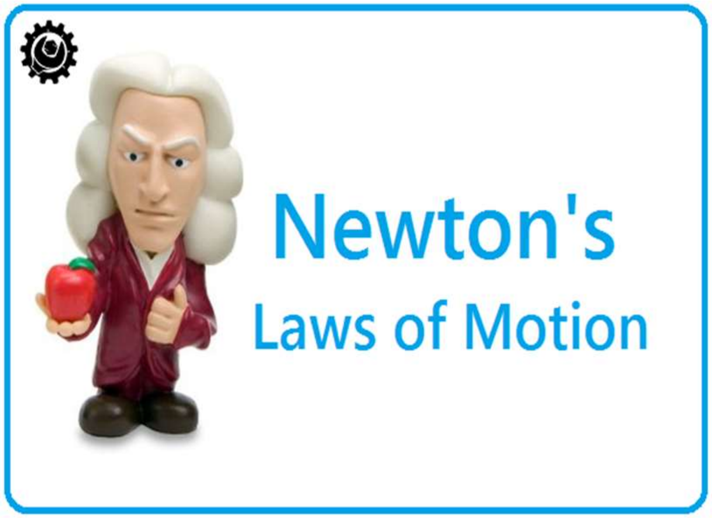
Vehicle-Track Modeling and Simulation

by Ralph Schorr, PE

Objectives for Multi-Body Simulations

- Safe operation of the railroad vehicles
- Provide best dynamic performance (pass required tests)
- Parametric studies
- Determine speed constraints for wheel/rail conditions
- Predict new and/or worn condition performance
- Determine cause of derailments
- Wheel/Rail wear and RCF prediction studies *

Governing Laws of dynamic simulations



1st Law An object at rest will stay at rest , and an object in motion will remain in motion at a constant velocity , unless acted upon by an unbalanced force.

Law of Inertia

2nd Law Force equals mass times acceleration. **Force = Mass * Acceleration**

3rd Law For every action there is a reaction.

Action - Reaction

Basic Motion equations

These Basic equations quickly evolve Into advanced Multi-Body systems with a large number of Degrees-of-Freedom in a stiffness Matrix

Multi-Body Simulation software

Equations: Linear vs. Rotational Motion

Linear Motion Equations	Rotational Motion Equations
$s = v_{avg}t$	$\theta = \omega_{avg}t$
$s = v_i t + ½a_{avg}t^2$	$\theta = \omega_i t + ½\alpha_{avg} t^2$
$v_{avg} = (v_f + v_i)/t$	$\omega_{avg} = (\omega_f + \omega_i)/t$
$a_{avg} = (v_f - v_i)/t$	$\alpha_{avg} = (\omega_f - \omega_i)/t$
$2a_{avg}s = v_f^2 - v_i^2$	$2\alpha_{avg}\theta = \omega_f^2 - \omega_i^2$

Currently available programs

Multi-body simulation programs

- NUCARS®
- VAMPIRE®
- GENSYS
- Adams/Rail
- SIMPACK Rail
- Universal Mechanism
- VI-Rail

Co-simulation add-ons

- Simulink
- Matlab
- CONTACT – Vortech.nl
- Archard's wear model

Train Operations and Energy Simulator (TOES™)

- **TOES™ is a comprehensive train dynamics model**
  - Developed for and licensed to AAR-member railroads
  - Models longitudinal motion of each vehicle in the train
  - Ability to simulate many operating scenarios
  - Contains several pre- and post-processor tools
    - Build simulation environments
    - Analyze simulation results

Simulation of Train Action to Reduce Cost of Operations (STARCO™)

- **STARCO™ is a version of the TOES™ software available to railways operating outside of North America**
  - STARCO offer the same basic simulation capabilities as TOES software
    - Models longitudinal train action given train, track, and operation inputs
  - Allows simulations using track profiles and rolling-stock specific to the licensed railway
  - Several licensed users around the world

starco™

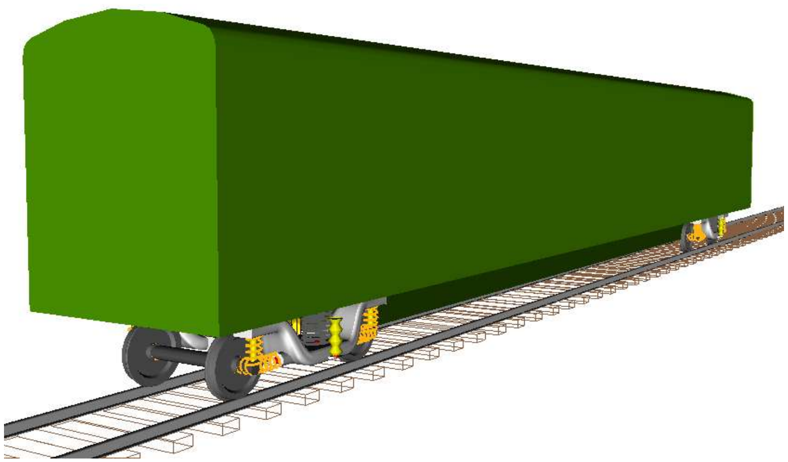
Software MBS validation

- **Manchester Benchmark 1997 originated by Simon Iwnicki at Manchester University**
  - **Results showed that 3 of the 5 programs provided good agreement with reasonable results**
  - **GENSYS, NUCARS® and VAMPIRE®**
  - **Models were produced by experts in the specific software being reviewed**

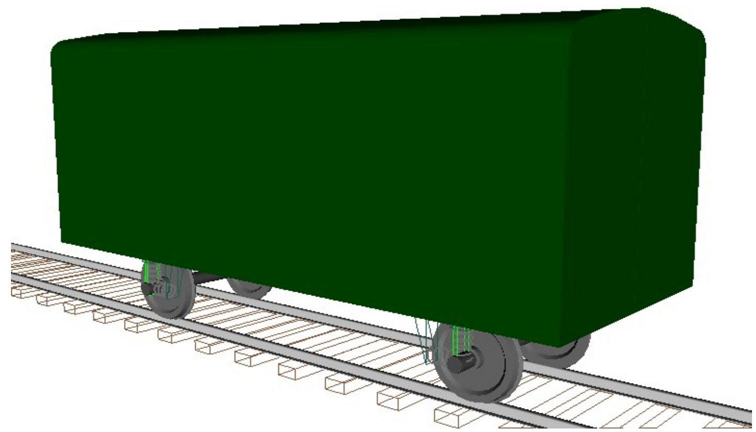
Manchester benchmarks: Universal Mechanism models

Manchester benchmark 1

Passenger coach



www.umlab.ru



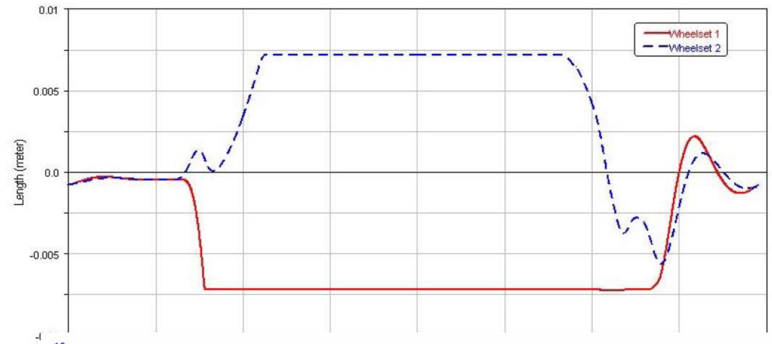
Manchester benchmark 2

Freight vehicle

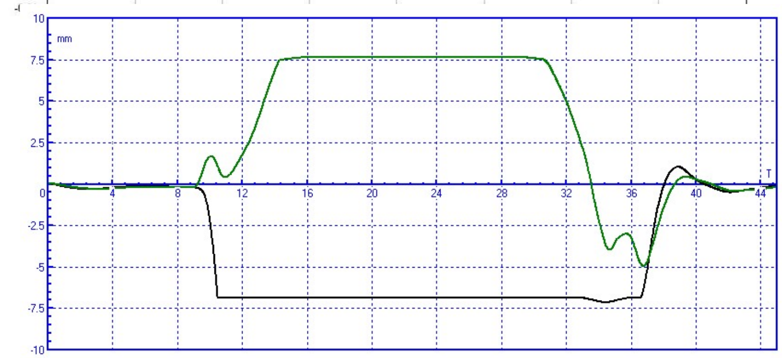
Manchester benchmarks: Comparison of simulation results ADAMS/Rail – UM

