

18 Wheel Truck Dynamic and Durability Analysis using Virtual Proving Ground

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Abstract

Virtual proving ground (VPG) simulations have been popular with passenger vehicles. VPG uses LS-DYNA[®] based non-linear contact Finite Element analysis (FEA) to estimate fully analytical road loads and to predict structural components durability with PG road surfaces and tire represented as Finite elements. Heavy vehicle industry has not used these tools extensively in the past due to the complexity of heavy vehicle systems and especially due to the higher number of tires in the vehicle compared to the passenger car. The higher number tires in the heavy vehicle requires more computational analysis duration compared to the passenger car. However due to the recent advancements in computer hardware, virtual proving ground simulations can be used for heavy vehicles. In this study we have used virtual proving ground based simulation studies to predict the durability performance of a trailer suspension frame, tractor suspension frame and combination of both frames with 18 wheel on a given PG event. The virtual proving ground was also used to predict the stress, strain time histories, spindle loads and the component fatigue life for the given PG event.

Keyword: VPG Tire, Airbag, Suspension, Road Load and Durability

Introduction

In the new product development of vehicle suspension system, the spindle or component loads are very important for optimization of component designs for weight and fatigue life. Accurate loads at the early stage of product development will help to reduce the number of design changes and hence shortening of the product development time and cost. Traditionally, the structural durability studies are carried out using generic load cases or based on the measurements from the previous vehicles. The steps involved in such studies are to estimate the component loads first and then carry out finite element simulations for strength and durability. The simplified assumptions on component boundary conditions during the structural FEA makes the component designs not fully optimized for strength and durability. Virtual Proving Ground (VPG) simulation studies are straightforward to estimate suspension components durability under various vehicle PG events and also useful for predicting the spindle and component loads using full vehicle FE models. In this approach, the vehicle tires, body, frame, suspension systems and road surfaces are represented as FE models. LS-DYNA[®] contact analysis is used with contact interfaces defined between the tire and road surface to predict the spindle loads as well as the component loads and component stress/strain time histories. VPG was also used to predict the critical areas of the components in the early stage of design and development, even before the

availability of the prototype components. Virtual proving ground is best suited for ultimate load events such as Curb striking, square-edge pothole events as these events cause considerable damage to the suspension and frame components. It is very difficult to accurately measure the loads for these events using prototype vehicle testing, as the controlling of vehicle by the test driver becomes very difficult.

VPG Analysis Process

The analysis procedure followed in VPG simulation is as shown in figure 1. The first step is to build the simplified tire FE model and correlate the vertical, lateral and fore-aft stiffness to the measured tire stiffness values. The next step is to build the suspension FE model with bushings, joints, springs, dampers and validate the suspension model under vertical suspension displacement to make sure the spring and jounce bumpers provide the design intent springing curve. The suspension frame or vehicle frame was modeled with shell elements as deformable body. The rigid PG road surface was generated with shell elements based on the physical PG road surface measurements. The next step is to assemble the suspension, frame, tires and road surface and defining the contacts between tire and the road surface to complete the full vehicle model. The sprung and unsprung masses as well as the trailer center of gravity were matched to the design intent vehicle specifications. The VPG (LS-DYNA[®]) analysis duration was estimated based on the vehicle speed and the length of the road surface.

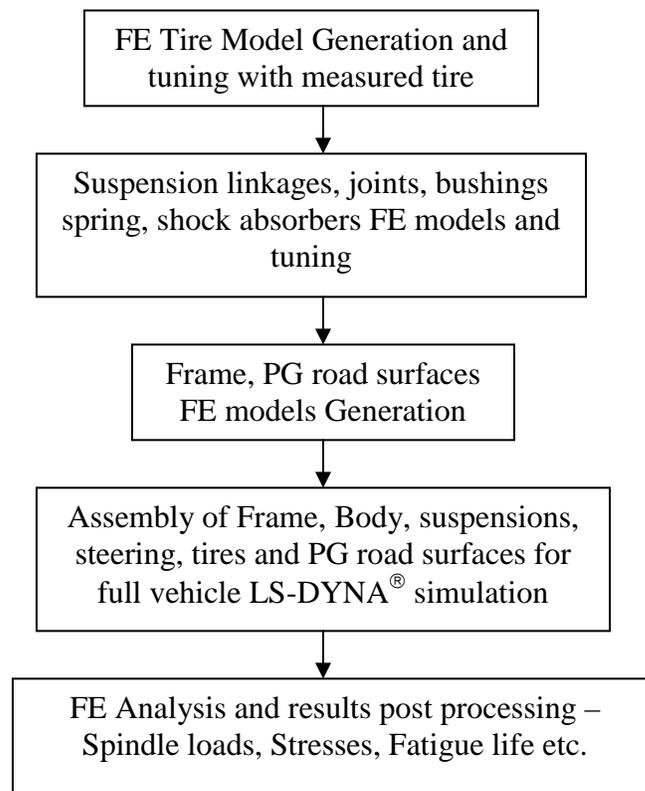


Figure 1: VPG Analysis Flow Chart

The typical analysis duration for single discrete PG event is 2-3 sec and for multiple bump surfaces such as staggered bumps is 15-20 sec. The typical 2 sec event requires about 75- 80 hours solver time (Clock time) for 8 tires trailer suspension with a 2 CPUs HP workstation.

