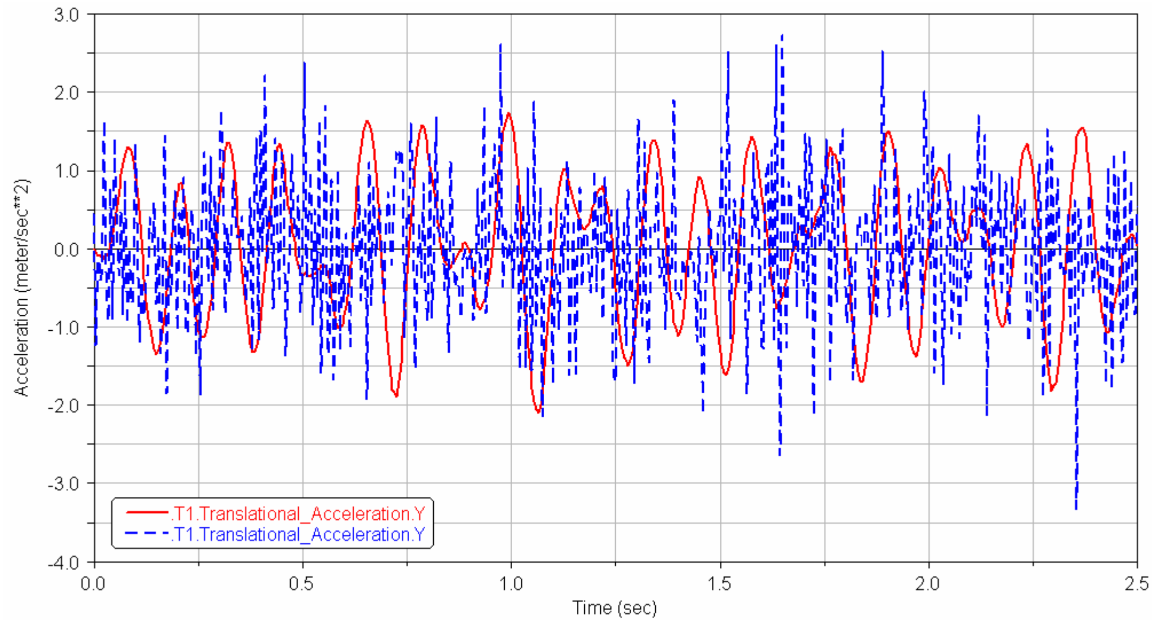

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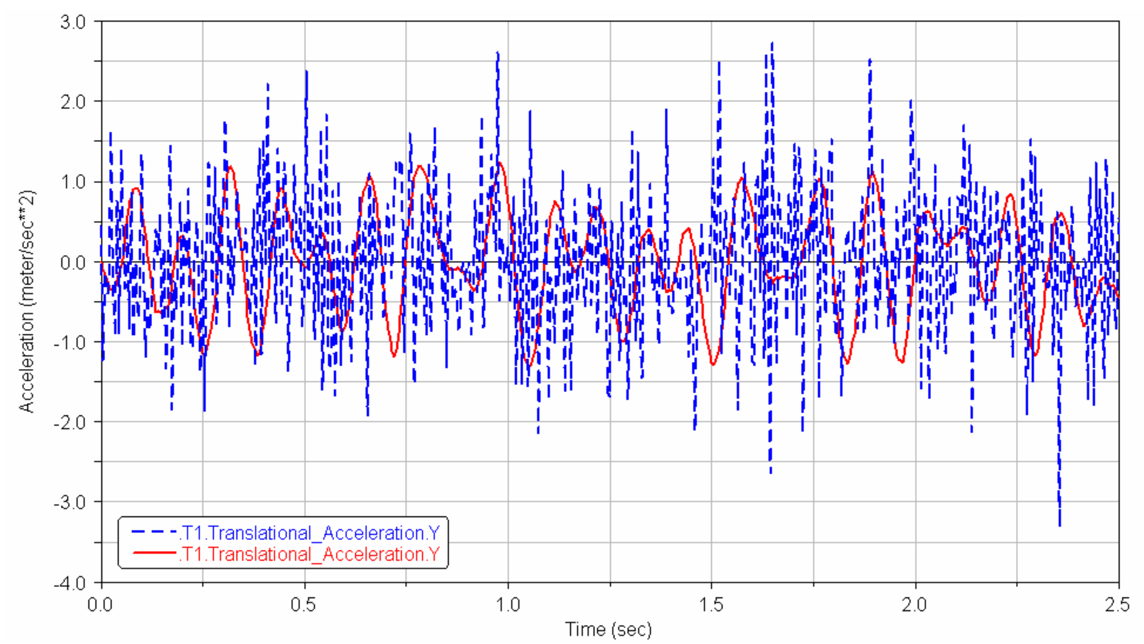
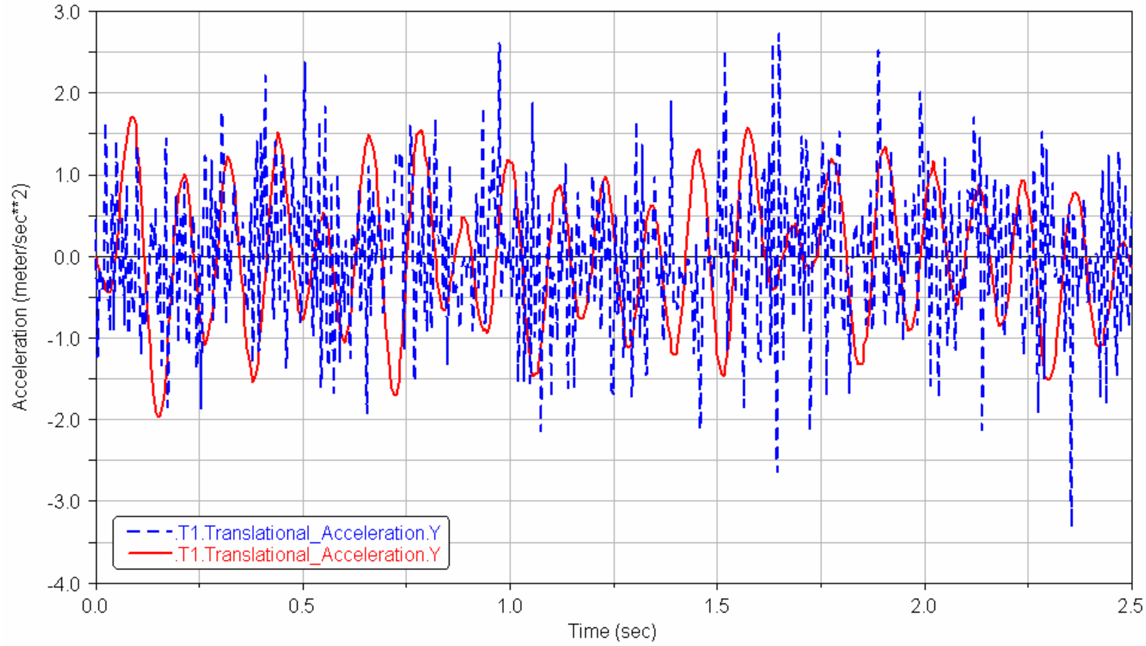


Figure A4-4 Interstate T7 predicts T1 Nov 20, 2008



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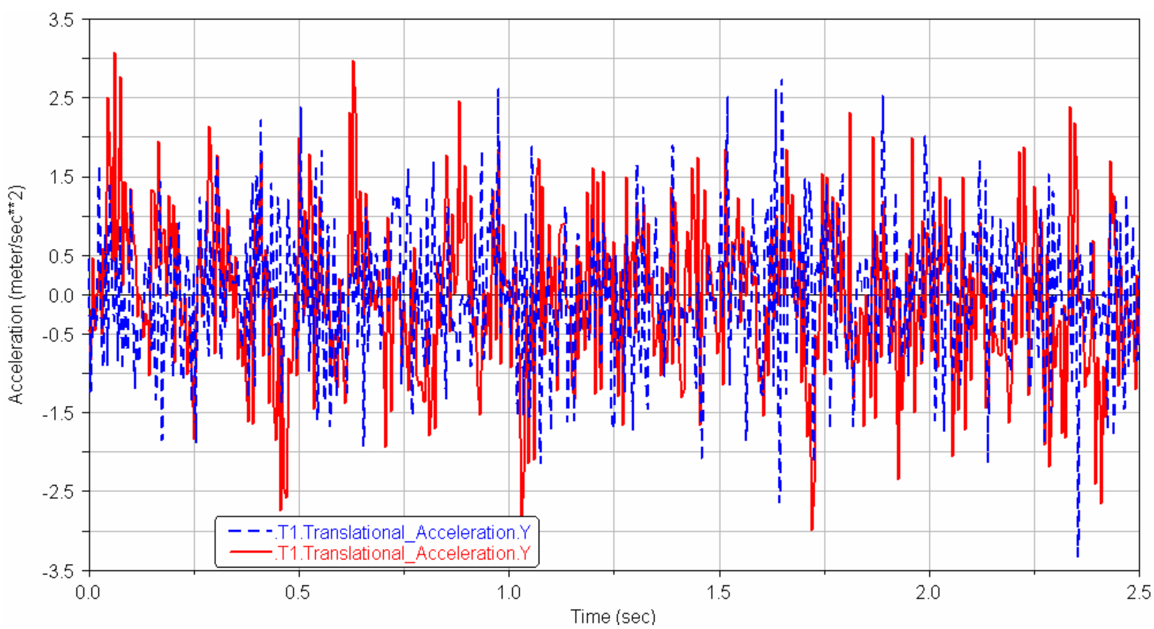

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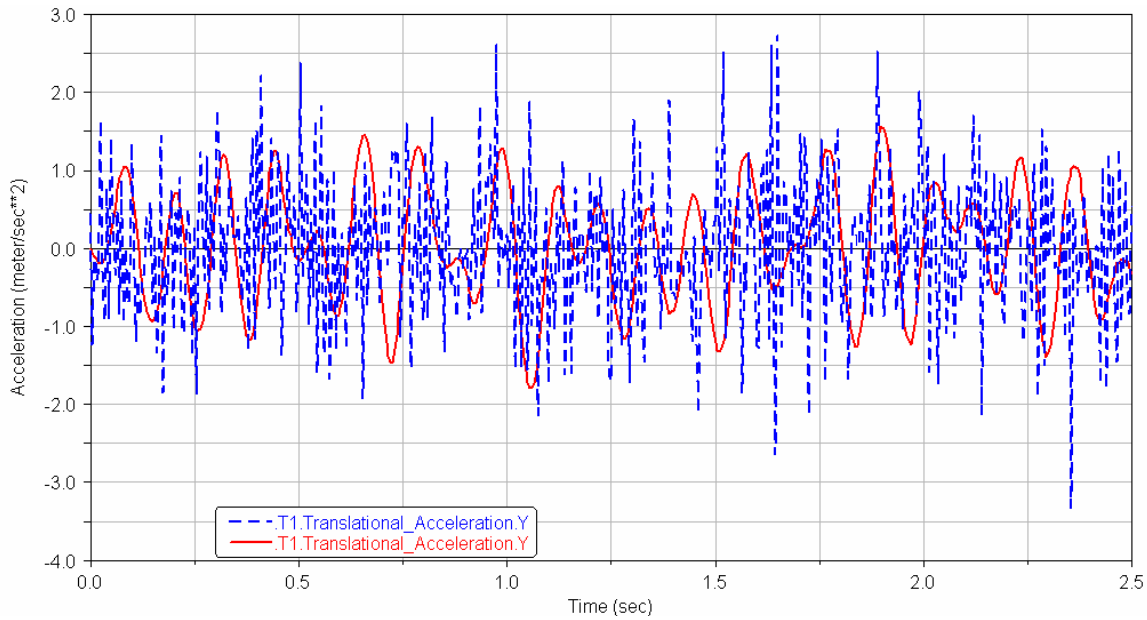