Vehicle 1, Track 1

Lateral displacement of wheelsets 1, 2



ADAMS/Rail



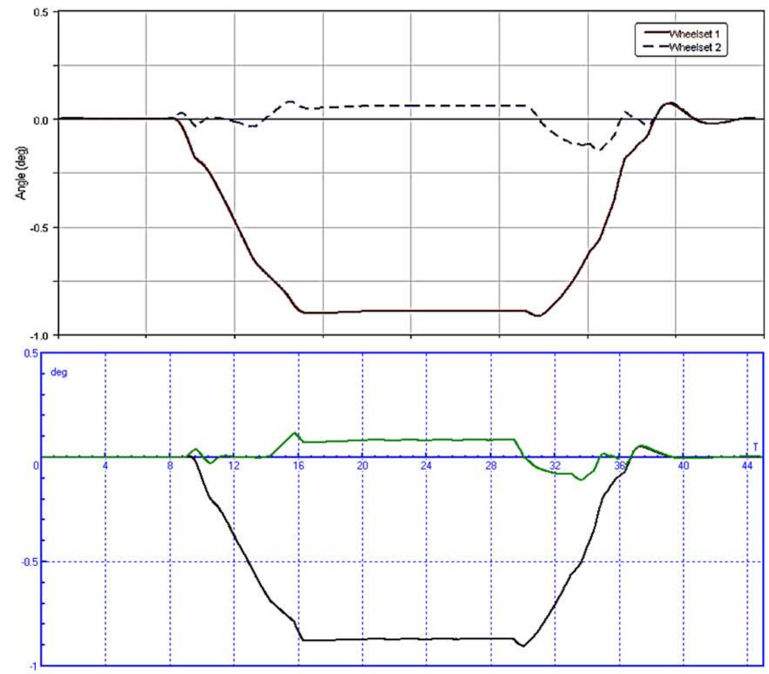
UM

Manchester benchmarks: Comparison of simulation results ADAMS/Rail – UM

Vehicle 1, Track 1

Yaw angle of wheelsets 1, 2

Angle in degrees

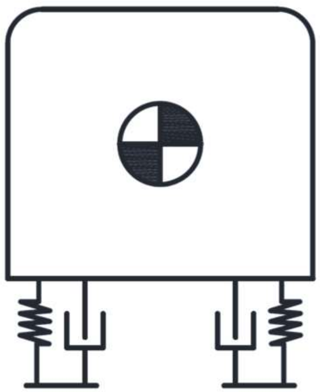


ADAMS/Rail

UM

Vehicle-Truck Dynamics

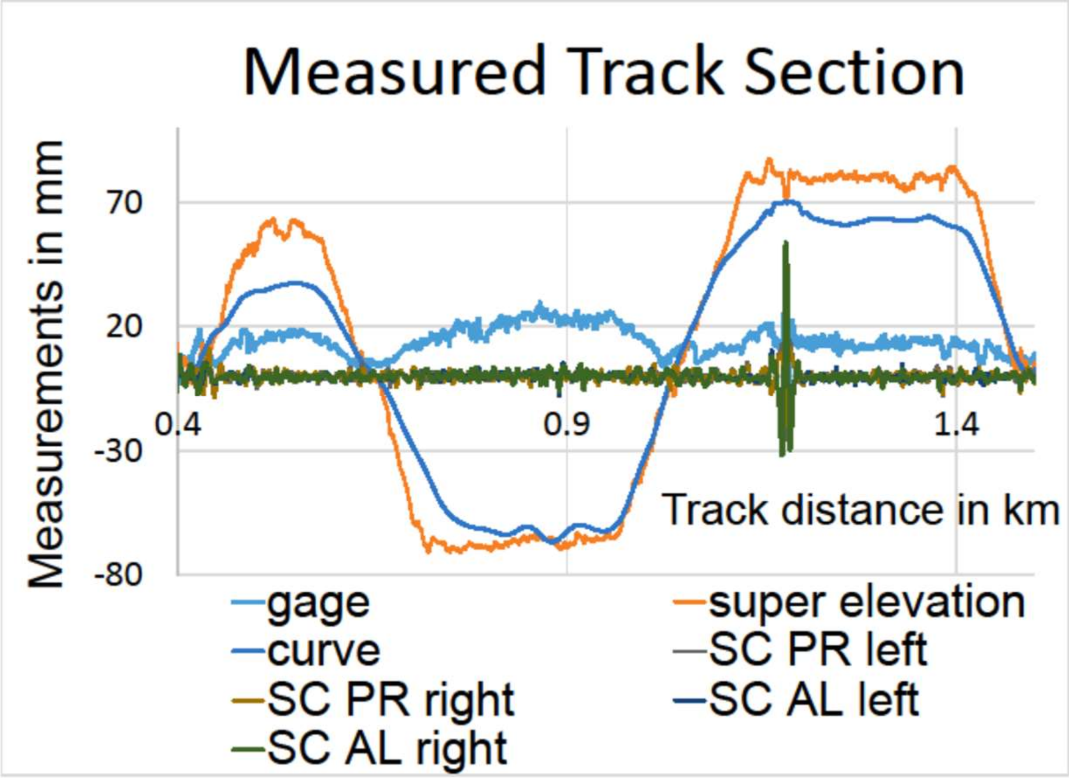
- Track Input
- Wheel to Rail Contact
- Mass/Inertias (Car Body, Truck Components)
- Dynamic Influences (CG, bogie center distance)
- Friction
- Spring Suspension
- Suspension Damping (or hydraulic damping)
- Speed (design or unbalance condition)



Track geometry files

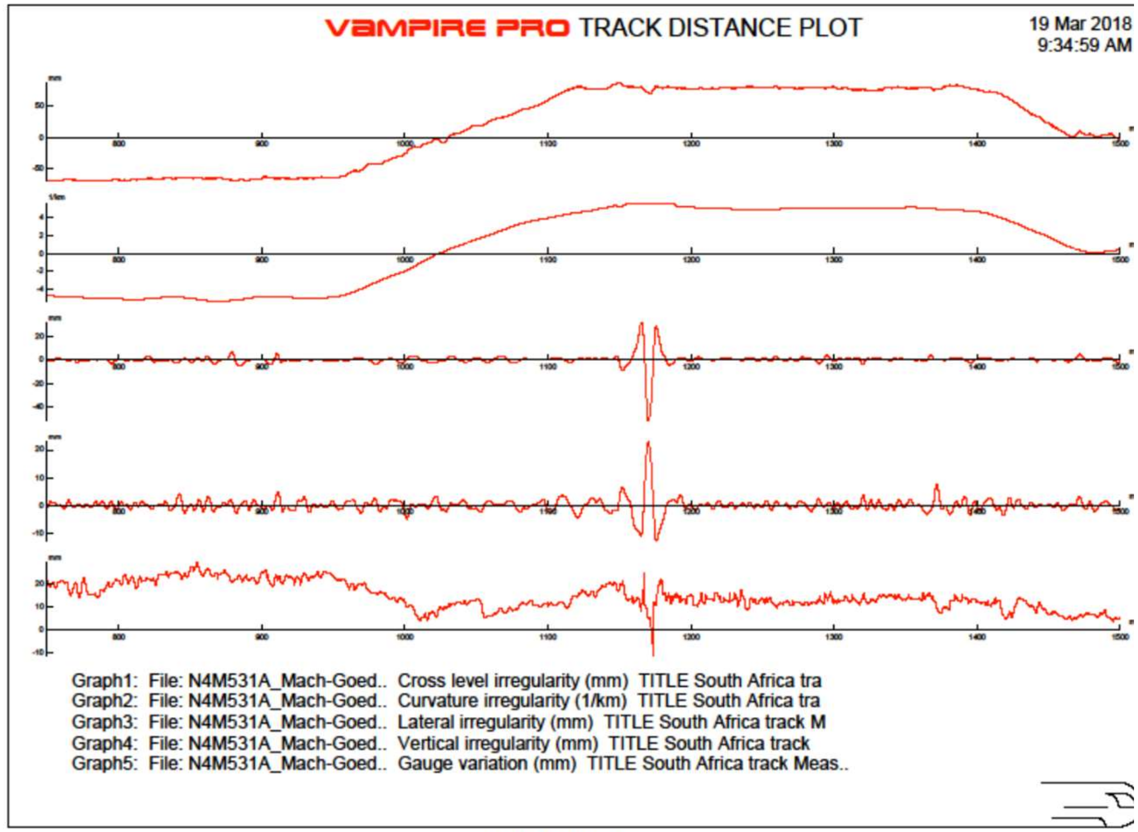
Measured track

SC for Space Curve
PR is Profile
AL is Alignment



Track Irregularity File

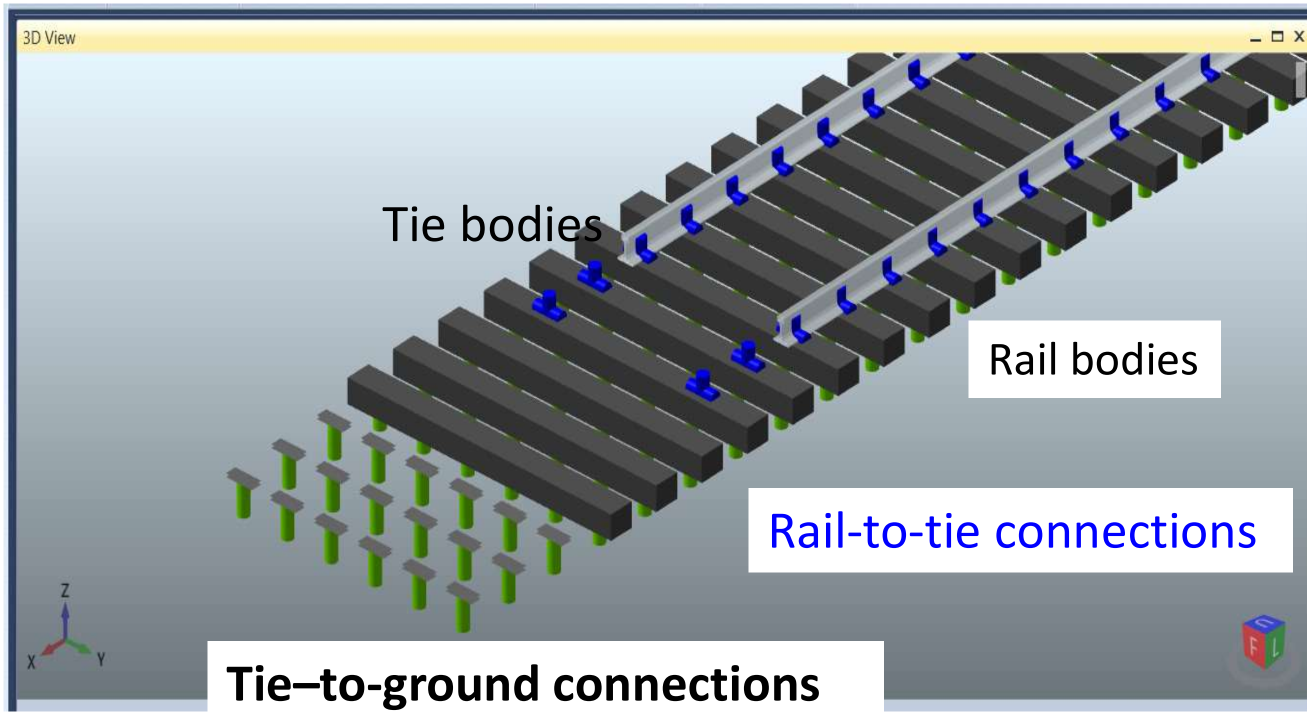
Measurement of turnout is displayed



VAMPIRE Plot

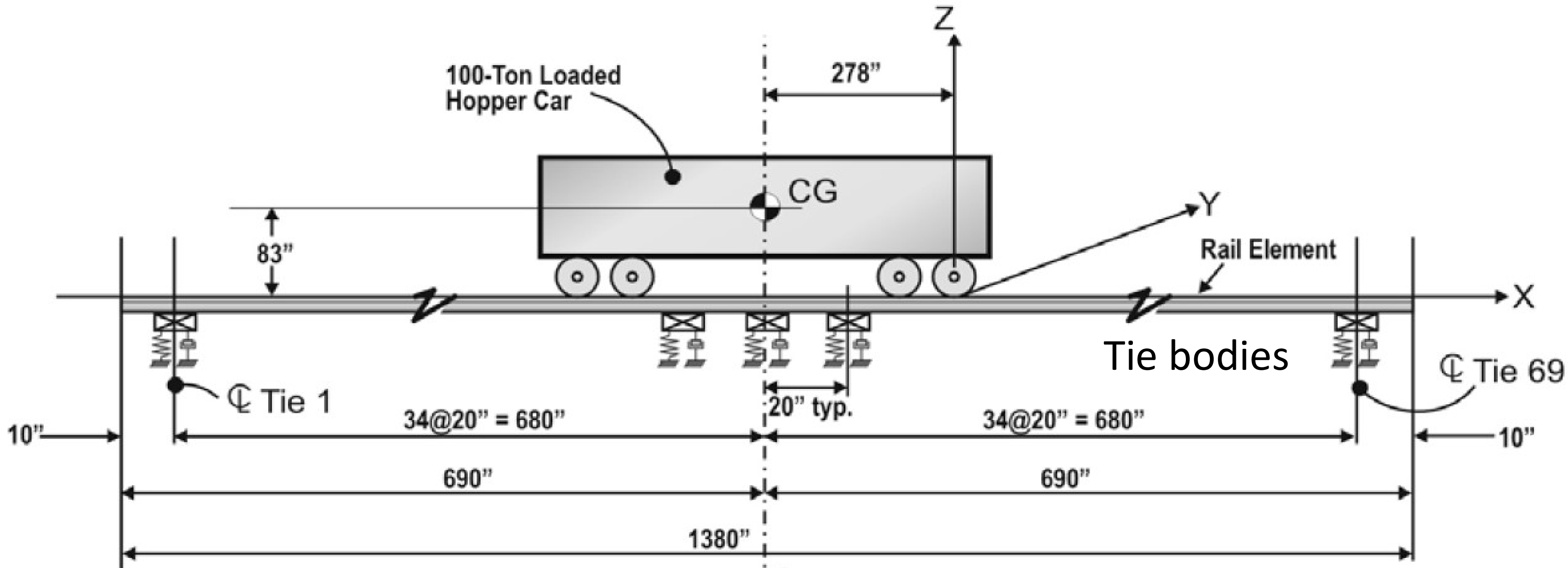
NUCARS® Track Model

- ♦ **NUCARS® UI track model available soon**



- ♦ **Multi-layer flexible track model capability.**
- ♦ **Simulations of single and multiple rail vehicles running on the track are possible.**