Tire FE Model

In VPG, the vehicle tire is represented as simplified FE model consisting carcass of the tire (but does not include the detailed tread pattern or plies). The tire FE model also contains an internal air bag with tire inflation pressure modeled as a control volume. The tire treads, chafer was modeled as solid elements with Mooney-Rivlin rubber and tire sidewall was modeled as shell elements with elastic material properties. The details of the tire FE model are as shown in figure 2 and 3.

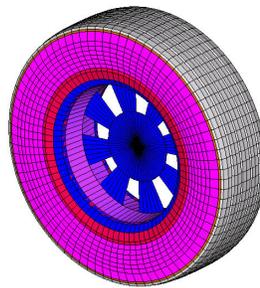


Figure 2: Heavy vehicle tire FE model

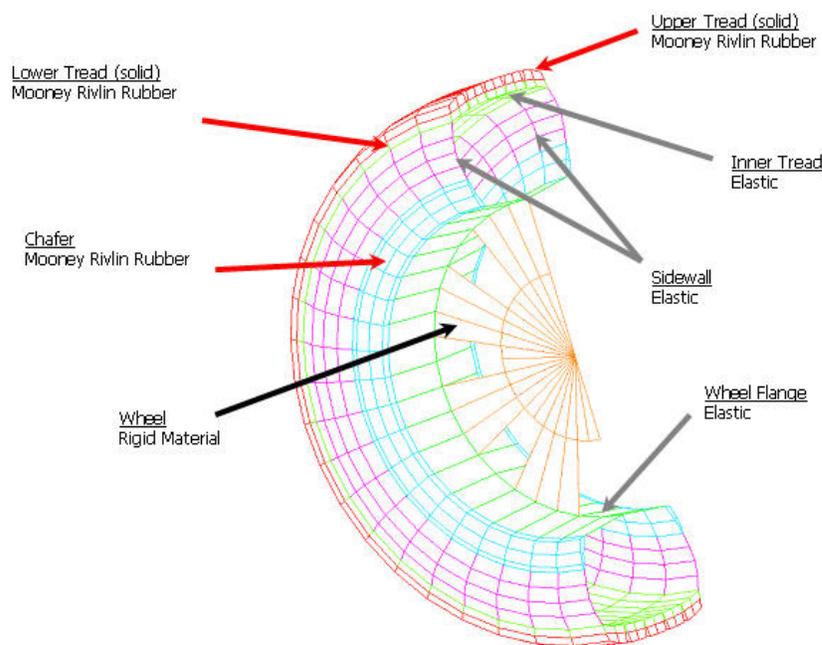


Figure 3: FE model construction in LS-DYNA®

The trailer suspension consists of 8 tires mounted on 4 spindles. The default tire model in VPG is inadequate to represent the heavy vehicle tire characteristics as the default mesh becomes coarse and is unstable during analysis. Hence the tire model for heavy vehicle was generated with finer mesh. Each VPG tire FE model consists of 4768 elements compared to 2500 elements with the default VPG FE model for the tire. The tire model is mounted on a rigid wheel, which was allowed to rotate about spindle axis when connected to spindle with a revolute joint.

The tire model was tuned to match the vertical, lateral and longitudinal tire stiffness at the rated vertical load. The parameters used for tuning of the tire FE model were sidewall thickness, sidewall Young's modulus (E) values. In vertical stiffness measurement using VPG, the wheel rim center was constrained and vertical load was applied at the tire contact patch. The load vs. deflection plot was generated from the simulation studies. Several analysis iterations were carried out to optimize the tire parameters and achieve the tire stiffness closer to the measured values. The wheel & tire mass and mass moment of inertia were matched to the physical assembly. Figure 4 shows tire displacement vs. vertical load and figure 5 shows tire longitudinal displacement with for-aft load at the rated tire vertical load.