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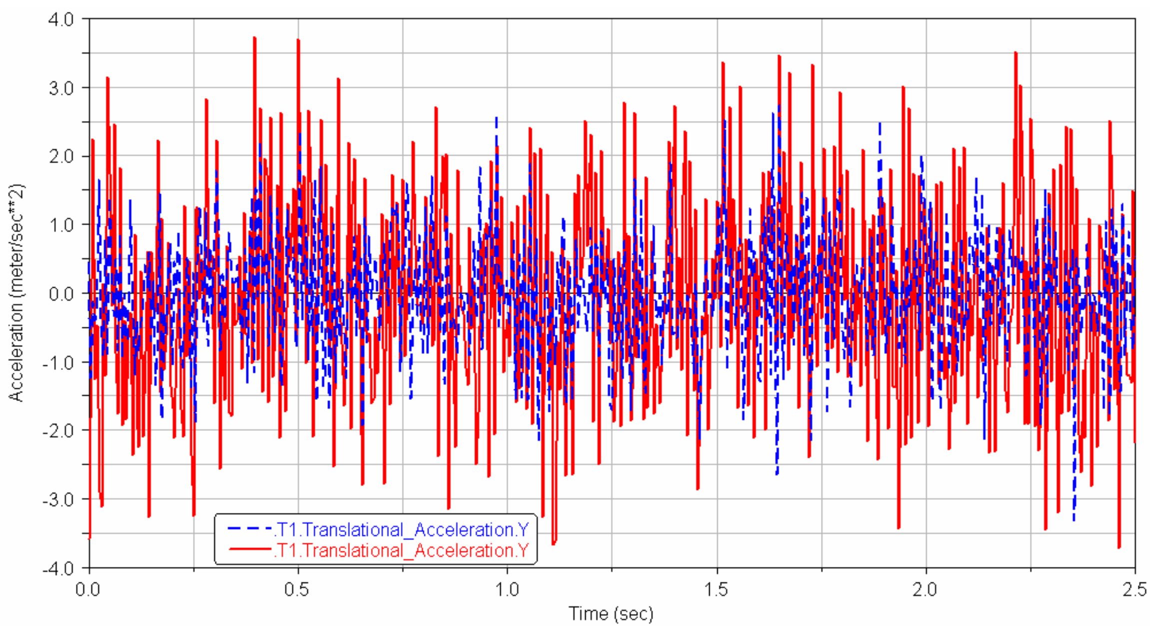