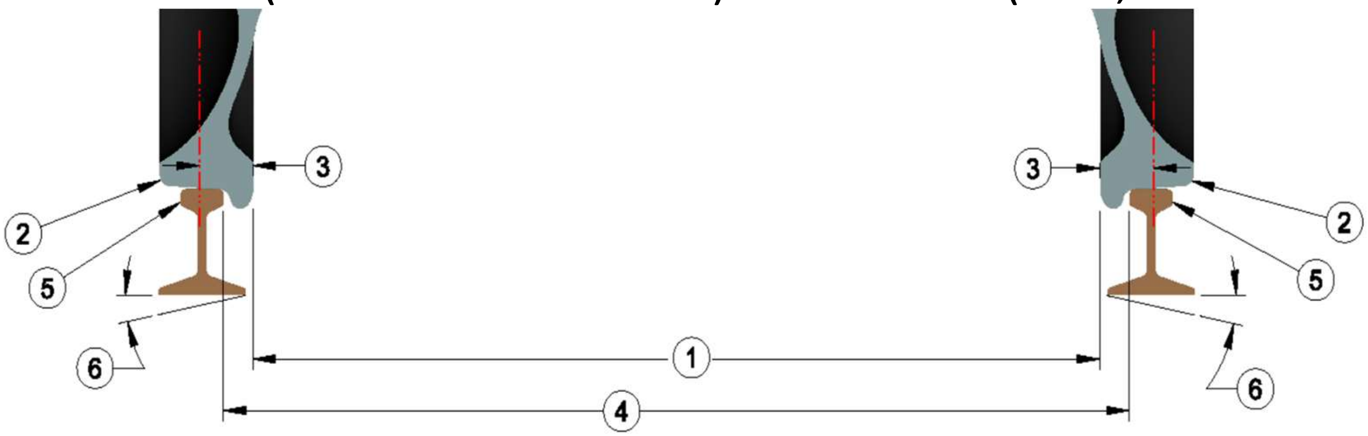
Vehicle-Track Model Display



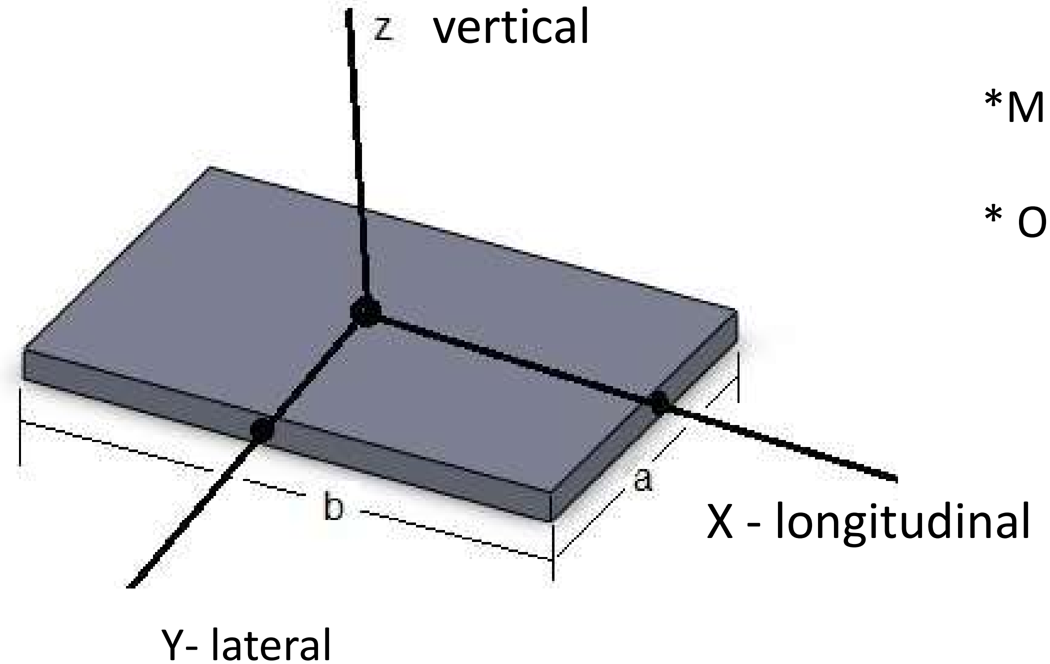
Note section of ties are hidden
to illustrate connections of
rail-to-tie and tie-to-ground (ballast)

Critical Modeling attributes

1. Wheel Set back-to-back dimension
2. Wheel Profile of both wheels
3. Wheel tapeline dimension of both wheels
4. Rail Gauge and how it is measured (I.E. gauge point)
5. Rail Profile of both rails
6. Rail Cant (incline or inward tilt) of each rail (1:20,1:30 or 1:40)

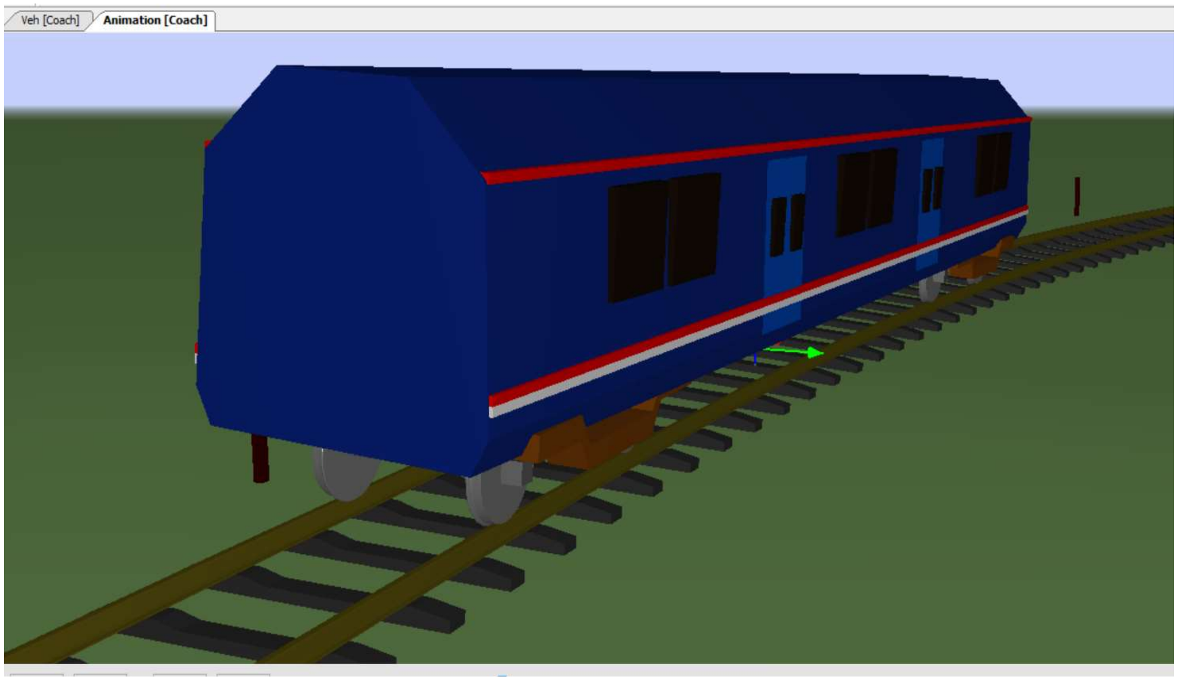


Modeling masses in rail direction



*MBS generally use this convention
but some variations exist
* Origin locations vary

Calculating Inertia



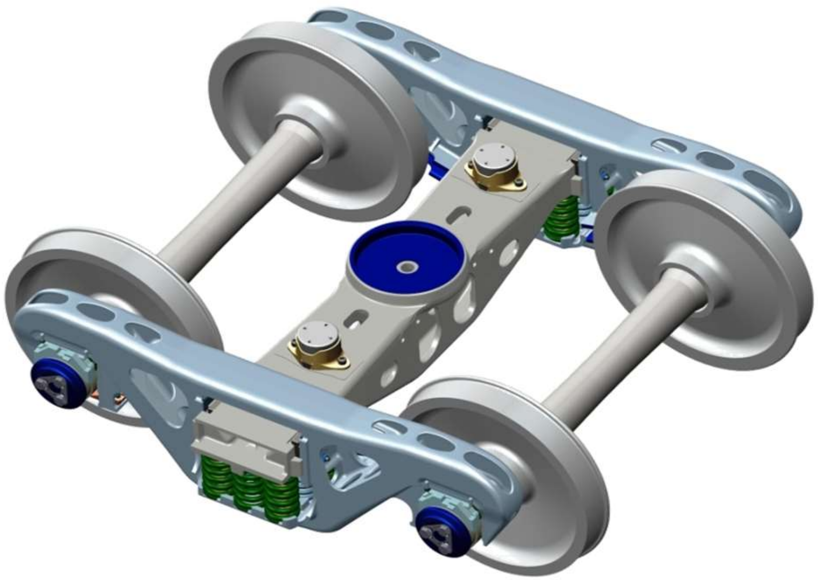
$Ix = (1/12)mass(h^2 + w^2)$
$Iy = (1/12)mass(L^2 + h^2)$
$Iz = (1/12)mass(L^2 + w^2)$

Additional mass Inertia

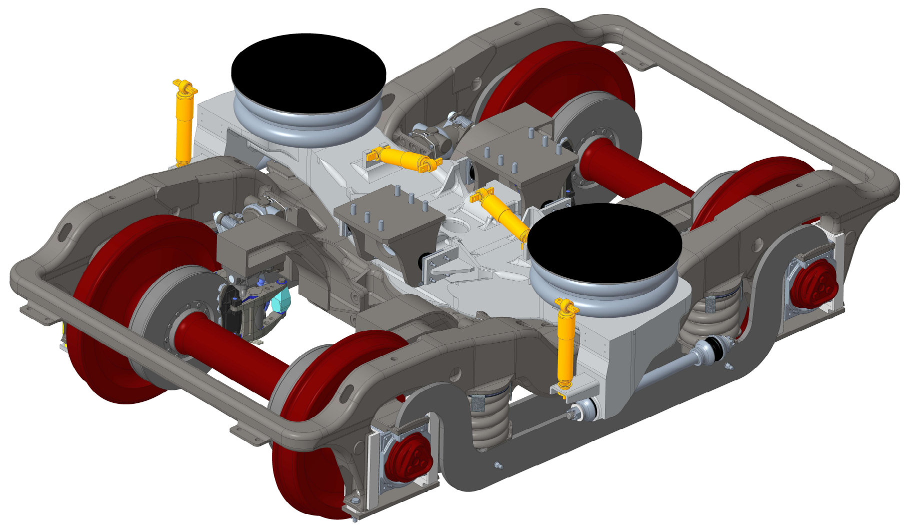
Ixx = Ix + mr^2
Iyy = Iy + mr^2
Izz = Iz + mr^2
r – distance to CG