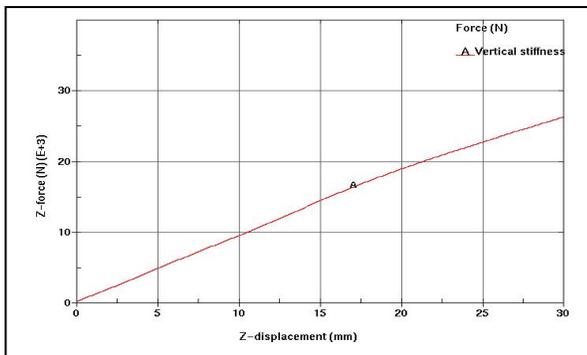


Figure 4: Tire vertical stiffness with FE tire model

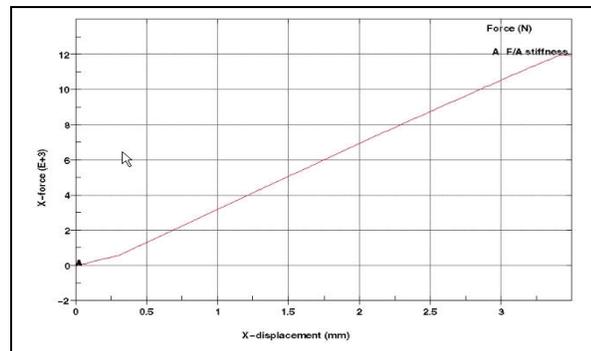


Figure 5: Tire longitudinal stiffness with FE model

Suspension FE Model

A parallelogram trailer suspension, namely upper control arm and lower control arms, were modeled as beam elements as the aim of this analysis was to predict the frame stresses. The suspension and axle components designs used in this model were from the existing system and these designs were already validated in PG and in the customer usage environment. The beam assumptions for suspension components helped to reduce the FE model size. The beams cross sectional properties were selected based on component sectional properties. Suspension component weights and mass moments of inertia in the FE model were matched to the physical component's weight and inertia measurements. The suspension components were attached to the frame using bushings. The bushings in the FE model were modeled as springs in 6 directions (3 translational and 3 rotational). The suspension springs and jounce bumpers were modeled as discrete one-dimensional spring elements. The spring preload as well as the jounce bumper contact point was maintained similar to the test vehicle. Figure 6 shows the trailer suspension FE

model. The suspension spring rates were verified by application of vertical force to the spindles after constraining the spring and shock absorbers at the frame mounting locations. The spindle reaction forces from analysis indicate the vertical stiffness with suspension travel as well as the ride heights at the design load and the jounce bumper contact position during suspension travel. Suitable adjustments were carried out to achieve the design intent suspension springing curves.

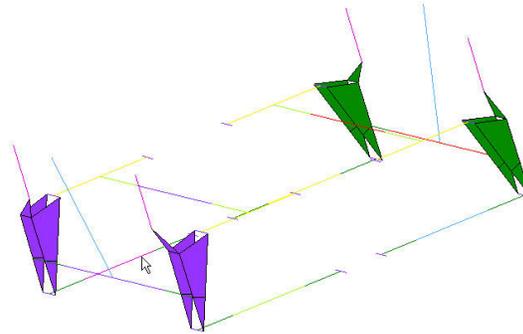


Figure 6: Parallelogram trailer suspension FE model

Frame FE Model

The suspension frame was modeled as shell elements with deformable material properties. Linear piece wise material properties were used. The welds between various frame components were represented as rigid one-dimensional elements. The non-structural masses and the payload on the frame such as air tank were modeled as mass elements at the measured center of gravity locations. The frame FE model is as shown in figure 7.

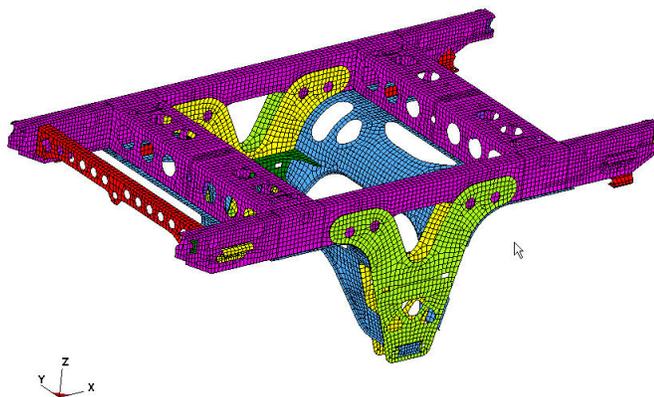


Figure 7: Trailer suspension frame FE model

PG Road Surface FE Model

The proving ground test surfaces were modeled as FE models. The PG road surface was modeled as shell elements with rigid material properties. The discrete events such as staggered bumps, potholes, and calibrated bump events were considered in this study. The PG road surfaces such as calibrated bump were easy to generate an FE model and are useful for vehicle FE model refinement and correlation with the test measurements when the physical prototypes are available. The modeling of the road surface is important as the analysis duration depends on the contact simulation between the road surfaces and tires. Many times, the road is modeled as separate left and right surfaces to reduce the number of elements in contact with the tire, as it reduces the solver duration.

Any PG road can be generated in VPG once we have the measurement data for the road profile. The calibrated bump road surface was generated using measurement data and is as shown in figure 8. The calibrated bump event is very useful for correlation studies between the test and simulation. Vehicle testing was carried out on the calibrated bump surface, to measure spindle vertical displacements as well as spindle accelerations in 3 directions. String pots were used for displacements and accelerometers were used at 4 spindles of the trailer.