Figure A4-8 Interstate T2, T6 and T7 predict T1 Nov 20, 2008

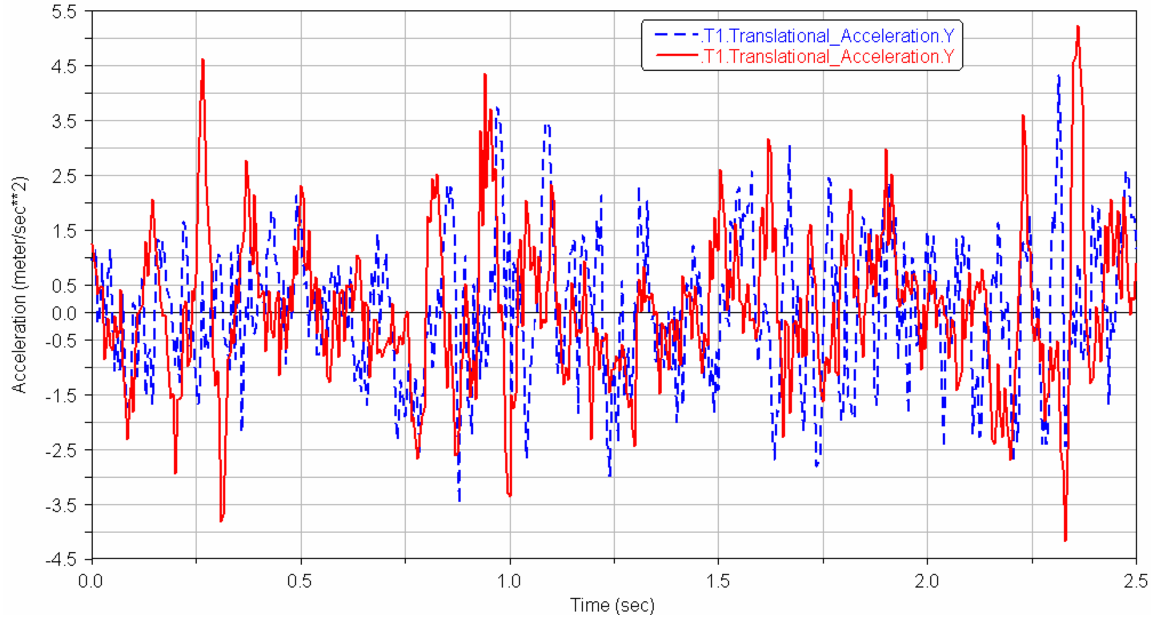

Figure A4-9 Rural T2 predicts T1 Nov 20, 2008

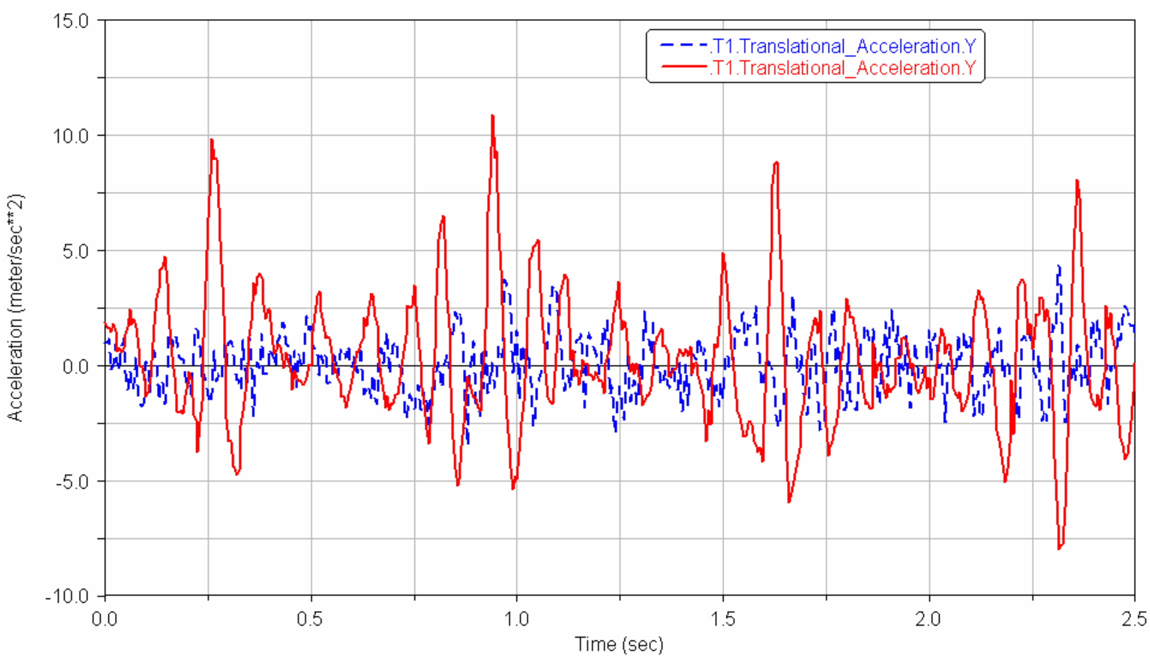

Figure A4-10 Rural T3 predicts T1 Nov 20, 2008

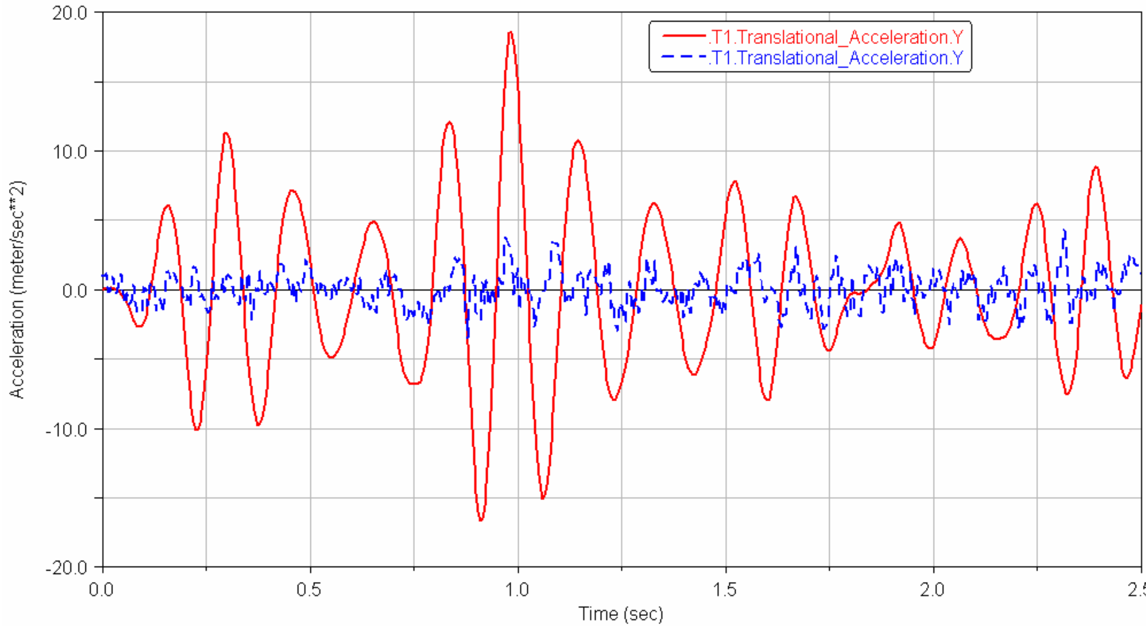

Figure A4-11 Rural T6 predicts T1 Nov 20, 2008

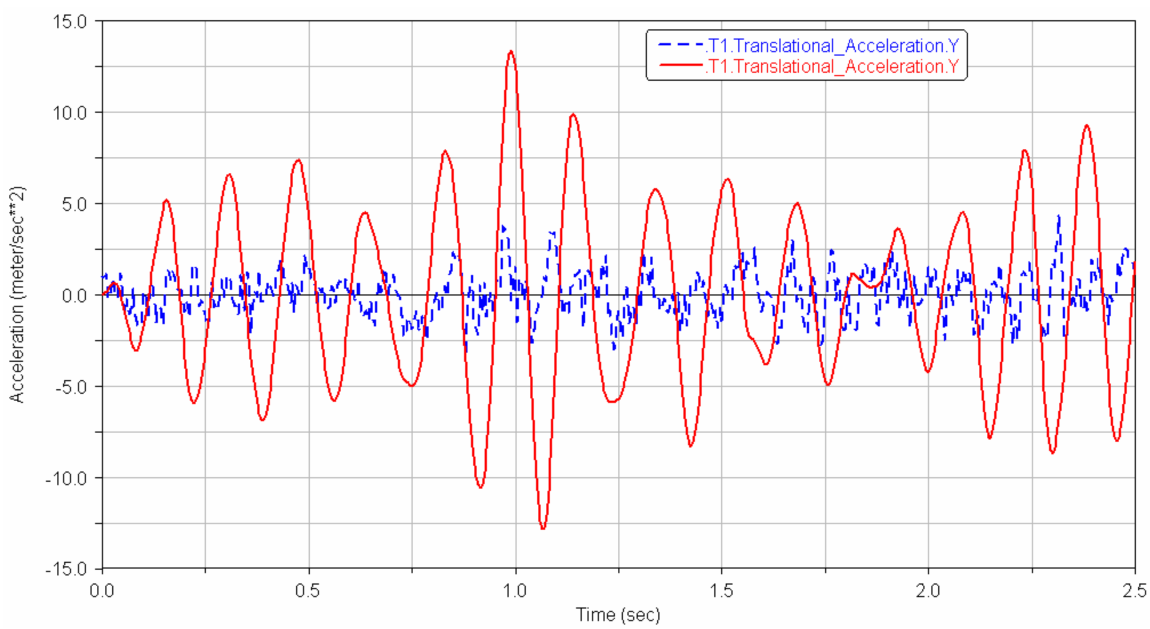

Figure A4-12 Rural T7 predicts T1 Nov 20, 2008

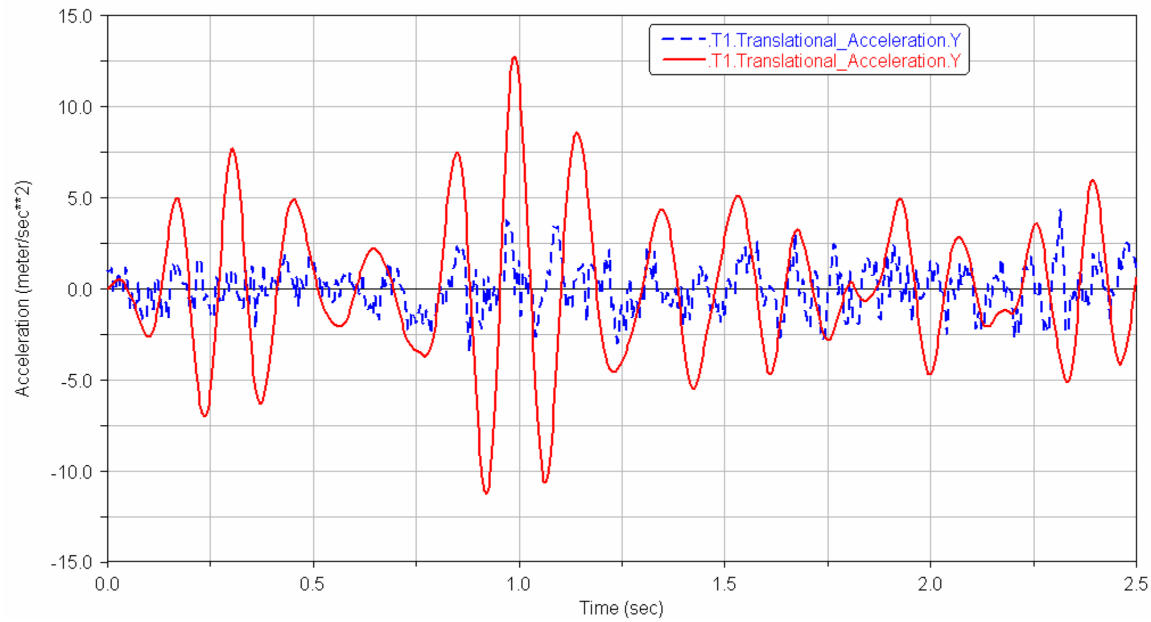

Figure A4-13 Rural T8 predicts T1 Nov 20, 2008

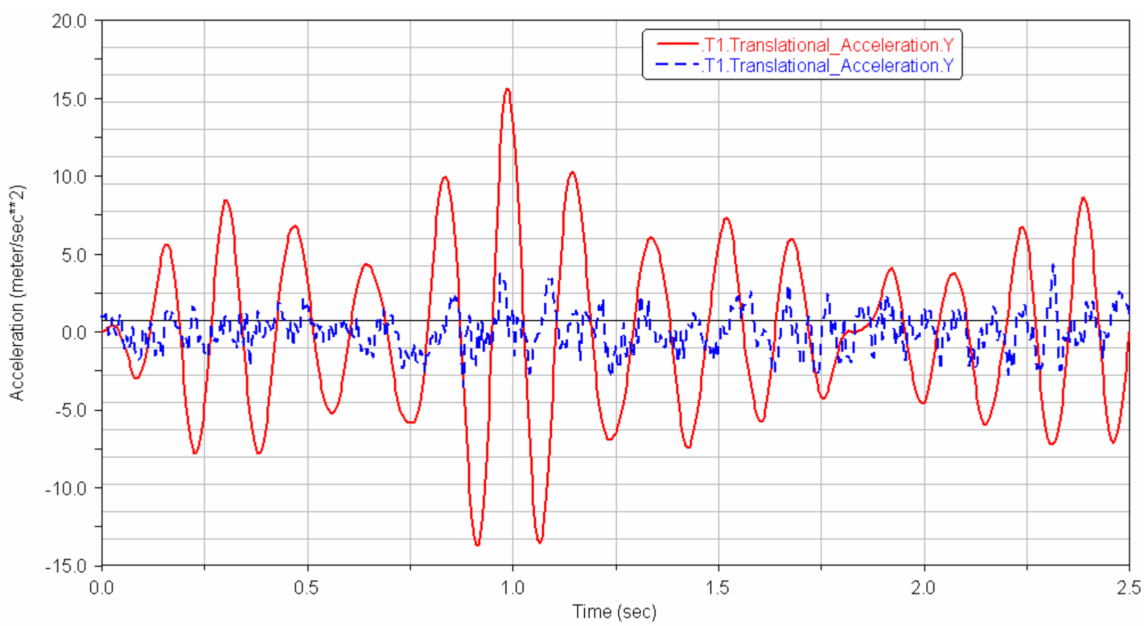

Figure A4-14 Rural T6 and T7 predict T1 Nov 20, 2008