Ixx --- roll inertia
Iyy --- pitch inertia
Izz --- yaw inertia

3D models for computing Inertia



TRAKMaster Truck

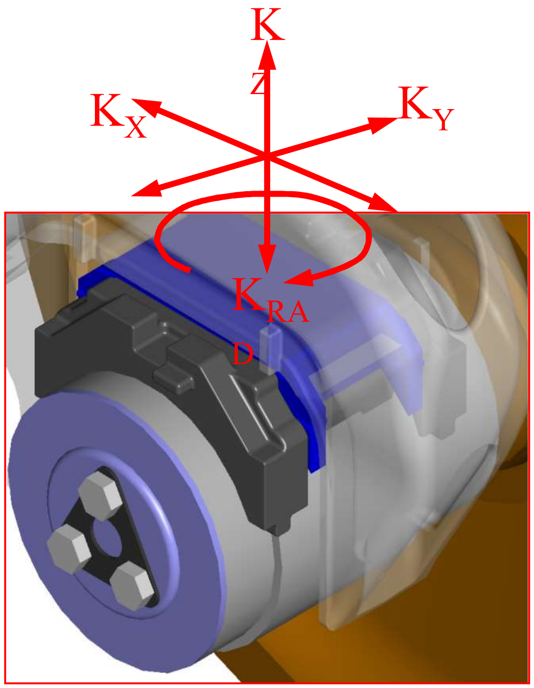


Equalizer GSI Truck

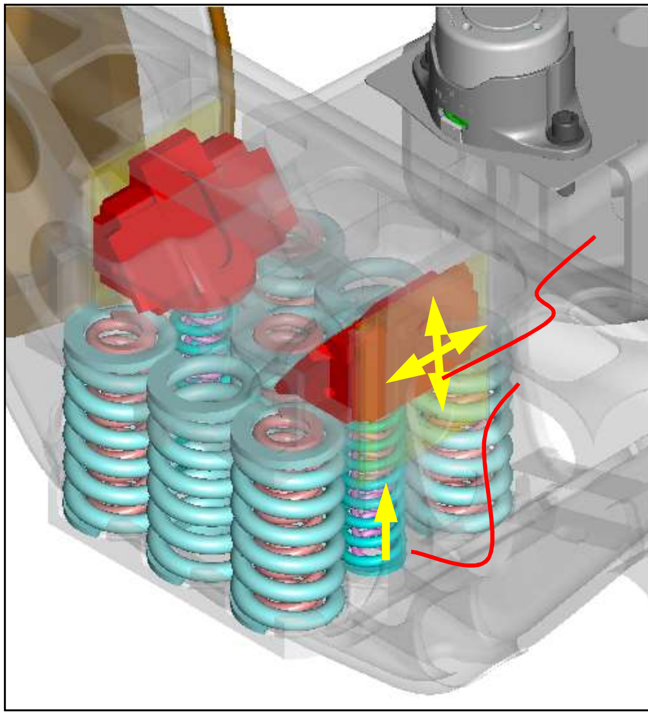
Modeling all Degrees Of Freedom

All masses must be properly constrained
- 6 DOF per mass, except axles with 5
- 3 Flexible body DOF (when needed)

- Dynamics analyst must decide how to represent each connection



Truck Friction Wedge Modeling



- Friction Wedge
- Springs

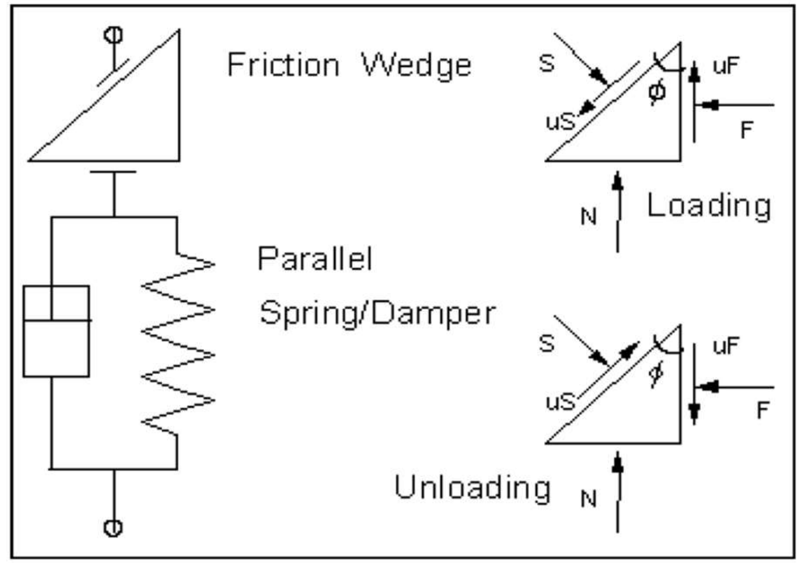
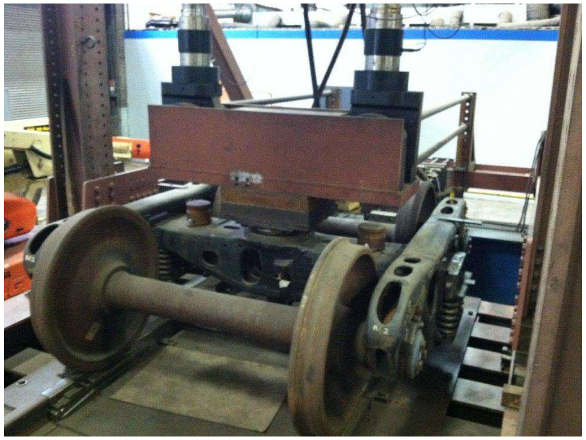
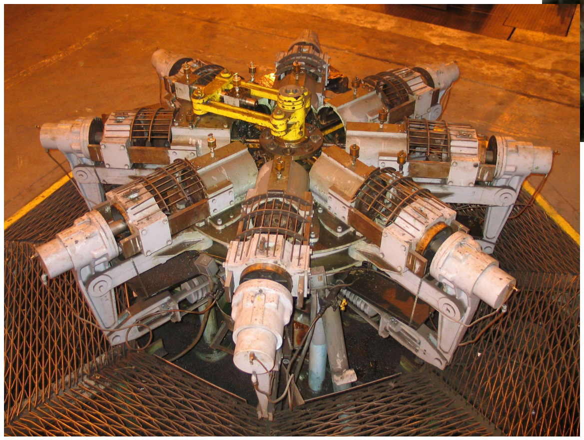


Figure 5-55 One-dimensional Friction Wedge Element

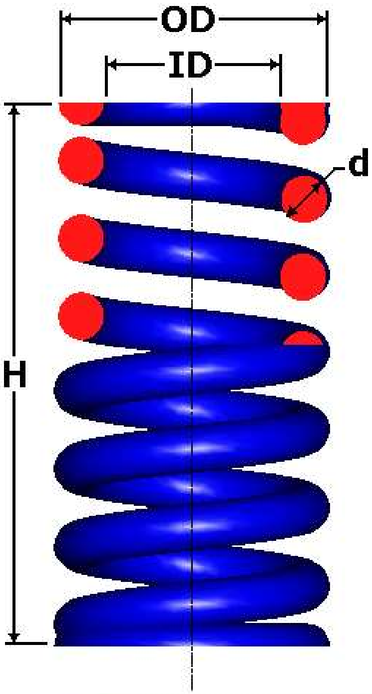
Laboratory Testing

- -Component Characterization
- -Suspension Testing
- -Spring Testing & Calibration





Springs (energy storage)

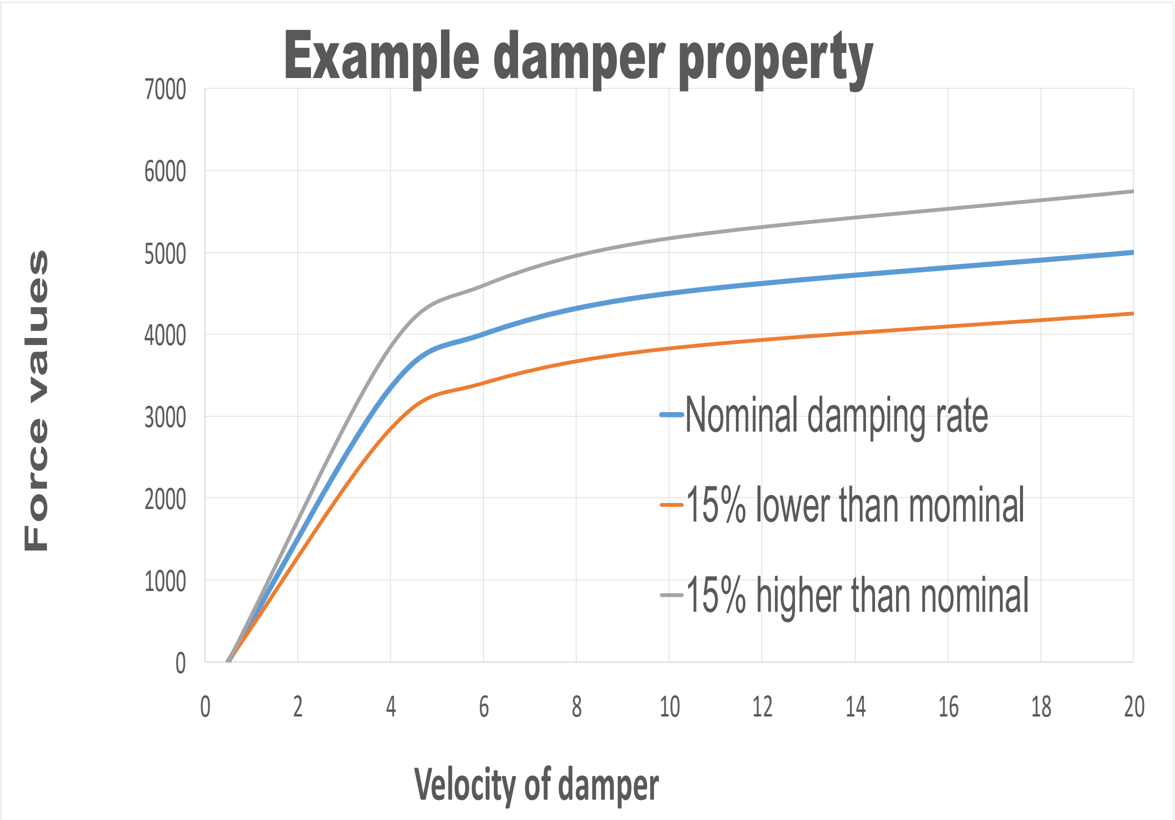


Vertical Spring rate = (G*d^4)/(8*(OD-d)^3)*N
Where: G = Shear Modulus of Elasticity
N = number of active coils

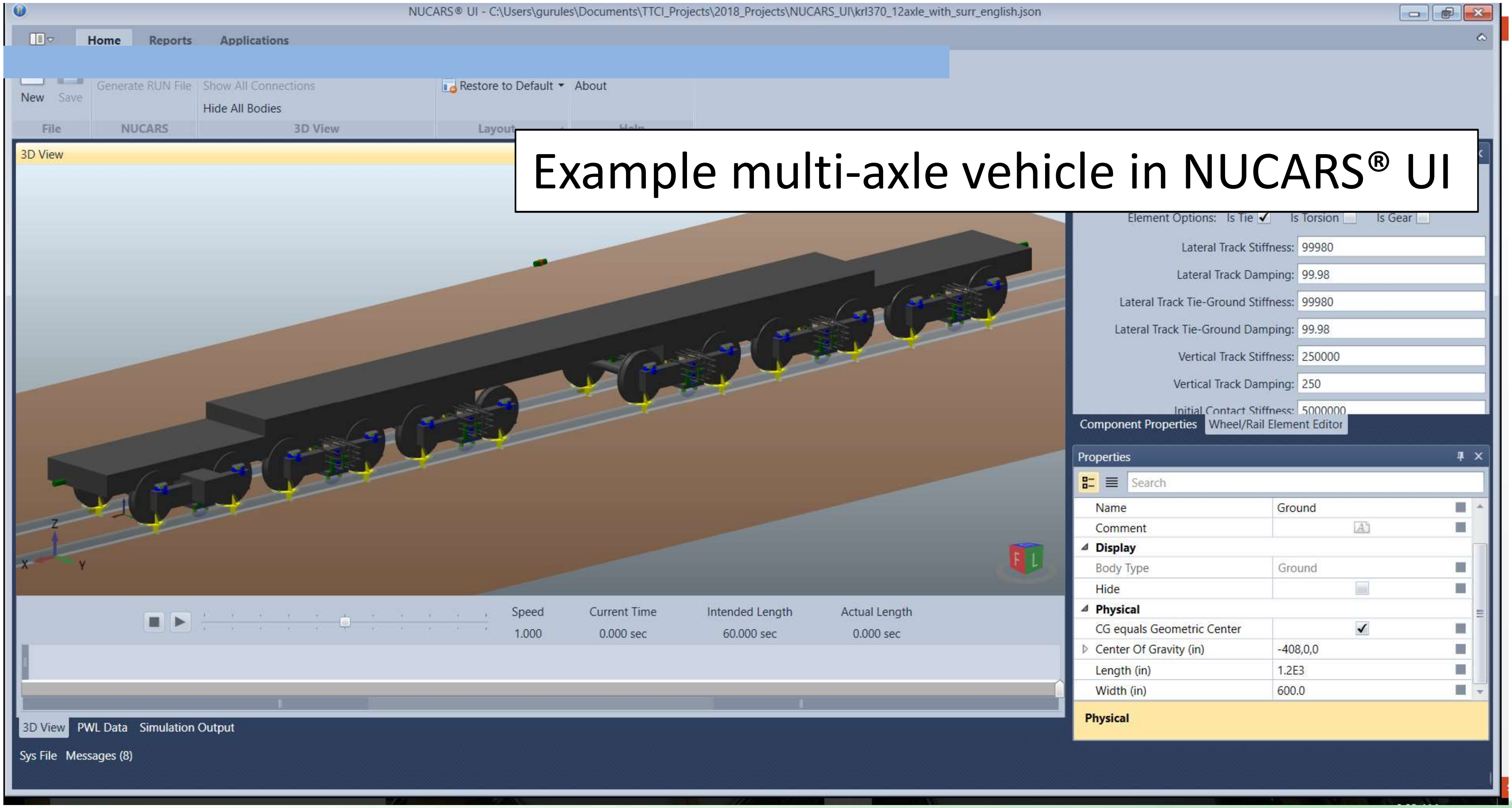
Shear modulus 11.0 E6 psi - 11.6 E6 psi
N equals (Solid height/wire diameter)-1.5