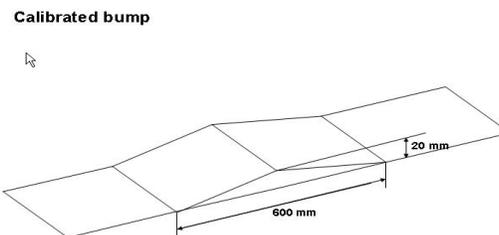


Figure 8: Calibrated bump road surface

Figure 9 shows some of the road surfaces available in VPG software proving ground road surface libraries.

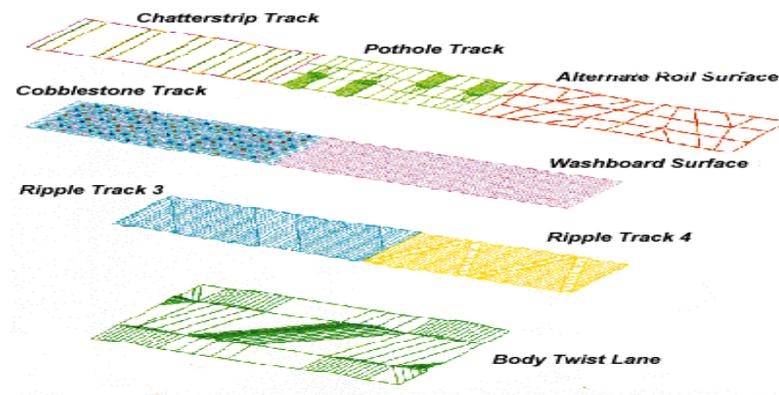


Figure 9: Various PG surfaces FE models

While generating the PG road surface FE model, sufficient length of smooth road surface was provided at the start of the simulation such that the vehicle or trailer FE model gets stabilized before entering on to the road disturbances such as potholes and road bumps.

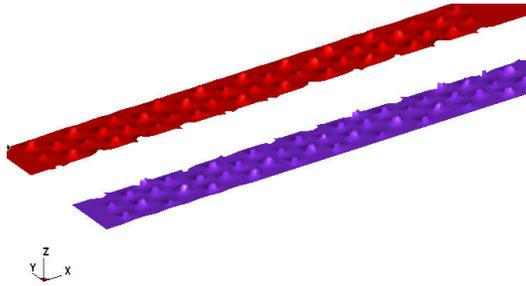


Figure 10: Cobble stone VPG road surface

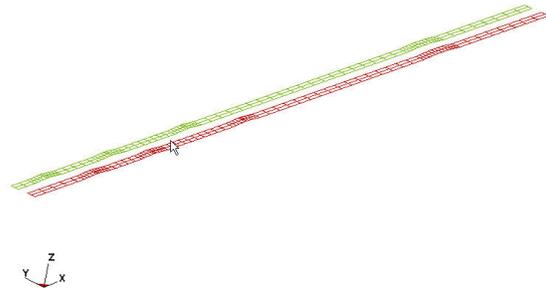


Figure 11: Staggered bump road surface FE model

Trailer System FE Model

The frame, suspension and tire models were assembled to build full trailer assembly FE model. The tire models were connected to the spindle using revolute joints. The weight and the center of gravity location of the trailer assembly were matched to the design intent trailer test vehicle. In order to simplify the contact between road and tire, null elements were added to the tires upper tread. The full trailer suspension FE model with staggered bump road surface consisted of 87,659 elements.

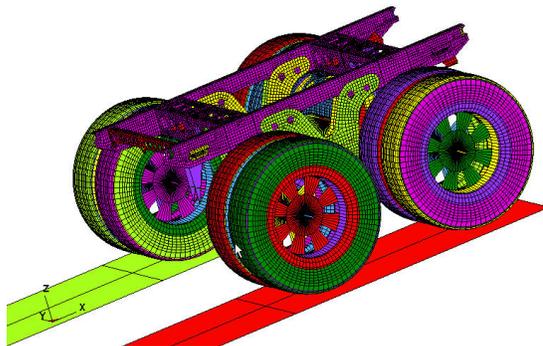


Figure 12: Trailer assembly with 8 tires and PG road

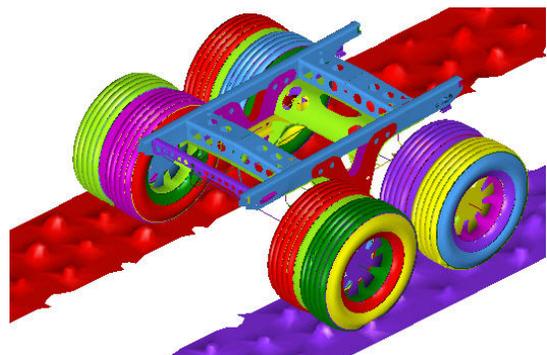


Figure 13: Trailer assembly on cobblestone PG surface

Simulation Duration

The VPG simulation duration depends on the PG event considered for the durability. The discrete events such as calibrated bump require about 2 sec as the vehicle speed for this event was 50 KMPH and the road length was 25 m. The PG event such as cobble stone road surface and staggered bumps located at different spacing require 14.3 sec simulation duration. The vehicle speed considered was 24 KMPH. The proving ground length for staggered bump was 96 meters.