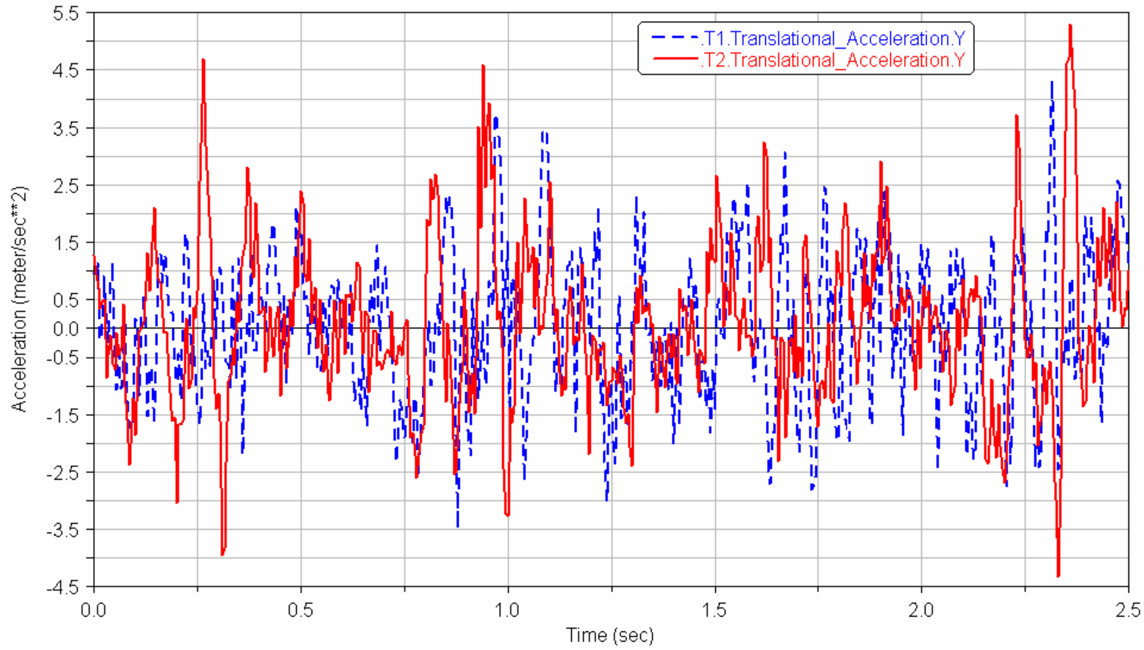

Figure A4-15 Improved rural T2 predicts T1 Nov 20, 2008

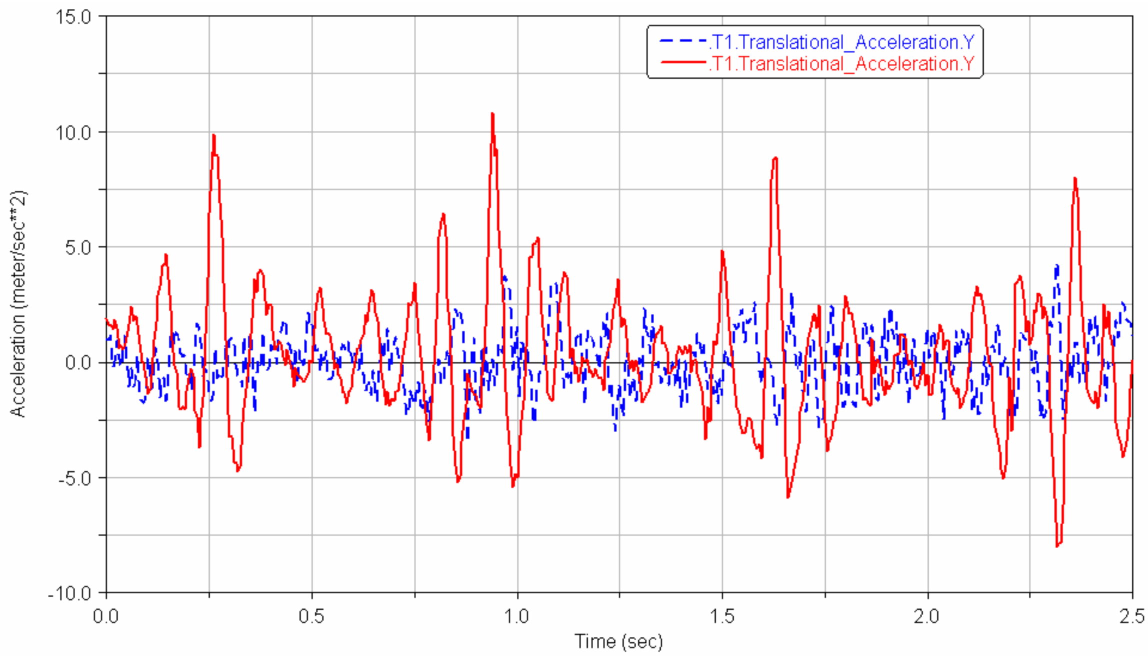

Figure A4-16 Improved rural T3 predicts T1 Nov 20, 2008

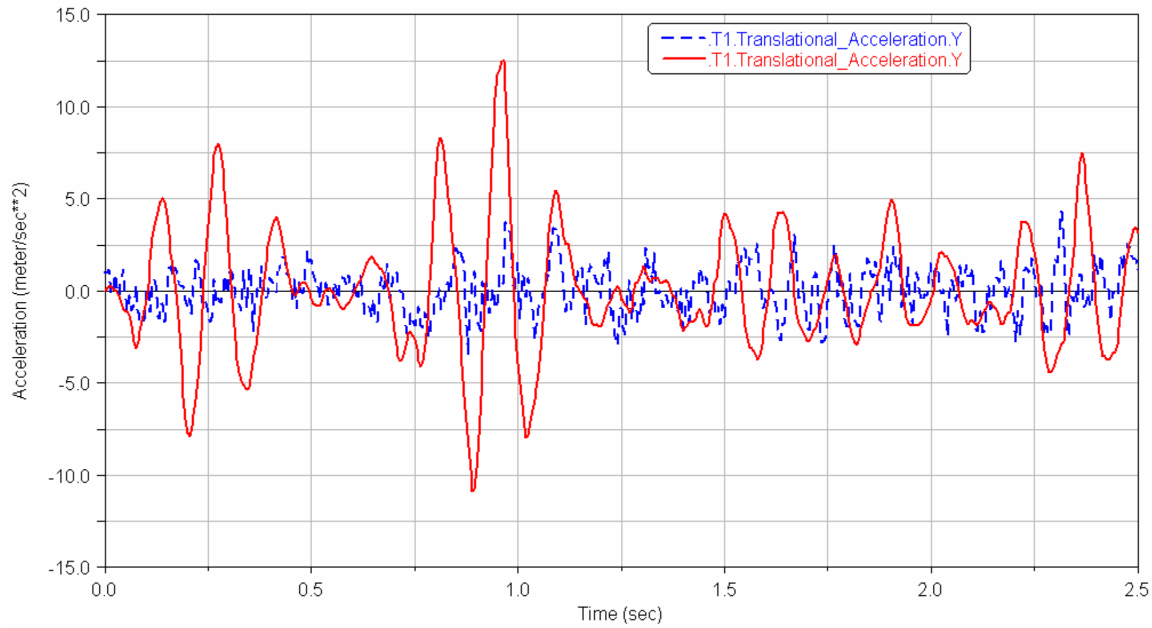

Figure A4-17 Improved rural T6 predicts T1 Nov 20, 2008

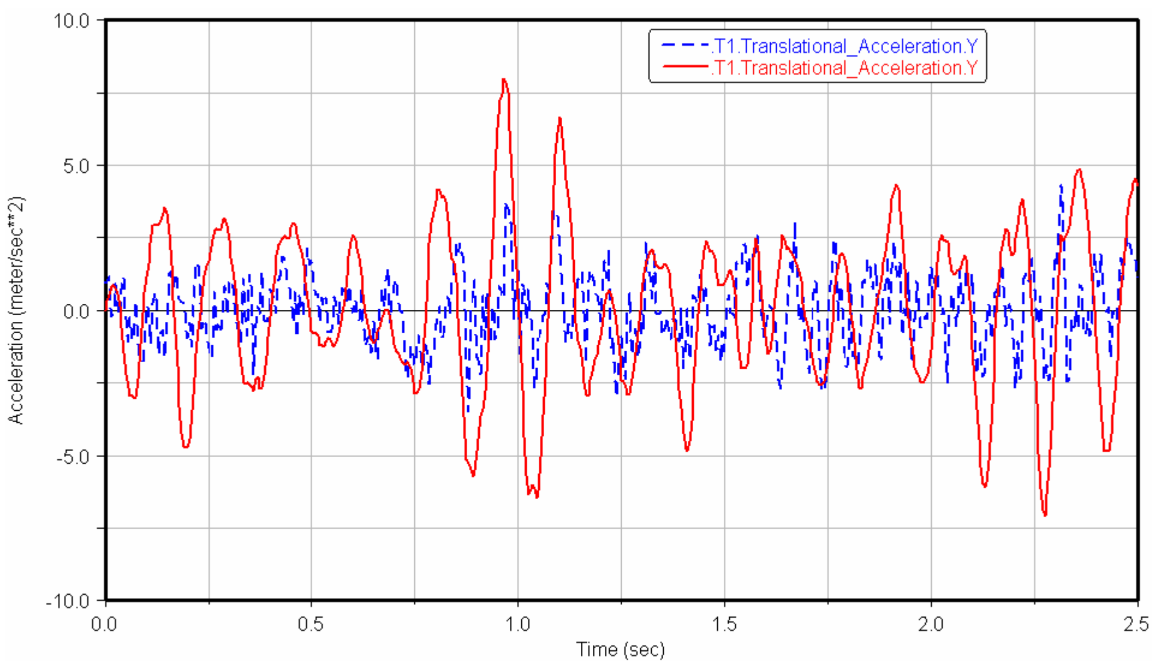

Figure A4-18 Improved rural T7 predicts T1 Nov 20, 2008

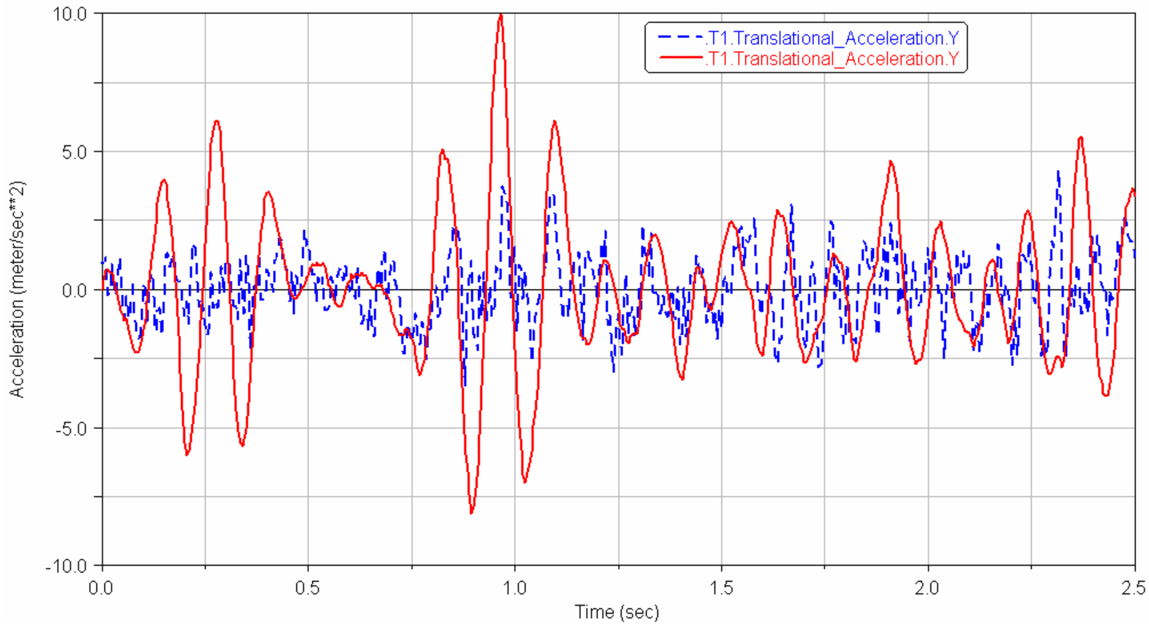

Figure A4-19 Improved rural T8 predicts T1 Nov 20, 2008

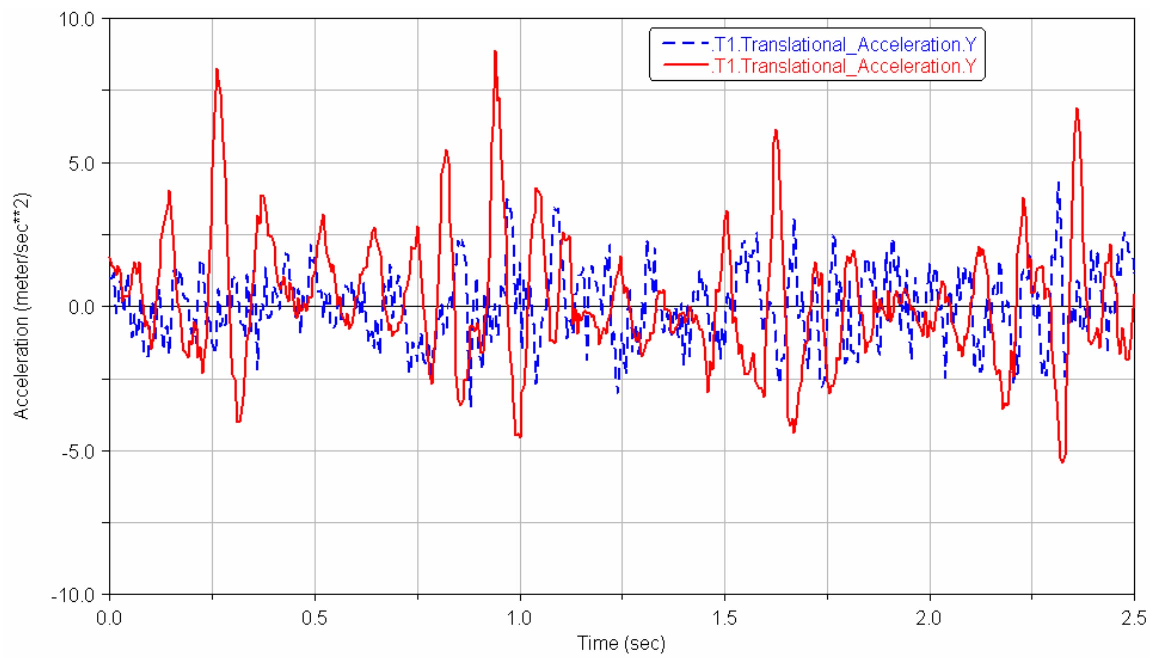

Figure A4-20 Improved rural T2 and T3 predict T1 Nov 20, 2008

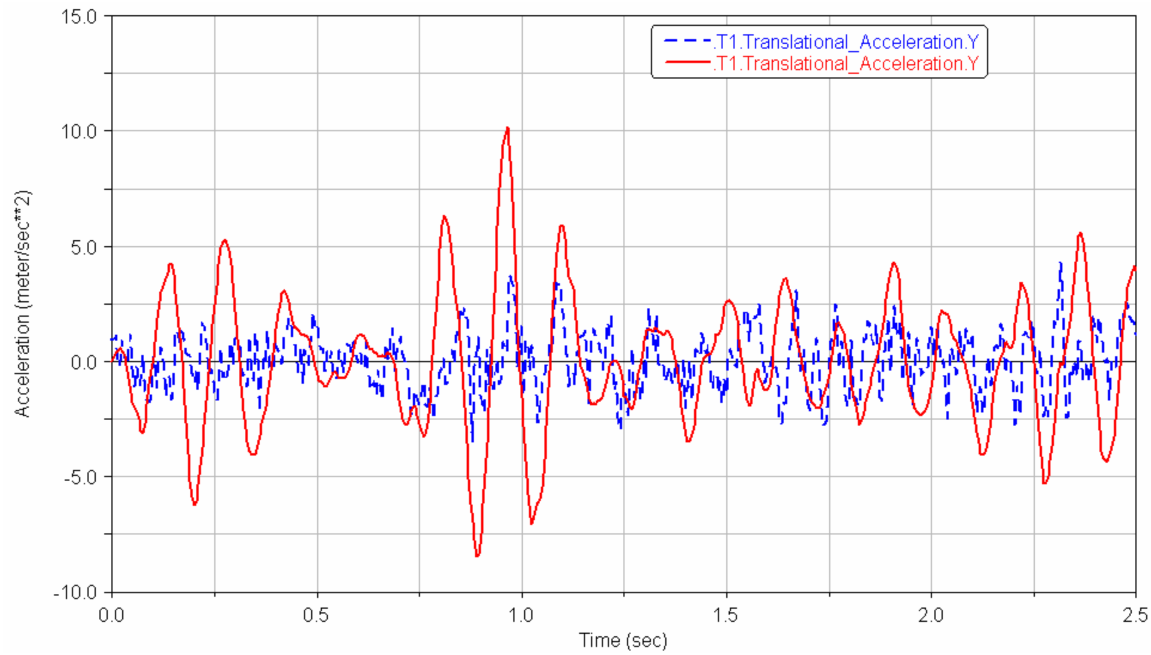