Hydraulic Dampers

- Non-linear
- Inactive zones
- Compression/Extension



Example multi-axle vehicle in NUCARS® UI



Example truck display

Stiffness – red

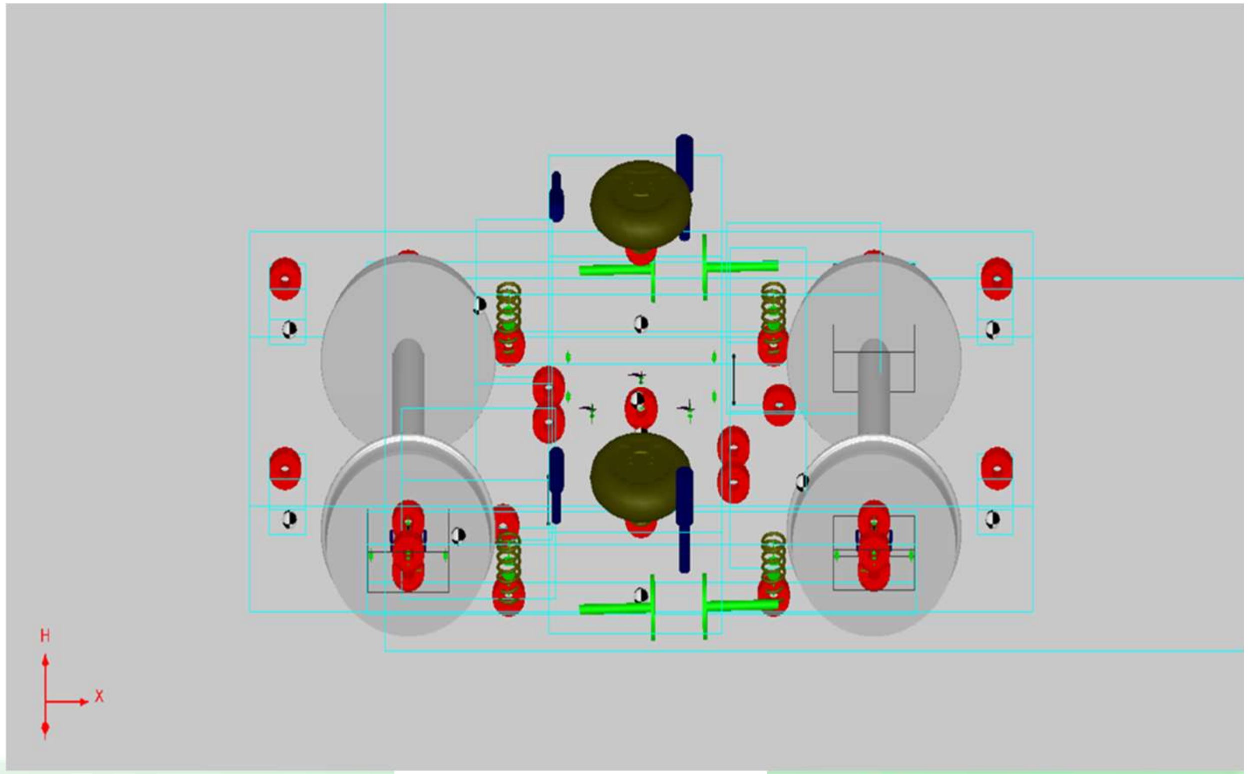
Springs – green

Gap - light green

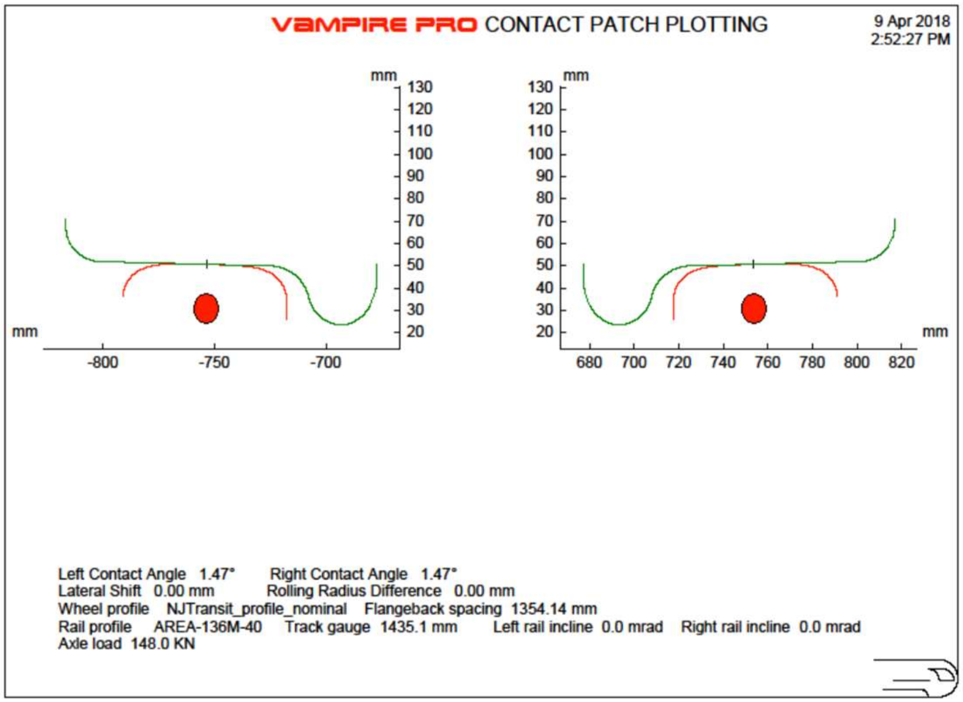
Damper – blue

Air suspension

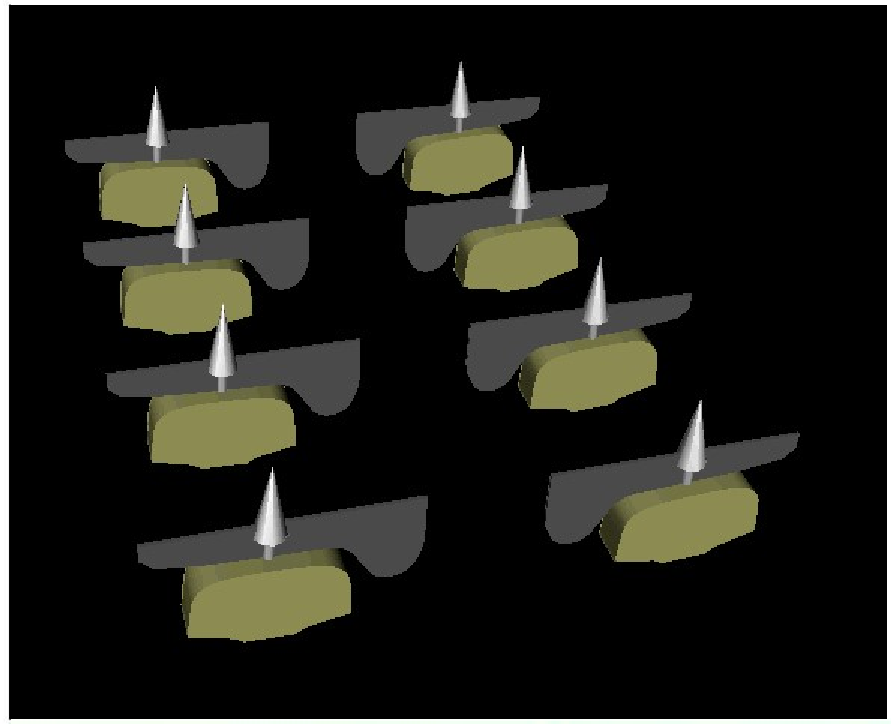
- deep green

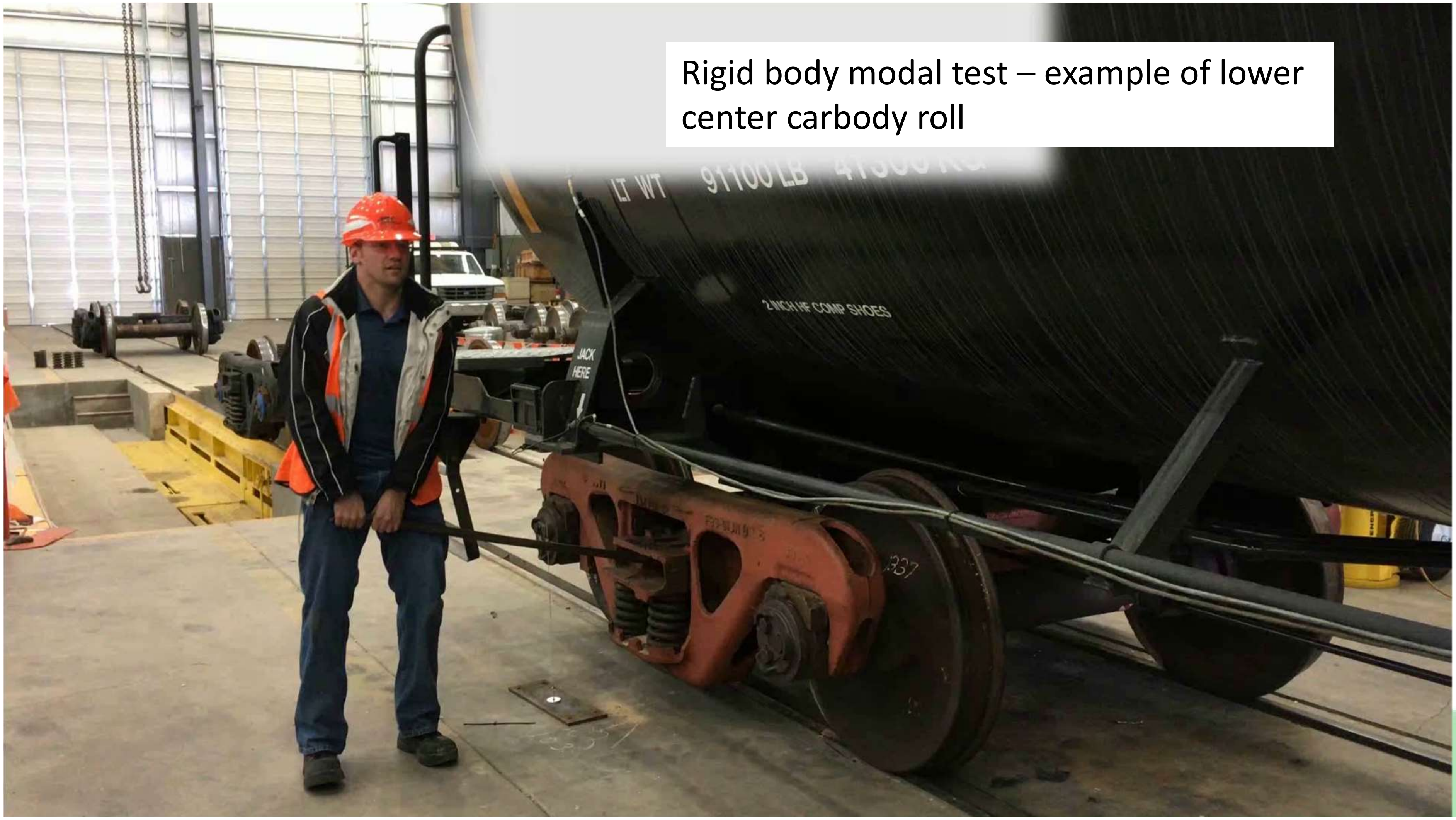


Display of wheel/rail results



VAMPIRE Plot





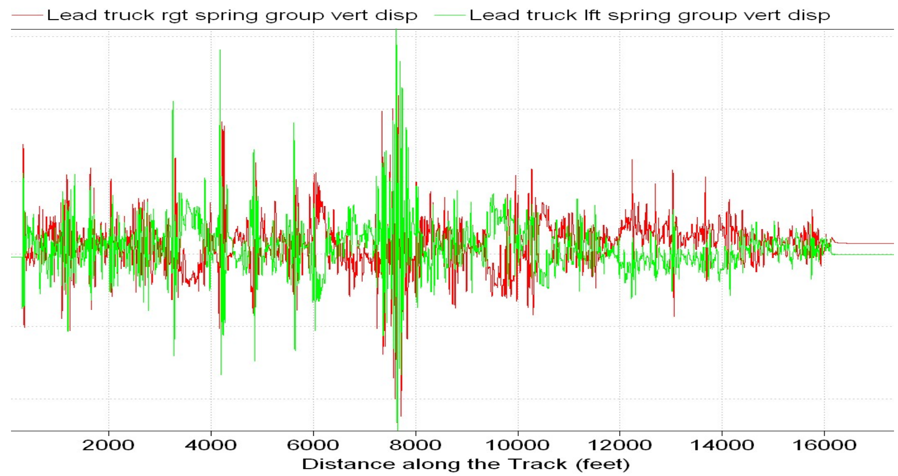