Computer Hardware Requirements

The 14.3 sec VPG (LS-DYNA) simulation for trailer with 8 tires with 87659 elements took about 586 hours of analysis duration with dual processor HP workstation. Since the contact simulation requires large computer resources, VPG studies may require about 2 Giga bites memory and as the analysis result outputs from VPG can vary, the disk space of about 1 – 10 Giga bites are usually required. In order to reduce the analysis duration, parallel processor computing is used along with LS-DYNA[®] MPP version. A typical 8 CPU cluster would reduce the analysis duration by about 5 times.

VPG Analysis Results

The VPG analysis was carried out on cobblestone as well as on the staggered bump proving ground events. The results were post processed using VPG software. The accuracy of the analysis was assessed by checking the hourglass energy. The hourglass energy was maintained to very small compare to kinetic or internal energy.

Figure 14 shows Von Mises stress contour plot for the suspension frame at a given time step. The identification of high stress areas in the early stage of the product design helped to reinforce the structure at high stress areas. VPG software has built in fatigue analysis module to estimate the fatigue damage per cycle for the given proving ground event.

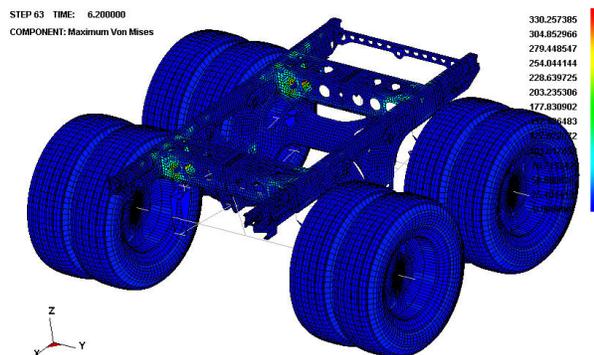


Figure 14: Von Mises stress contour plot of the suspension frame on staggered bump

Figure 15 shows the fatigue damage contour plot for the suspension frame for staggered bump PG event. The strain time history data along with material fatigue properties were used to

estimate the suspension frame fatigue life. Figure 16 shows the suspension frame Von Mises stress contour plot on the cobble stone proving ground event.

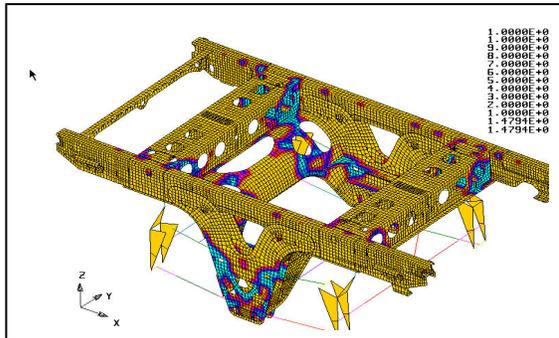


Figure 15: Frame Fatigue damage contour plot on staggered bumps

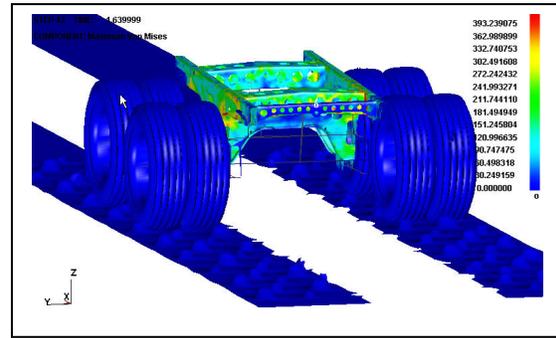


Figure 16: Frame Von Mises stress contour plot on cobblestone road

Figure 17 shows the vertical displacement correlation between the vehicle test and the VPG simulation for staggered bump event. The maximum suspension displacements predicted by VPG were found to be comparable to the vehicle test measurement. The spacing between the bumps in the proving ground and the VPG model were different. The spacing between the bumps was reduced in VPG to reduce the simulation time.

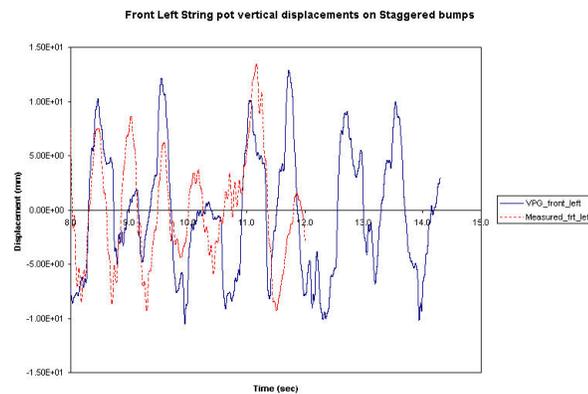


Figure 17: Front left string pot vertical displacements correlation with the test

The spindle loads were predicted for the trailer suspension in this study. The right wheel vertical spindle load was shown in figure 18 and the maximum load was found to be about 2g (where 1g = spindle load corresponding to maximum trailer pay load). The loads seem to be reasonable as the jounce bumpers were not in contact for these staggered bump heights did not activate the jounce bumper. Figure 19 shows the longitudinal spindle loads on the front trailer wheel for staggered bumps event. The maximum load was found to be 0.2 g. Figure 20 shows the vertical spindle load for the rear right wheel of the trailer. The maximum load in this case was also found to be about 2.0 g.