Figure A4-21 Improved rural T6 and T7 predict T1 Nov 20, 2008

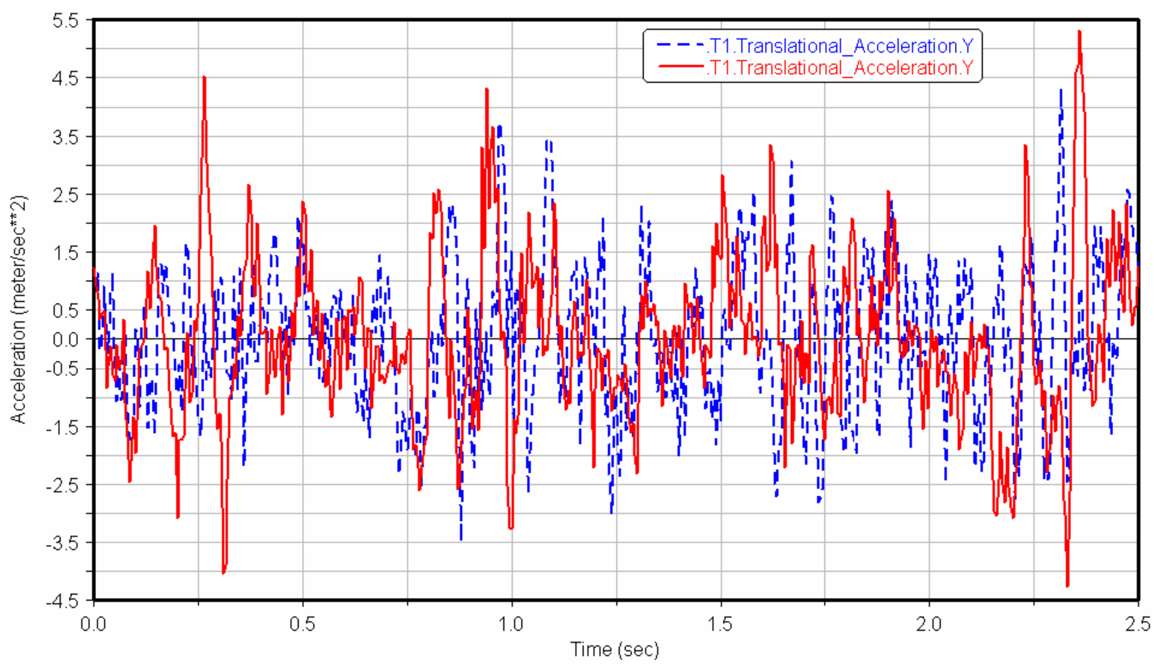

Figure A4-22 Improved rural T2, T6 and T7 predict T1 Nov 20, 2008

Appendix V: February 27, 2008 road test modeling results

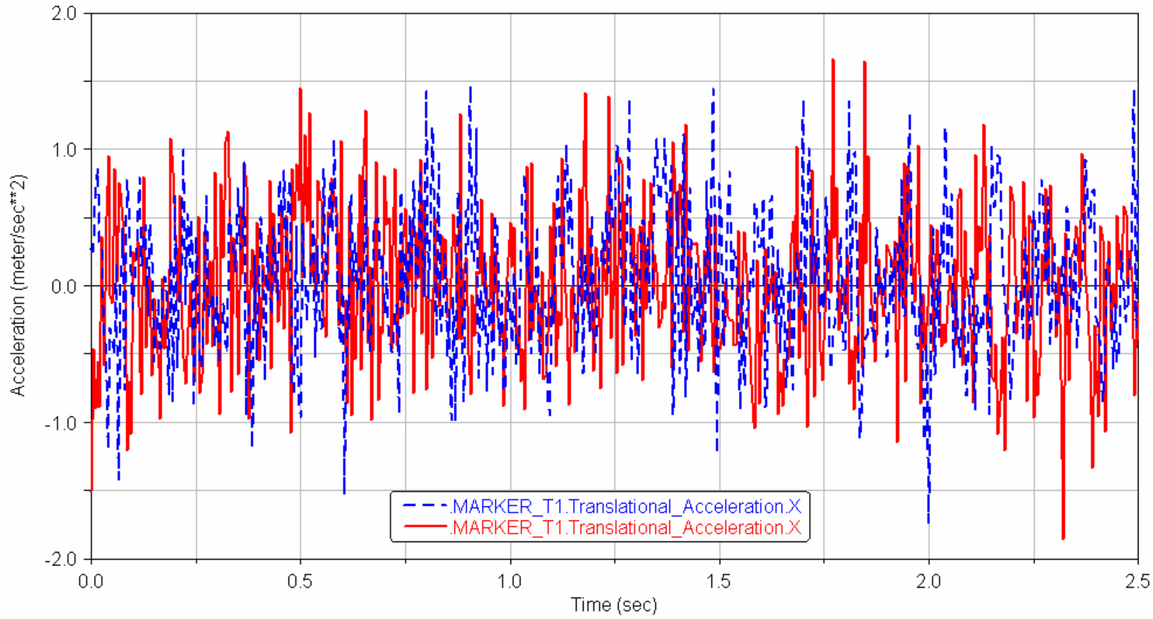

Figure A5-1 Interstate X-direction T2 predicts T1 Feb. 27, 2008

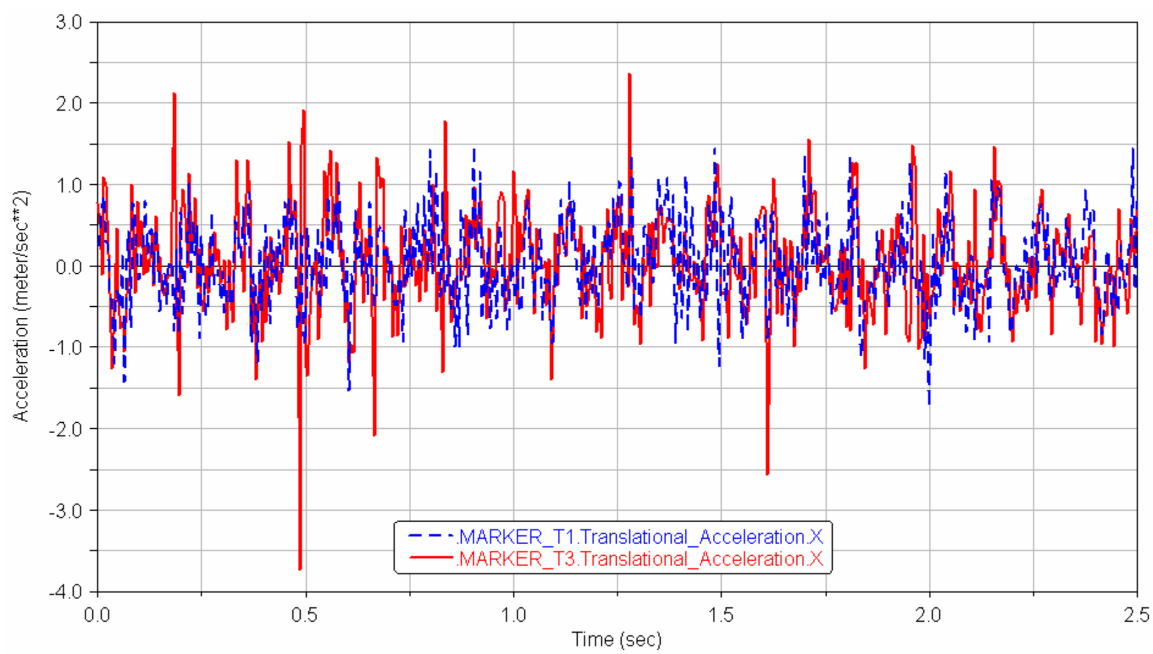

Figure A5-2 Interstate X-direction T3 predicts T1 Feb. 27, 2008

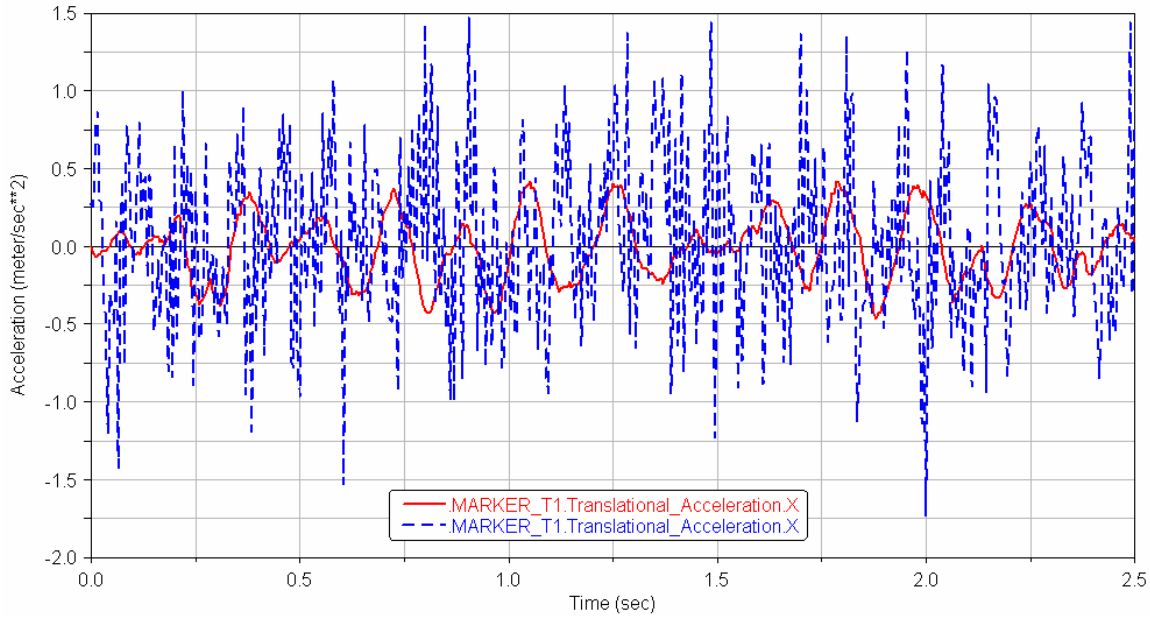

Figure A5-3 Interstate X-direction T6 predicts T1 Feb. 27, 2008

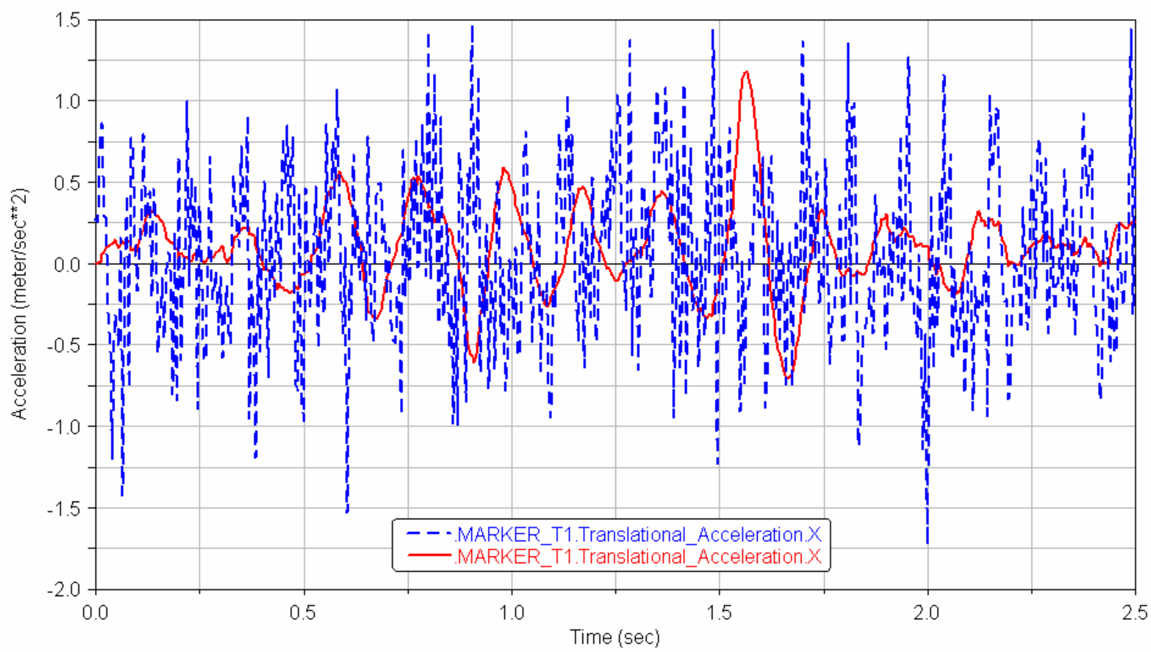