Rigid body modal test – example of lower center carbody roll

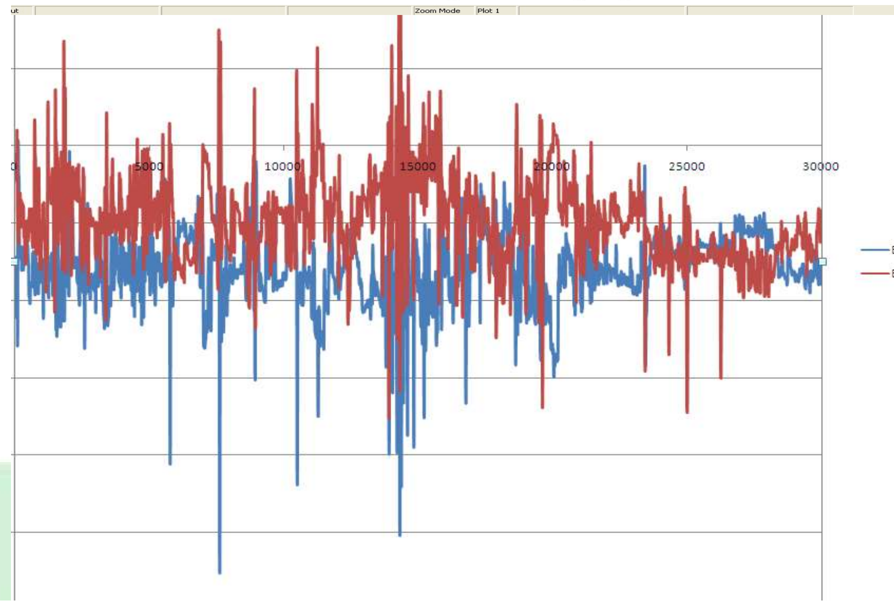
Model Validation

Comparison of lead
Truck Suspension travel

Vampire result +/ -1.1”

Test result +0.2” to -1.1”

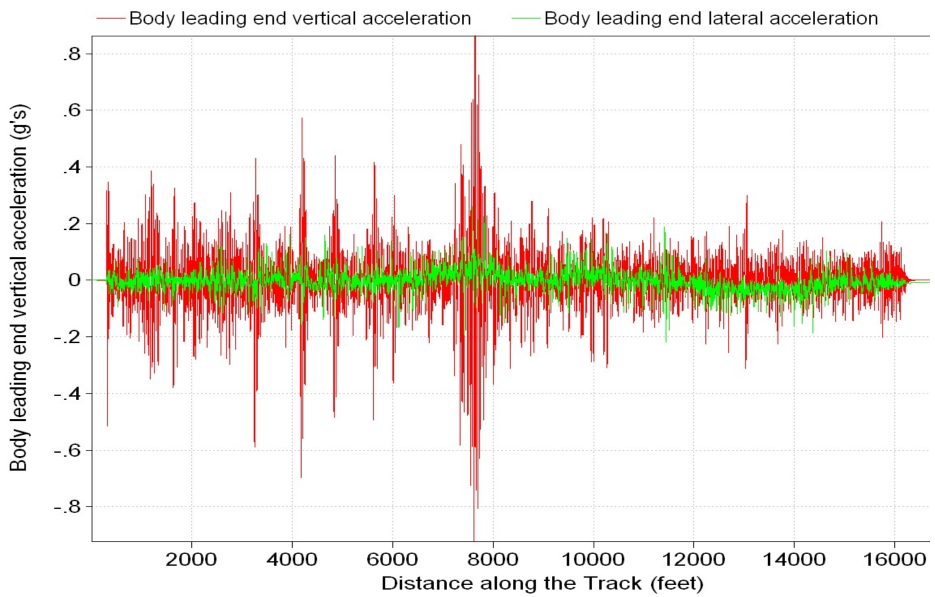


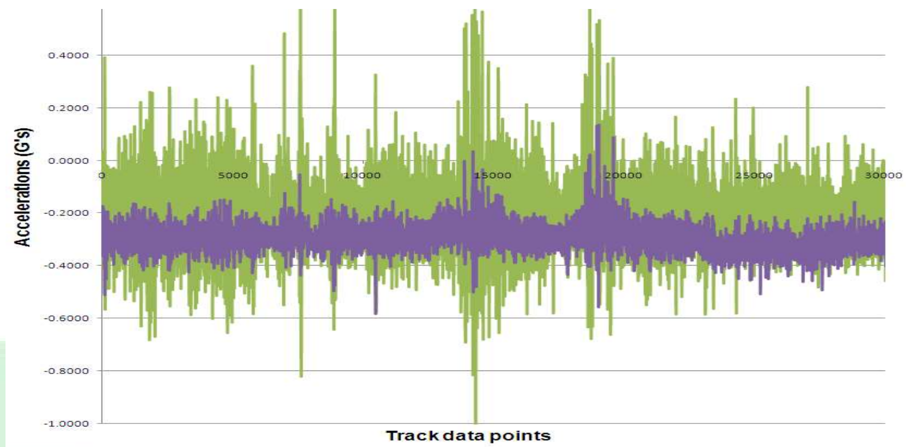


Comparison of lead bolster vertical and lateral accelerations

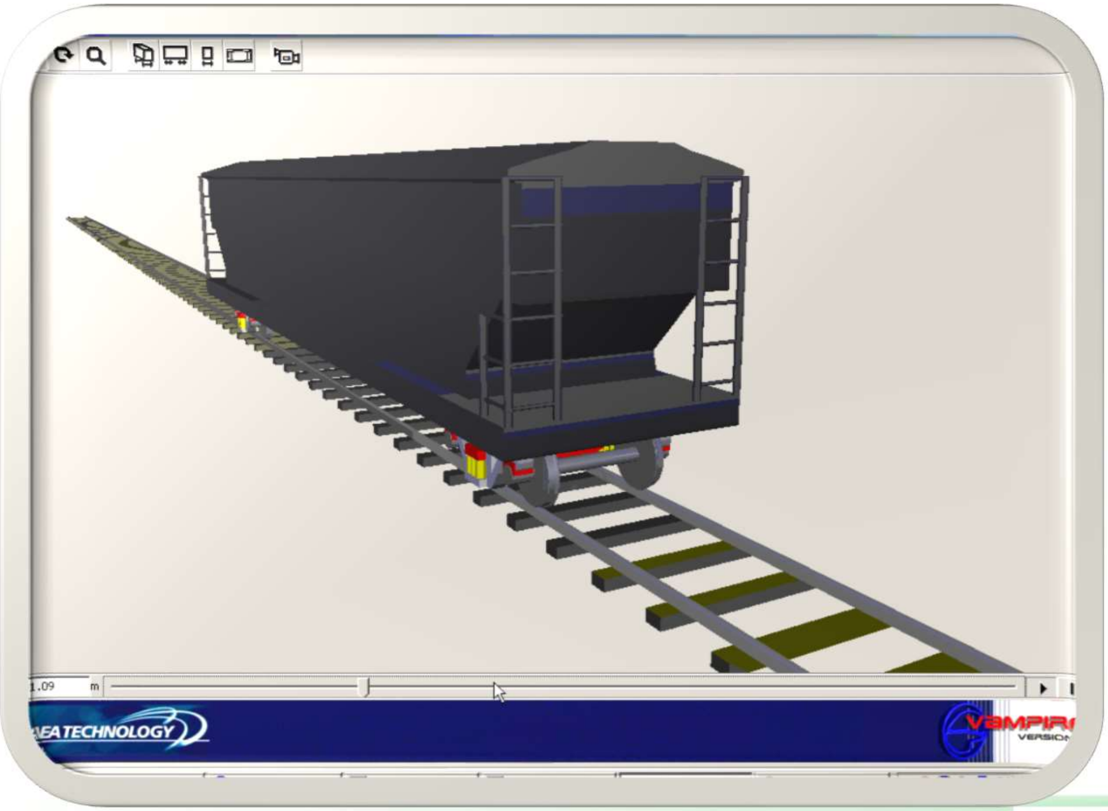
Vampire result vertical g's
+.855 to -0.911 in red