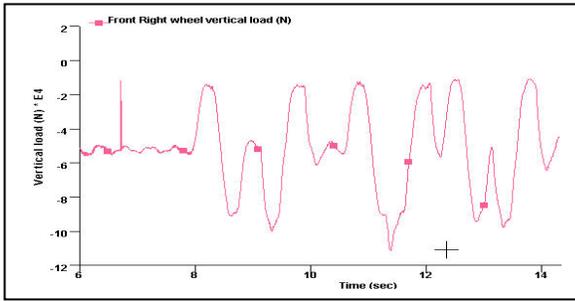


Figure 18: Staggered bump PG event – predicted Spindle Vertical forces on right front wheel

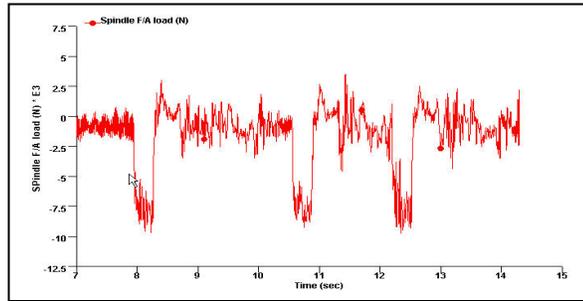


Figure 19: Predicted Staggered bump spindle F/A loads

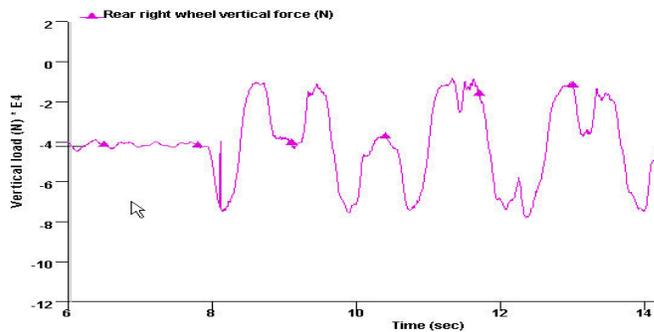


Figure 20: Staggered bump PG Event – Predicted Spindle vertical loads at the rear tire

The predicted spindle loads were not correlated with the test measurement loads in this study as the spindle loads were yet to be measured using wheel force transducers. The spindle loads correlation would be carried out after the vehicle test measurements.

Tractor System FE Model

Upon successful simulation of the trailer model, the tractor model for the same truck was considered for the same purpose of analysis. This is again to find out the road load and stress level on the tractor chassis component and carry out fatigue assessment of the necessary critical parts. Figure 21 and 22 show a view of the chassis frame and the suspensions.

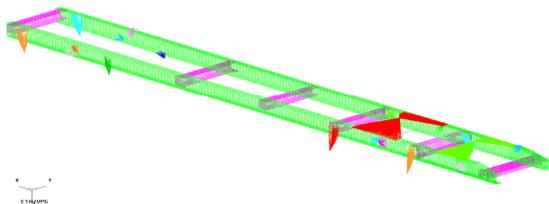


Figure 21: Tractor chassis



Figure 22: Front and rear tractor’s suspensions

The chassis model in NASTRAN format and the suspension models in ADAMS format were both translated to LS-DYNA® model using the VPG preprocessor. After necessary checks, the suspension models were connected to the chassis model at the predefined specified location via constrains or bushings.

To ensure the integrity of all the connectivity of the suspensions and chassis models, an initial gravity run was performed by fixing all spindles. After successful runs, the constraints on the spindles were removed and 10 VPG tire model that were previously tuned, were attached to the spindles via revolute joints. Further more a rigid body representing the cap were attached to appropriate locations on the chassis model to take into account the mass and moment inertial of the cap during the simulation. Figure 22 shows a view of the suspensions, chassis, tires and the cab for tractor model. Figure 23 shows the tractor set to run on a cobblestone road with 15 mph.