Figure A5-4 Interstate X-direction T7 predicts T1 Feb. 27, 2008

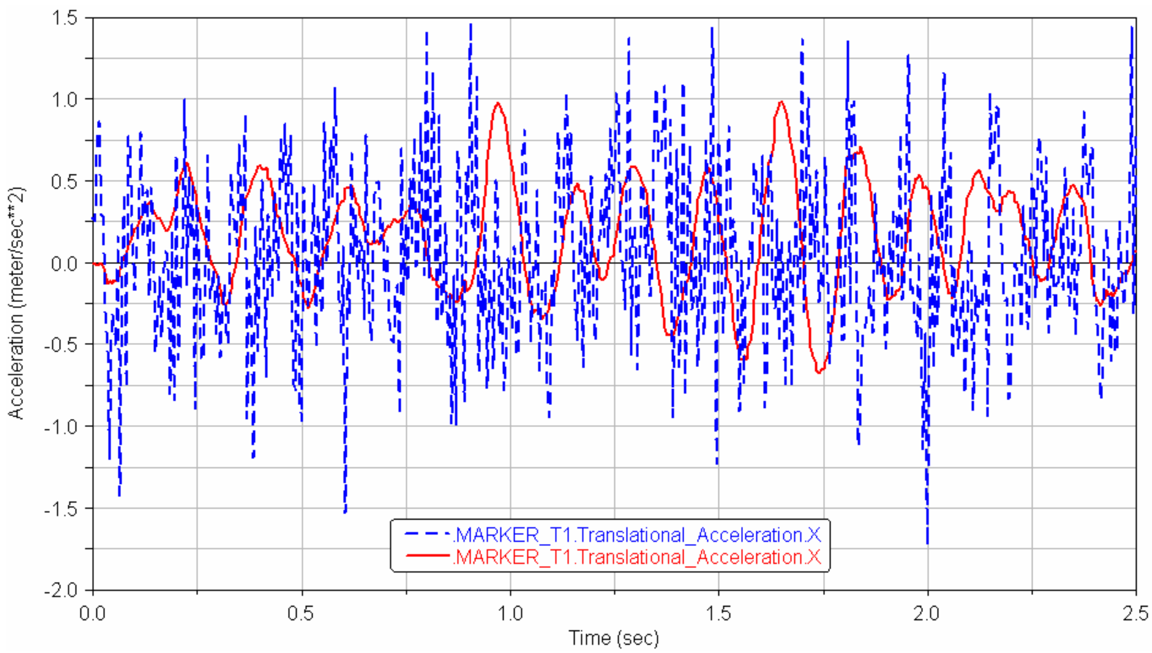

Figure A5-5 Interstate X-direction T8 predicts T1 Feb. 27, 2008

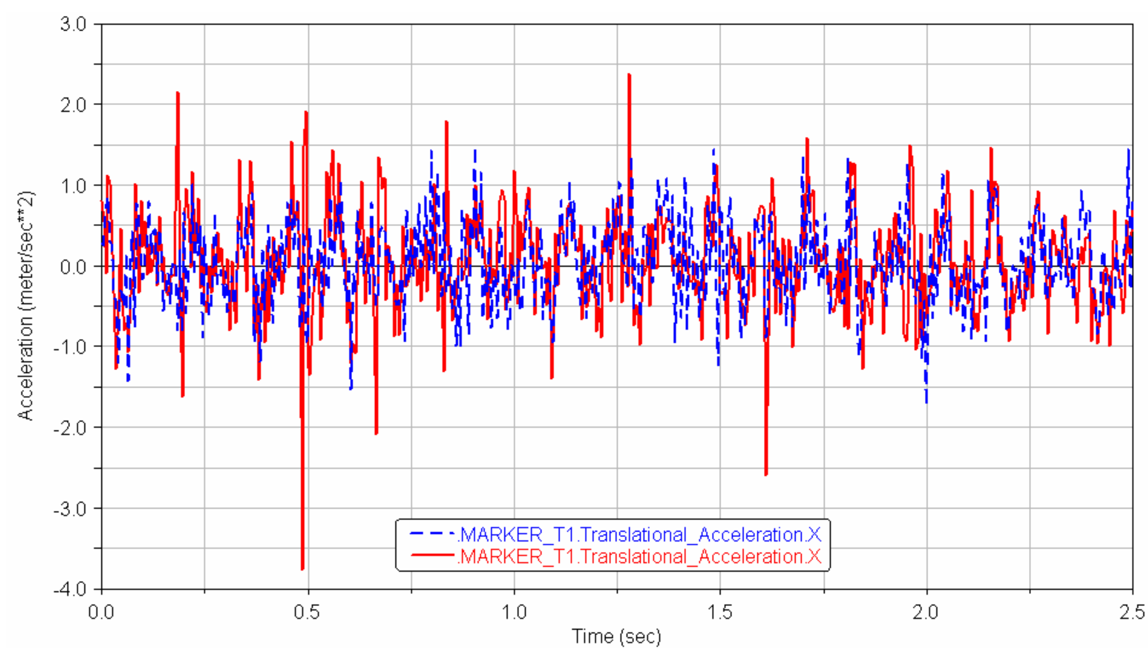

Figure A5-6 Interstate X-direction T2 and T3 predict T1 Feb. 27, 2008

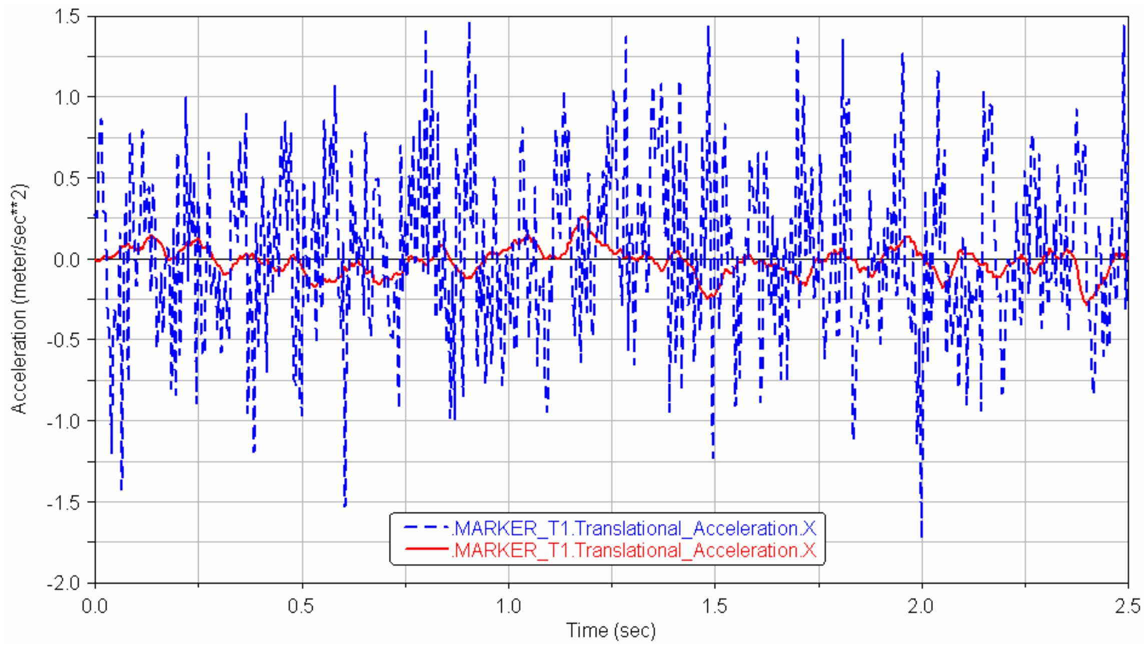

Figure A5-7 Interstate X-direction T6 and T7 predict T1 Feb. 27, 2008

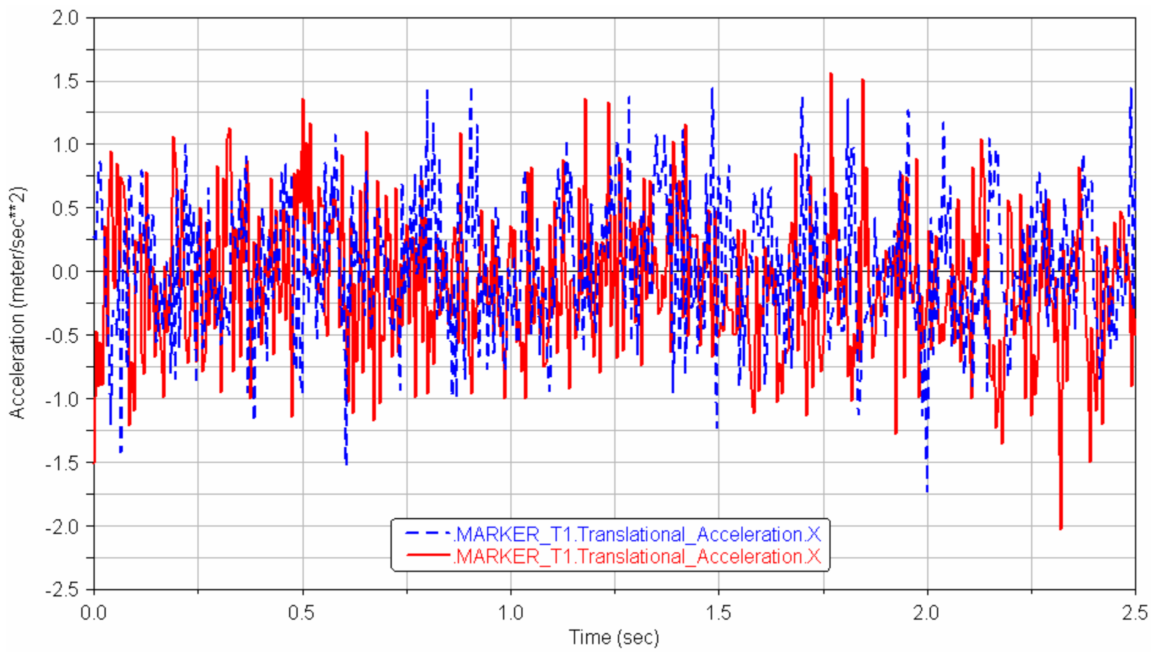

Figure A5-8 Interstate X-direction T2, T6 and T7 predict T1 Feb. 27, 2008

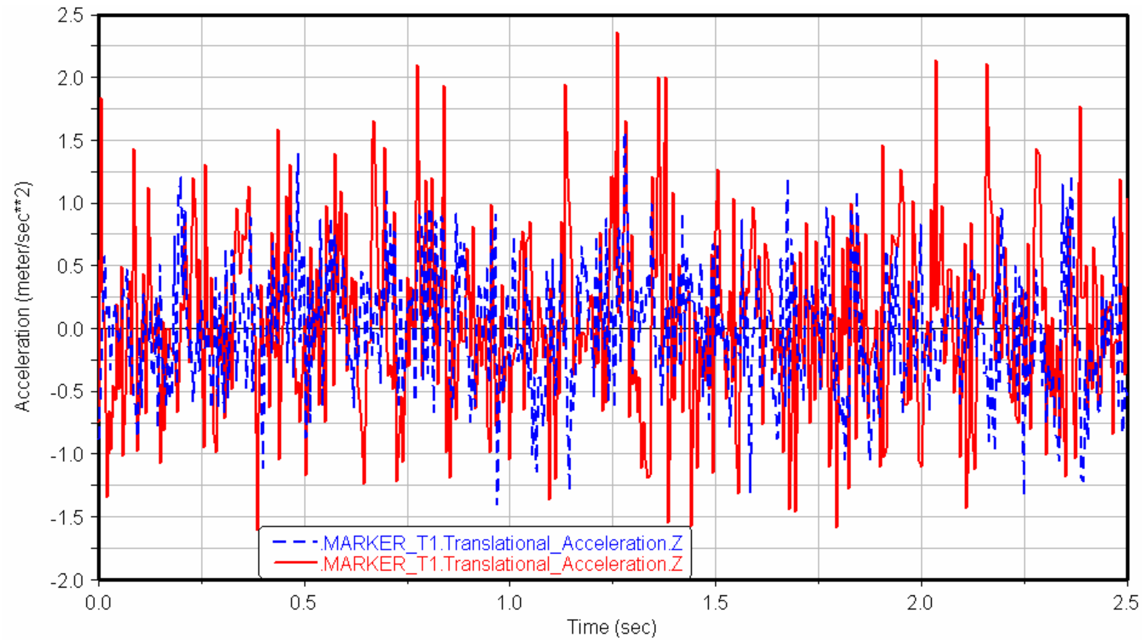

Figure A5-9 Interstate Z-direction T2 predicts T1 Feb. 27, 2008