Test result vertical g's
+0.663 to – 1.07 in green



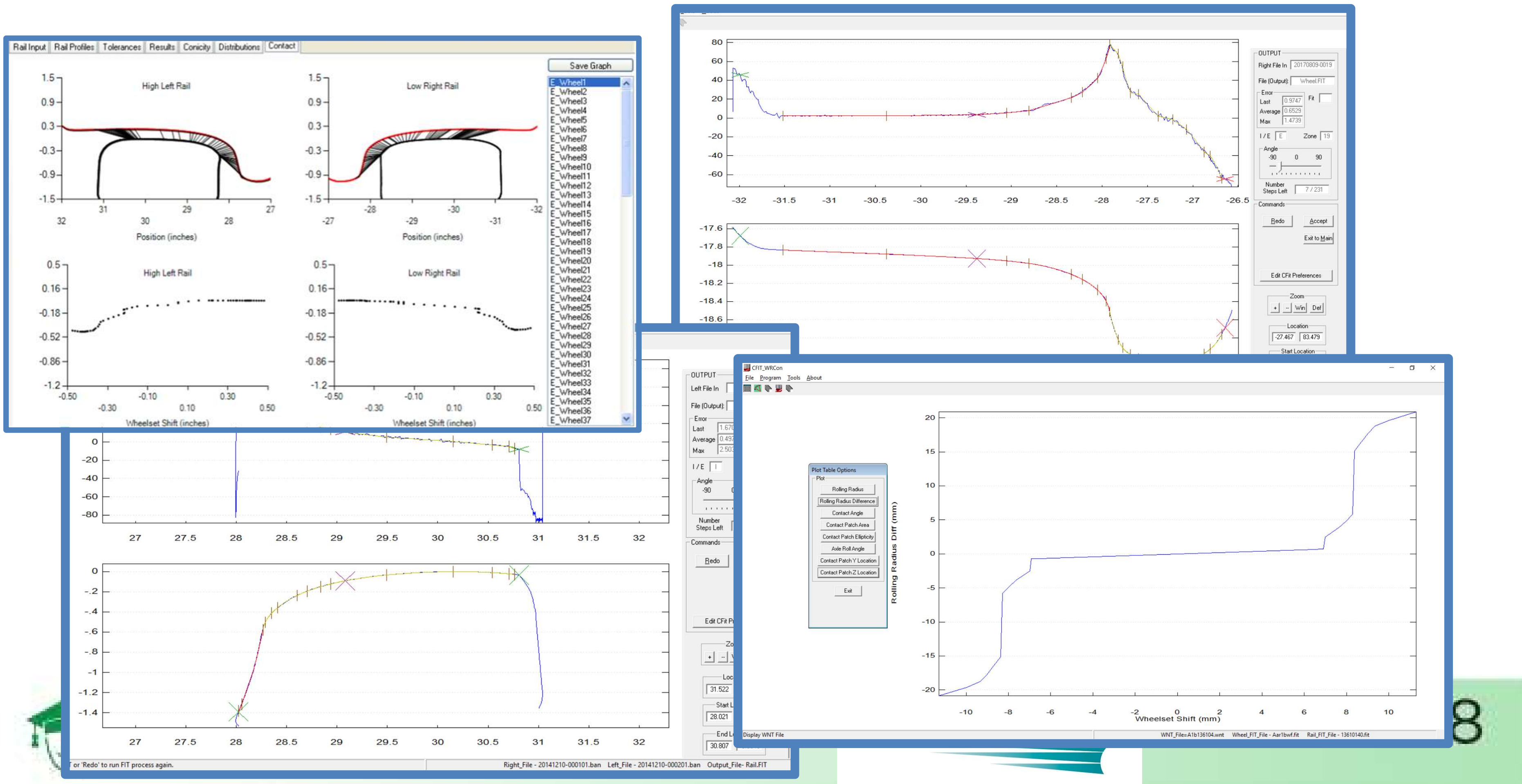


Review of Animation

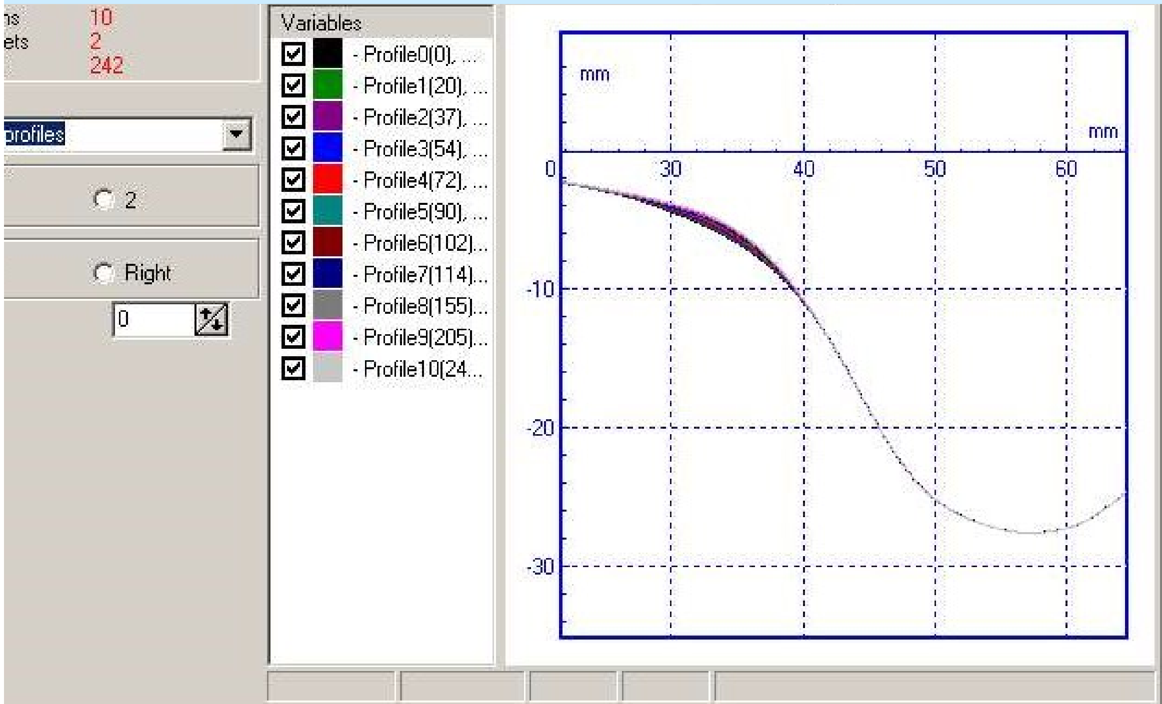


Covered Hopper on
Twist and Roll track- TTCI

Wheel/Rail Processing & Analysis Tools



Wheel wear result window - UM

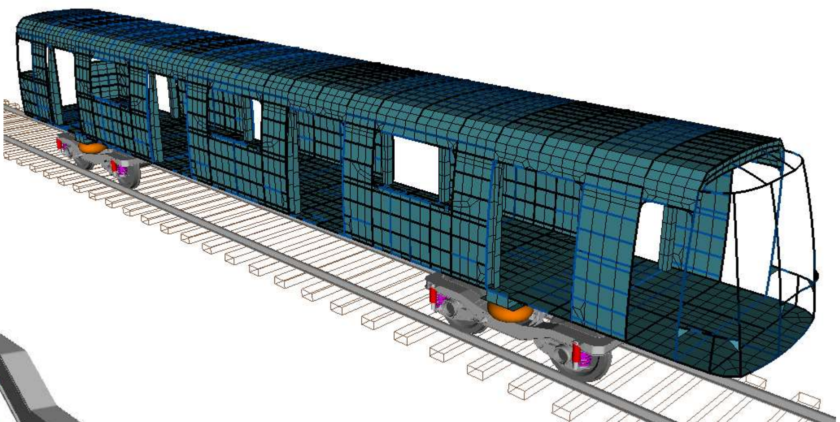


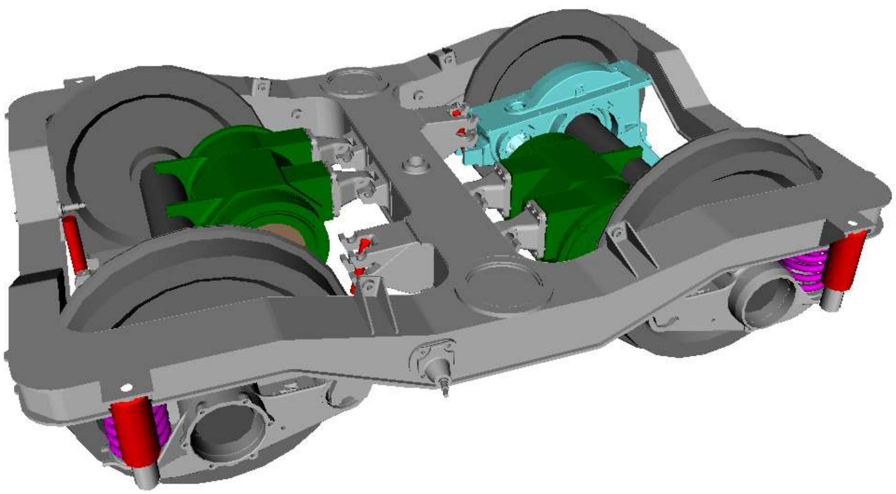
M-976 Testing Regimes

- AAR M-1001 Chapter 11
  AAR M-976
  Truck Performance Specification

Regime	Car Type	Condition
Hunting	Covered Hopper 4427 cu.ft.	Empty
Steady State Curving	Covered Hopper 4427 cu.ft.	Empty
		Loaded
Curve Resistance	Covered Hopper 4427 cu.ft.	Loaded
Spiral	Covered Hopper 4427 cu.ft.	Empty
		Loaded
	Covered Hopper 6000 cu.ft.	Empty
Twist, Roll	Covered Hopper 4427 cu.ft.	Empty
		Loaded
Pitch, Bounce	Covered Hopper 4427 cu.ft.	Empty
		Loaded
Yaw, Sway	Covered Hopper 4427 cu.ft.	Loaded
Dynamic Curving *	Covered Hopper 4427 cu.ft.	Loaded