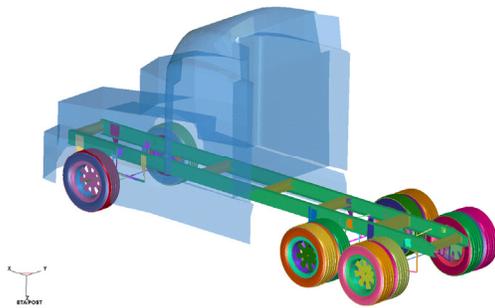


Figure 22: Tractor model, showing suspension, tires, chassis and the cab

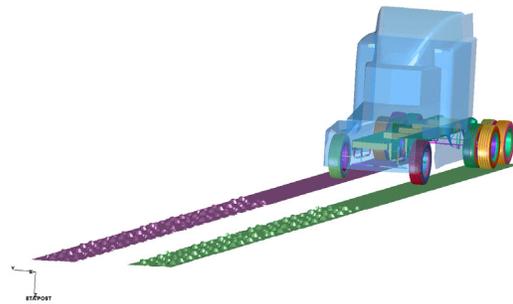


Figure 23: Tractor model on cobblestone road

The resulting simulation contact forces of all tires to road are graphically shown in Figures 24.

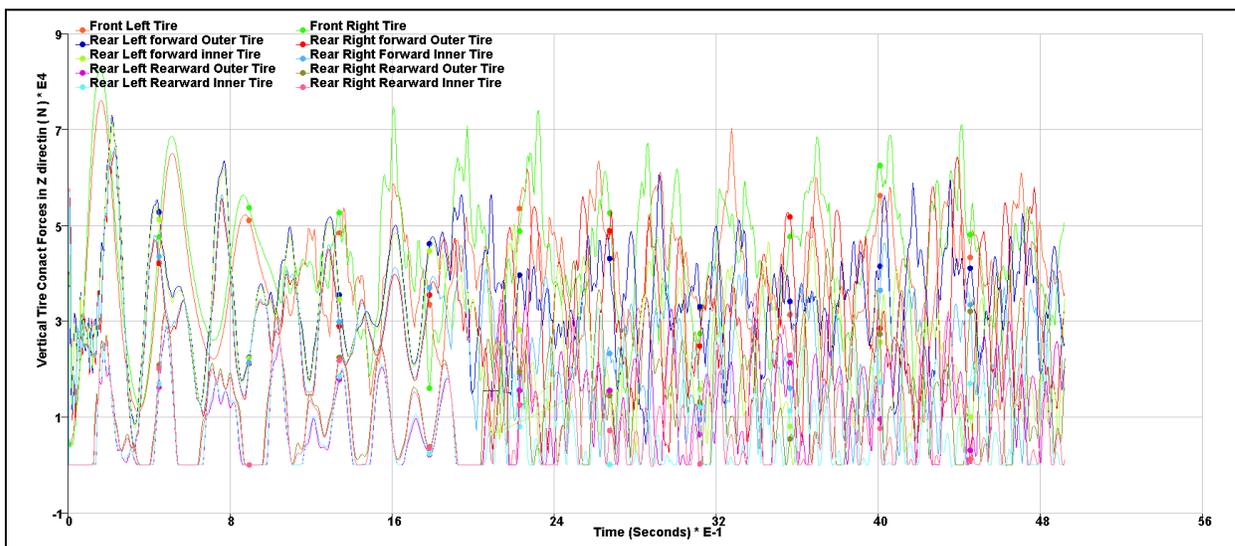


Figure 24 showing the contact forces of all tires to cobblestone road

From Figure 24, the zero contact forces are indications of tires being out of contact with road. The comparison of contact forces with the available spindle forces from test data has indicated a good correlation between the test and VPG simulation results. The correlation curves are not available at this time.

Furthermore, the stress distributions of chassis components are taken to do fatigue assessment.

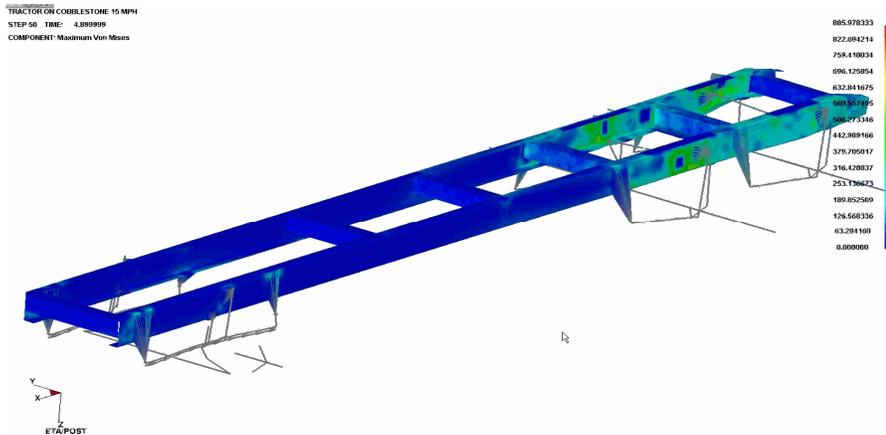


Figure 25: showing the Von Mises stress distributions.