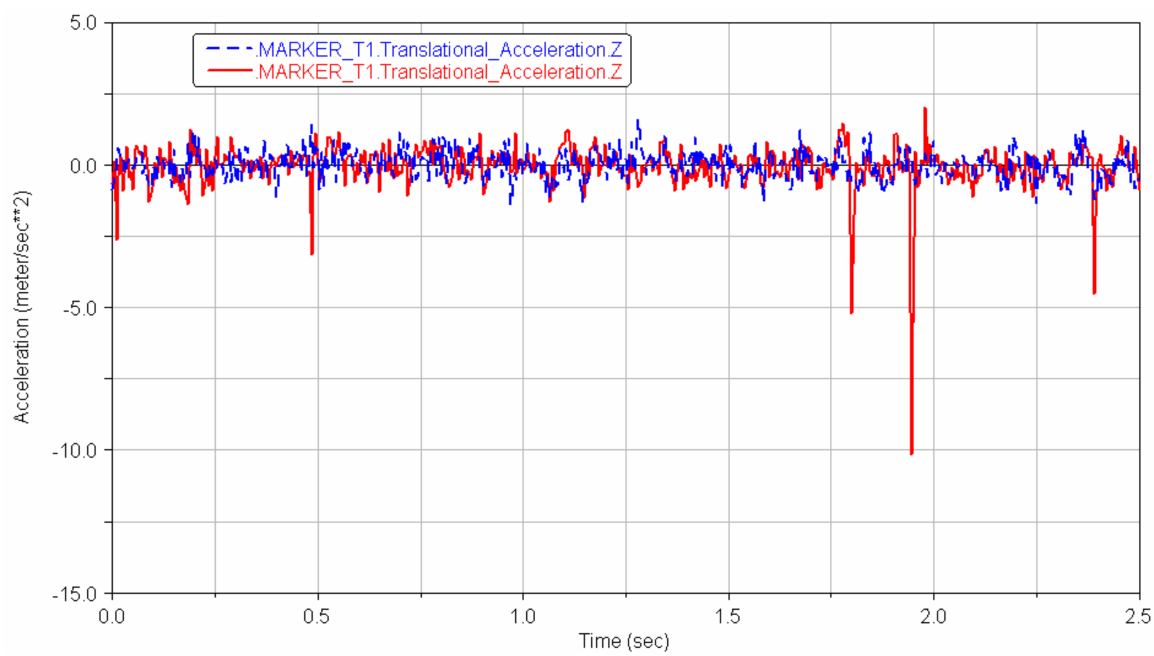

Figure A5-10 Interstate Z-direction T3 predicts T1 Feb. 27, 2008

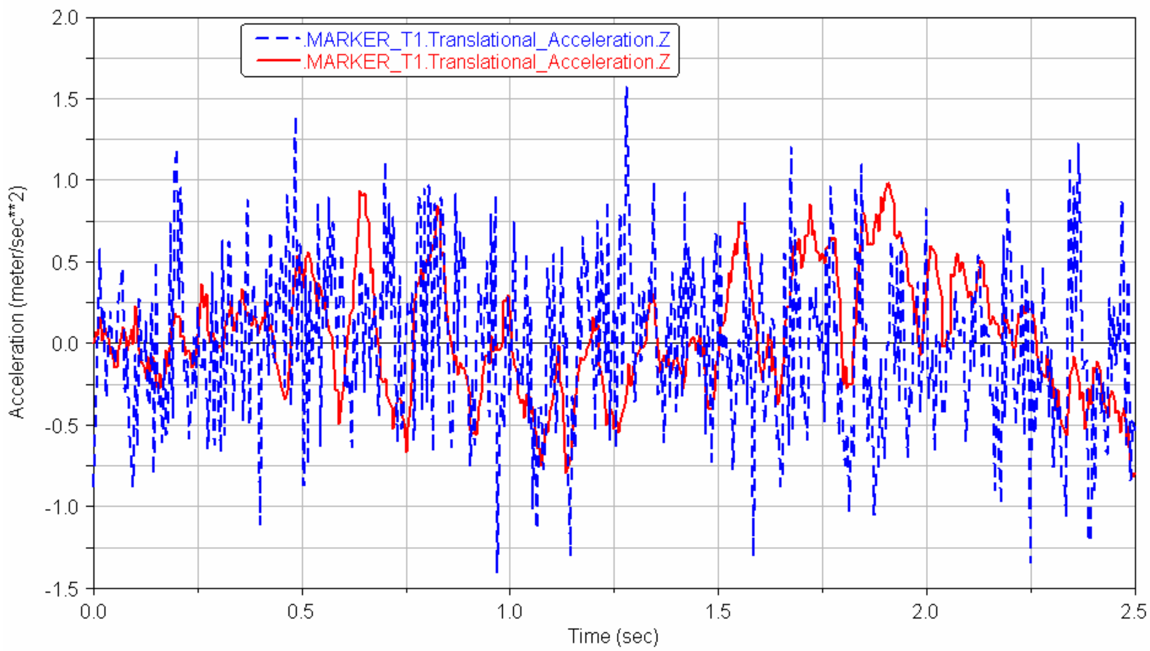

Figure A5-11 Interstate Z-direction T6 predicts T1 Feb. 27, 2008

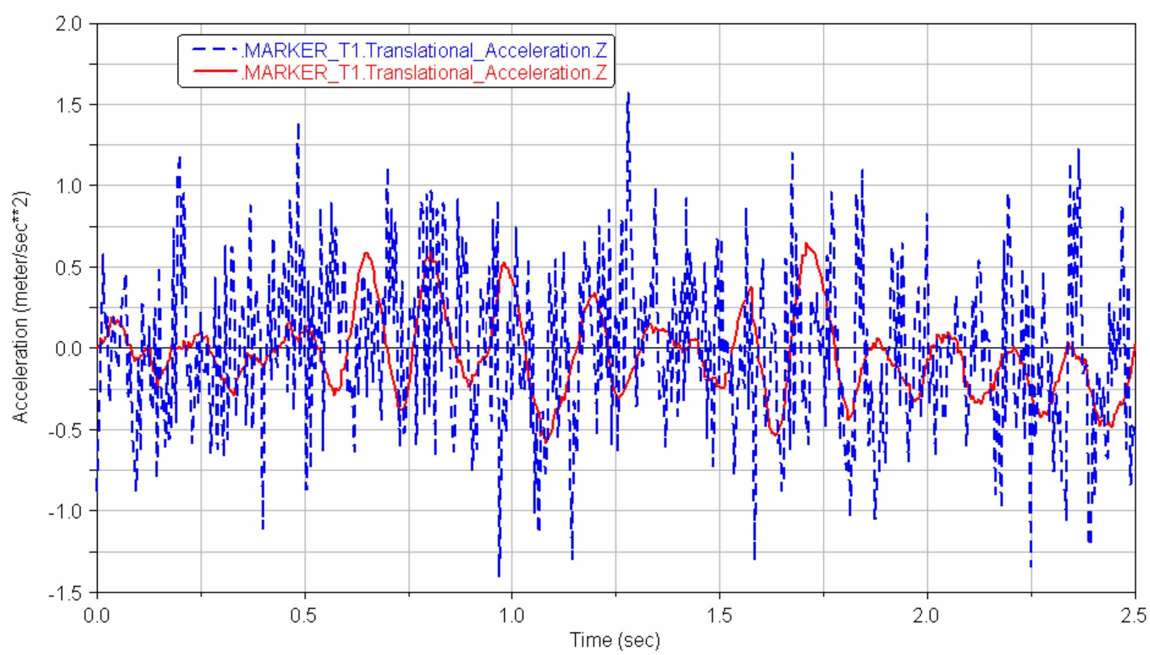

Figure A5-12 Interstate Z-direction T7 predicts T1 Feb. 27, 2008

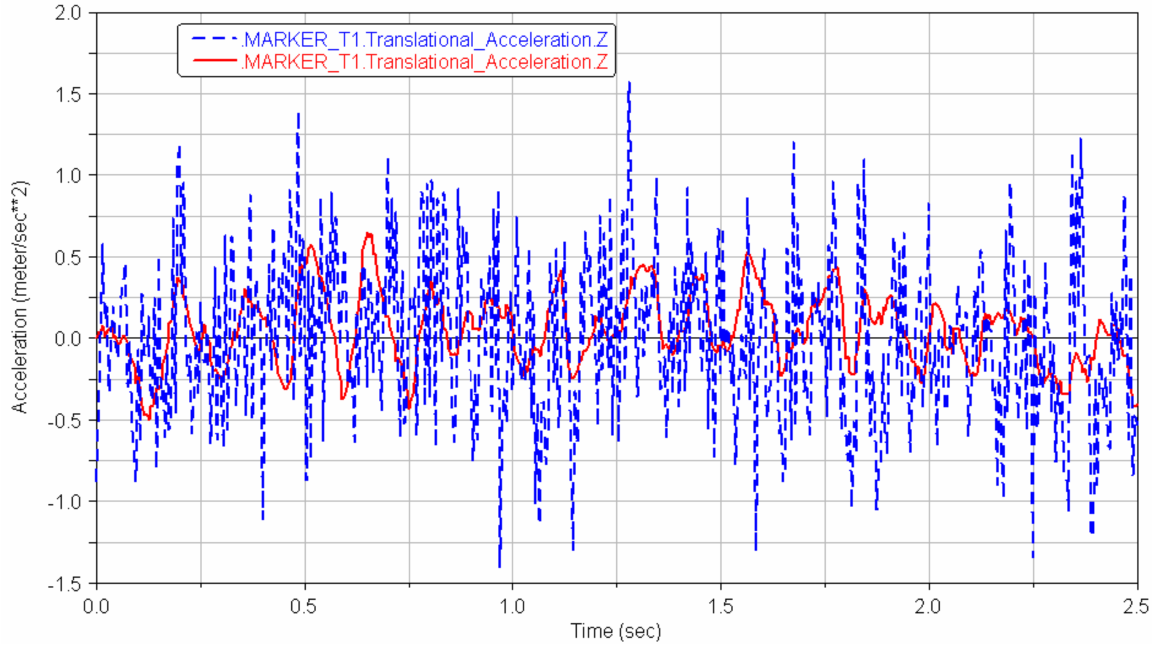

Figure A5-13 Interstate Z-direction T8 predicts T1 Feb. 27, 2008

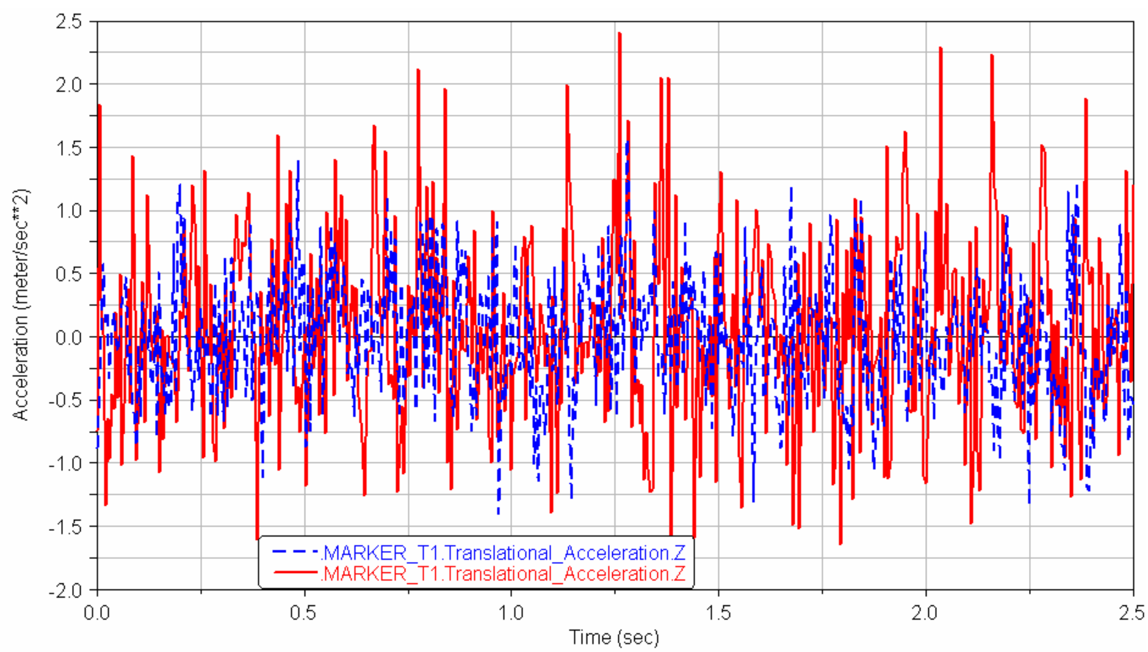

Figure A5-14 Interstate Z-direction T2 and T3 predict T1 Feb. 27, 2008

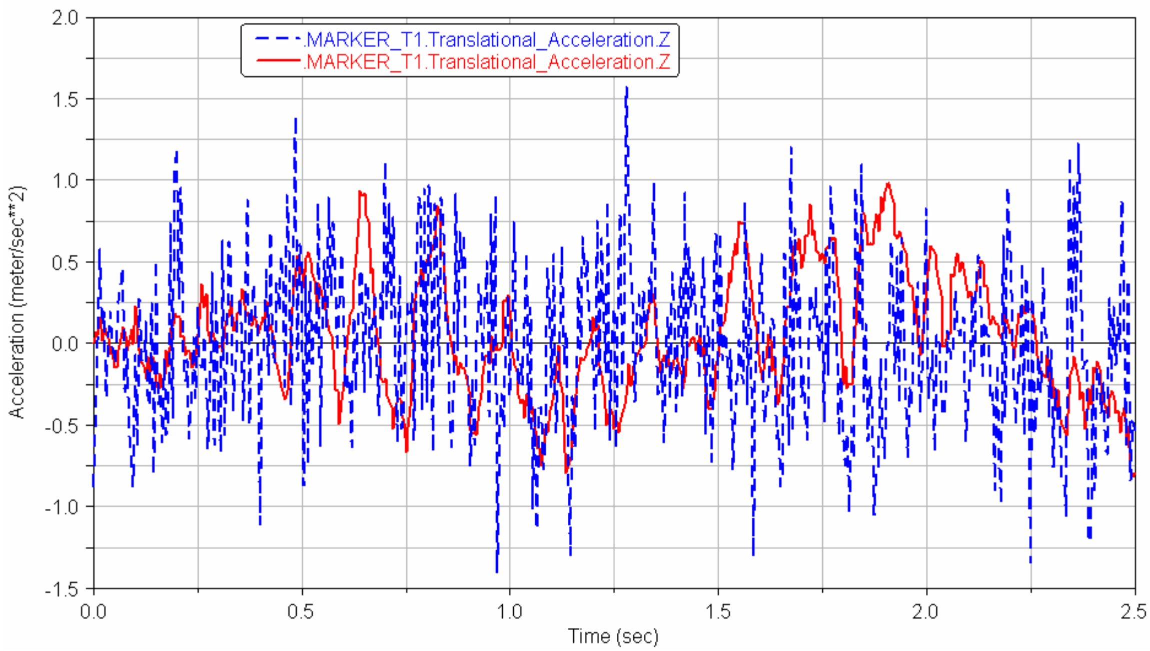

Figure A5-15 Interstate Z-direction T6 and T7 predict T1 Feb. 27, 2008

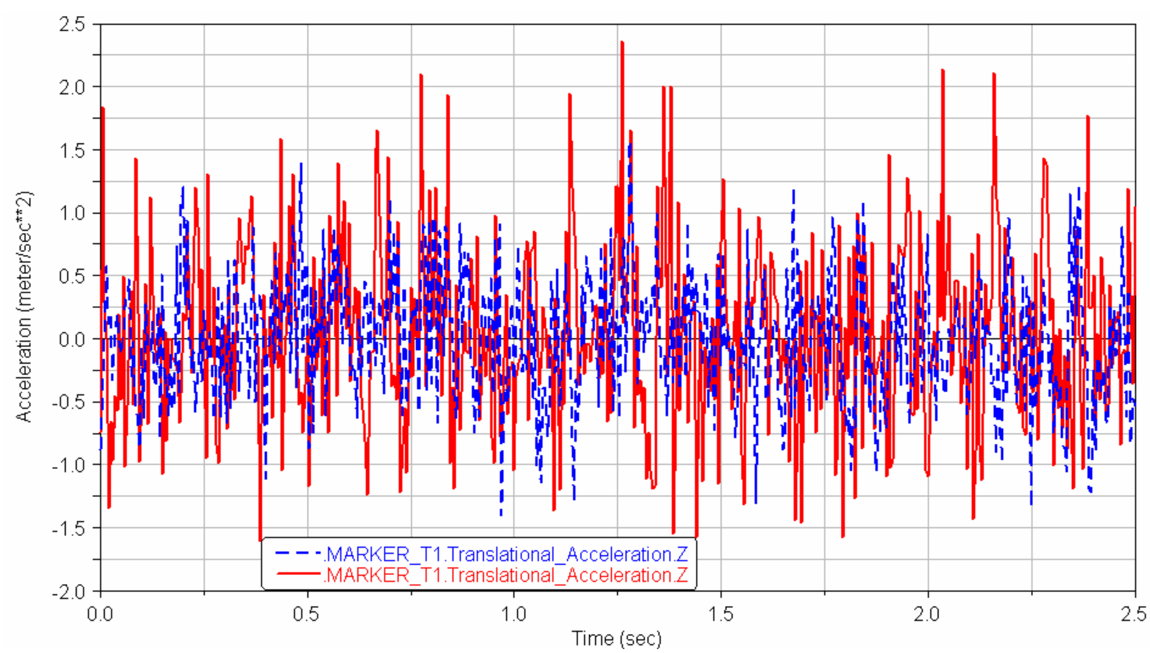

Figure A5-16 Interstate Z-direction T2, T6 and T7 predict T1 Feb. 27, 2008

Vita

Chris Campbell was born in Knoxville, Tennessee on April 4, 1983. He got his Undergraduate degree in Biomedical Engineering from the University of Tennessee, Knoxville in December of 2005. He worked for the University of Tennessee as a graduate research assistant from July 2007 until September 2009, while he attended the school. He graduated from the University of Tennessee with a Master's degree in Biomedical Engineering in December of 2009.