18 Wheel Truck System FE Model

Upon complete successful simulation and validation of the trailer and tractor model, it was decided to put both model together and do the necessary changes to make the full 18 wheel truck model. Figure 26, shows the complete 18 wheel truck model with cab and the container box modeled as a rigid body.

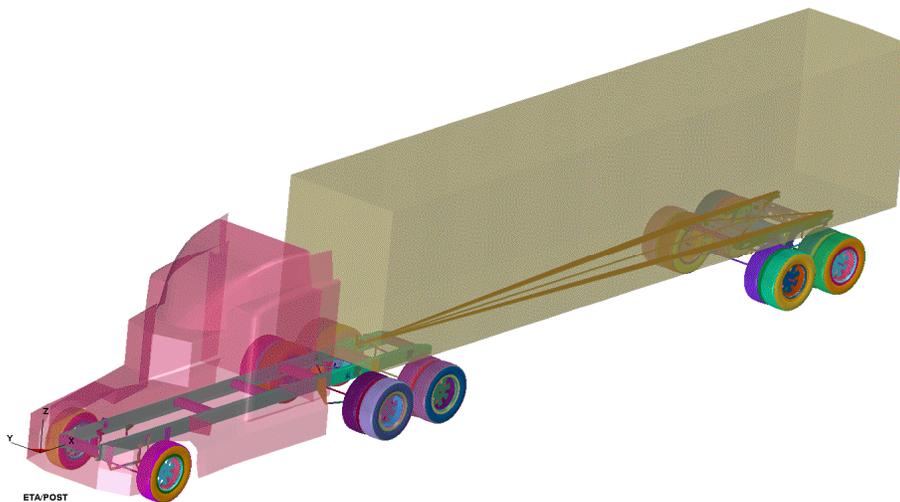


Figure 26, shows the complete 18 wheel truck model

The 18 wheel truck model was set to travel with 20 mph on a staggered road for 15 seconds simulation as shown on Figure 27.



Figure 27: showing the 18 wheel truck on a staggered road

The comparison of contact forces with the available spindle forces from test data has indicated again a good correlation between the test and VPG simulation results. The correlation curves are not available at this time.

Figure 28 shows the contact tire forces with staggered road only for left hand side for observation. From Figure 28, the zero contact forces are indications of tires being out of contact with road. Should the speed be reduced form 20 mph to 10 or 5 mph, there tires might be found to be in contact with the road at all time.

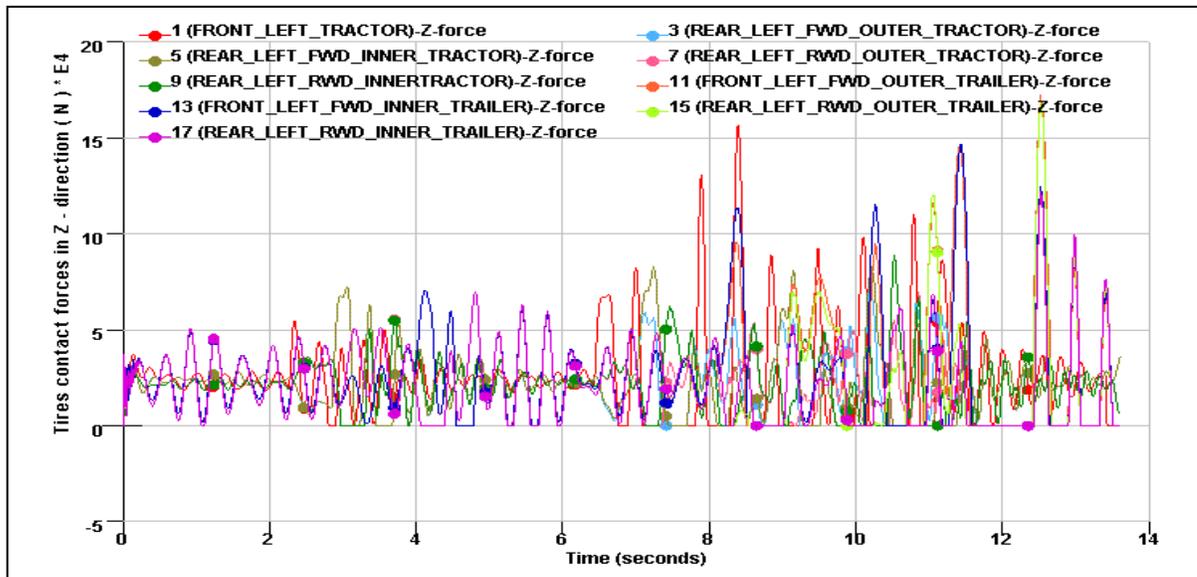


Figure 28 showing the contact forces of all tires to staggered road

Conclusion

Through vehicle suspension virtual prototyping and the virtual proving ground simulation the suspension system durability performance can be estimated before physical prototypes build resulting in robust suspension system. At Arvin Meritor, the advantages of this approach and virtual simulation models have been developed and are being utilized.

Acknowledgments

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