Transit car requirements

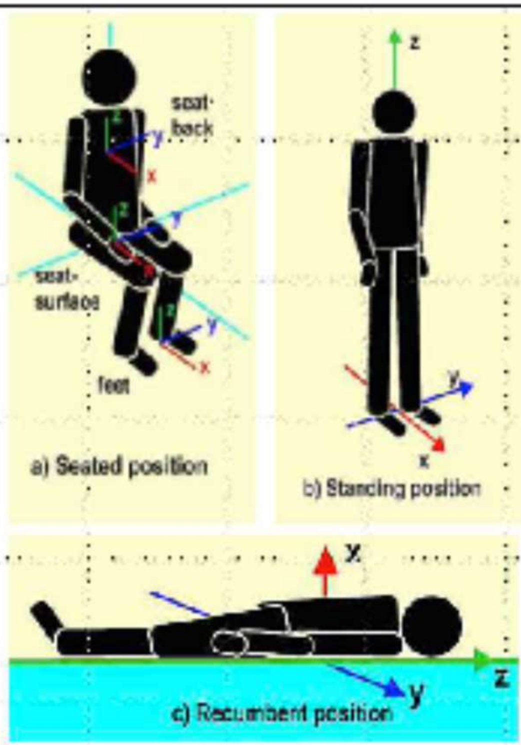




* Courtesy of Universal Mechanism

Metro car , Metrovagonmash JSC, 2008

Evaluation of exposure to whole body vibration



Position

Standing position

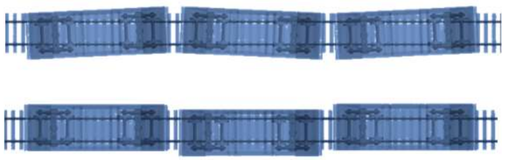
Seated position

Recumbent position

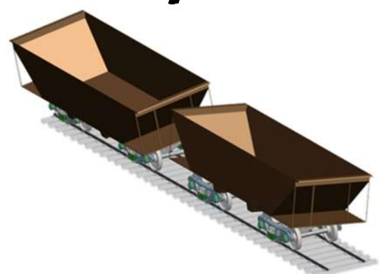
ISO 2631-1 Standards

- Comfort
- Health
- Perception
- Motion sickness

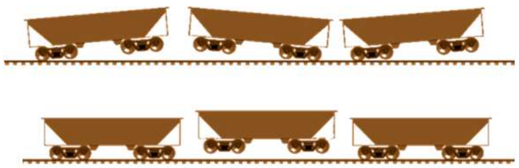
Truck Dynamics



Yaw & Sway
Car / Suspension Specific



Twist & Roll
15-25, 50-60 mph

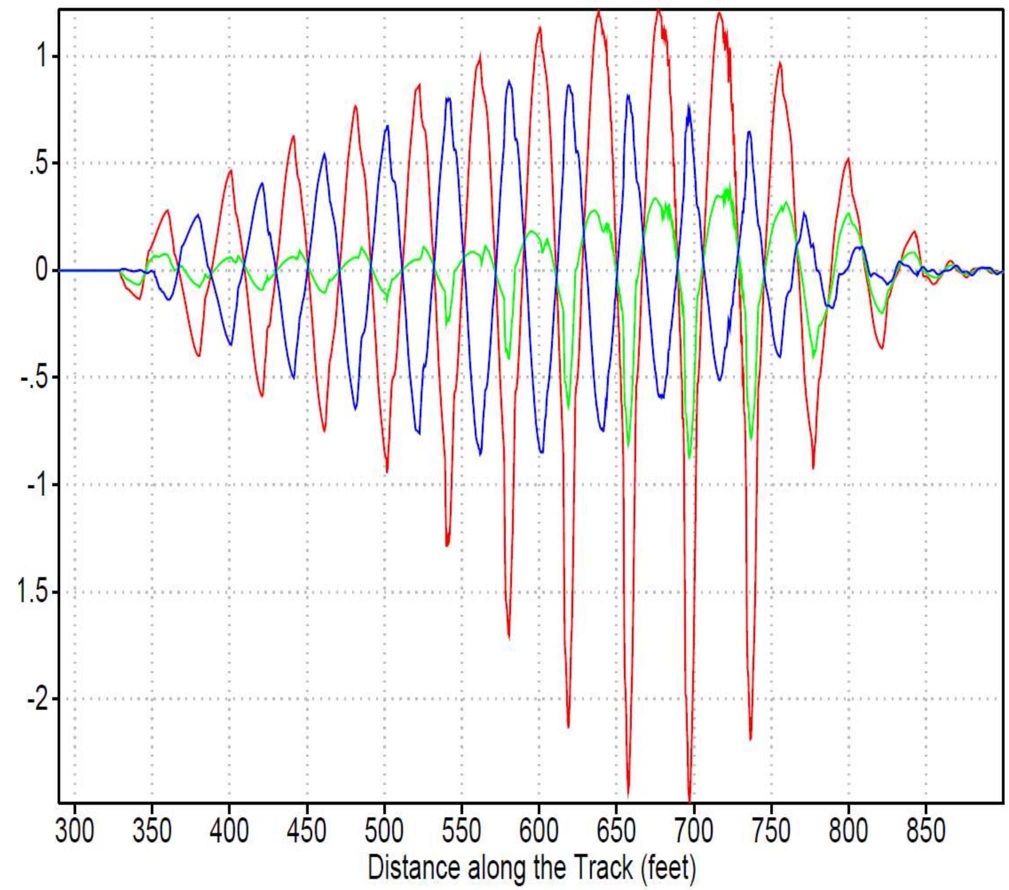


Pitch & Bounce
50-70 mph

Truck Hunting
Truck Warp, Truck Rotation, Wheelset Movement
40+ mph

Under-damped suspensions in Pitch and Bounce

Vertical car body accelerations
Lead – red
CG – green
Trail – blue



Dynamics In Action Pitch and Bounce

Dynamics In Action high speed stability

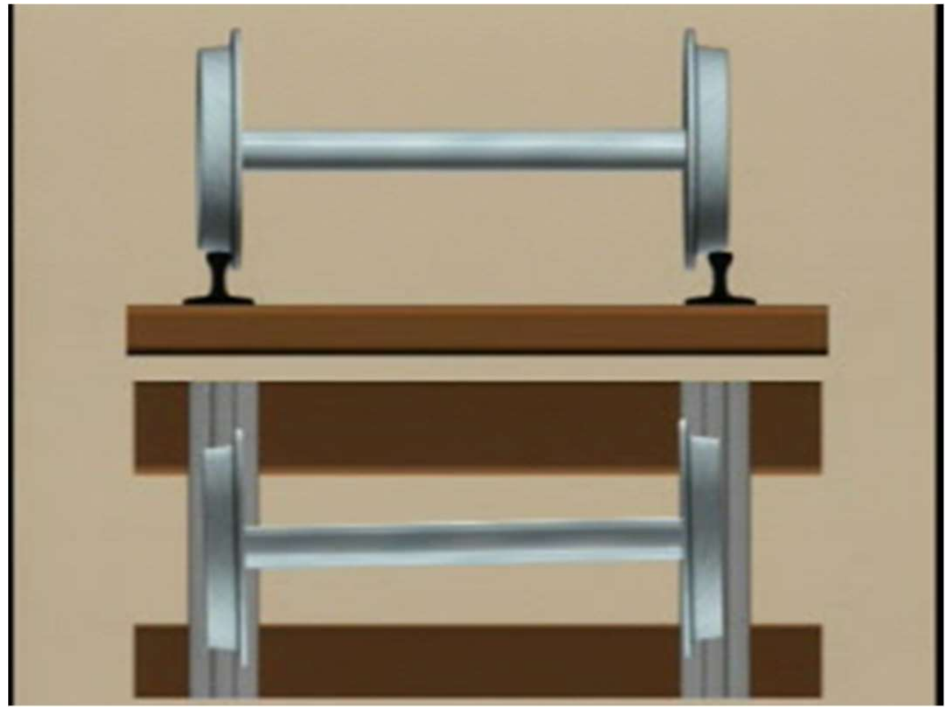
Wheelset/track Dynamics

- Wheel-set / Track Alignment
- -Tapered Wheels

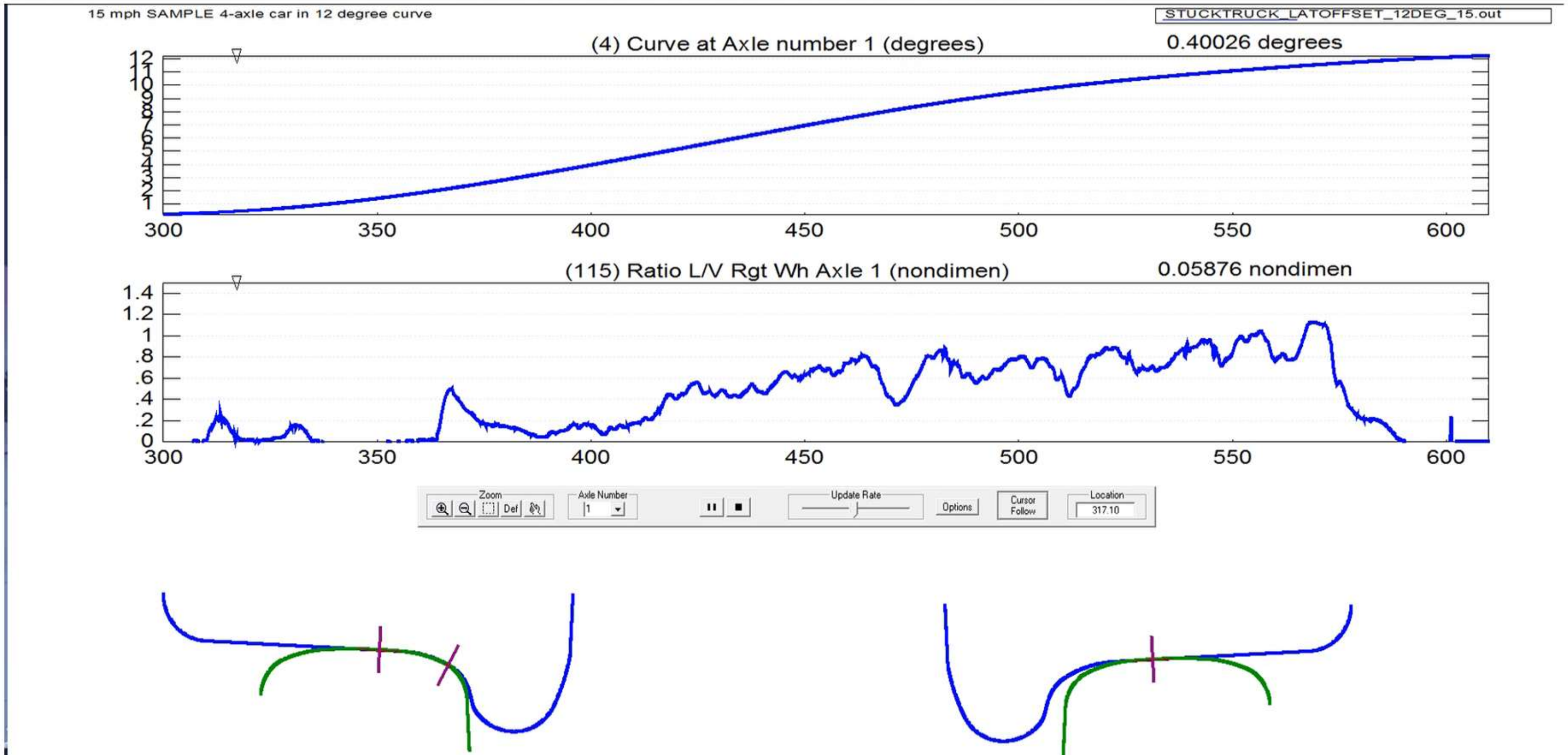
- -Rolling Radius
- Tangent – same
- Curve – outside larger than inside

- - Wheels over travel and do not reach steady-state

- - Wheels search or “hunt” for center, moving in a sinusoidal path

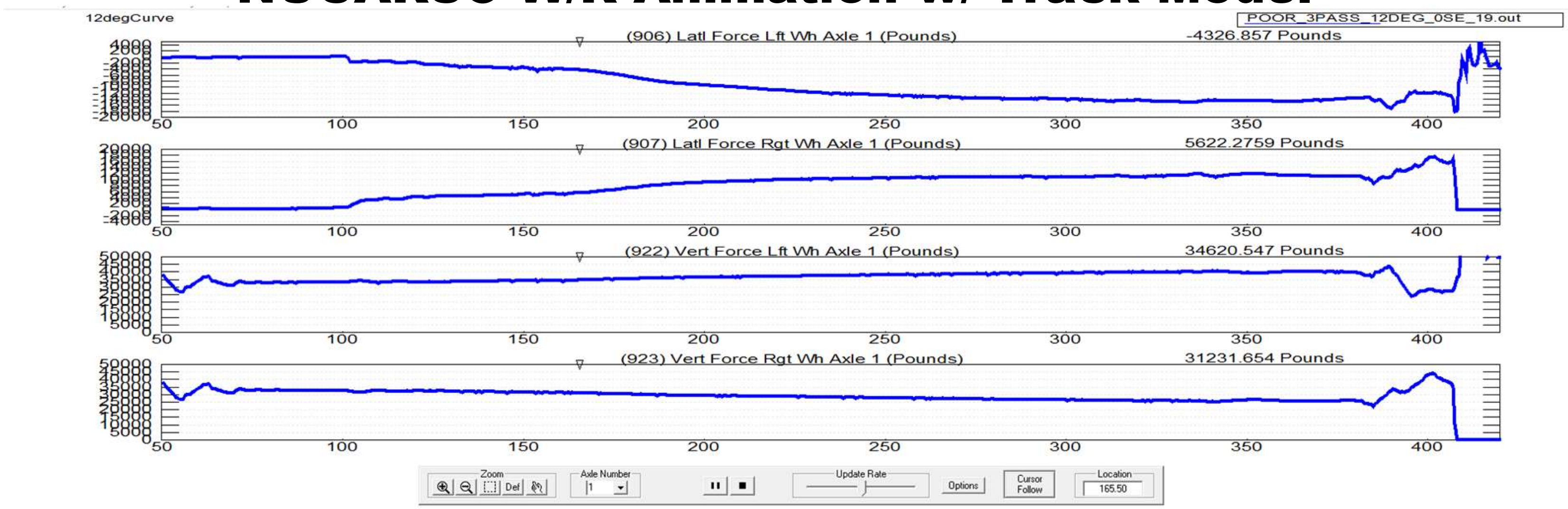


NUCARS® Output & W/R Animation in Curve



Wheel/rail interface showing flange climb

NUCARS® W/R Animation w/ Track Model



Wheel/Rail interface showing rail roll.

Scandinavian Vibration transmission issue

Problem: 5.5 hz to 6 hz reported at cabin
 *6 hz measured as wagons pass cabin resulting in observed cracks in foundation

- New ore wagons with revised spring group
- Dynamic analysis was suggested

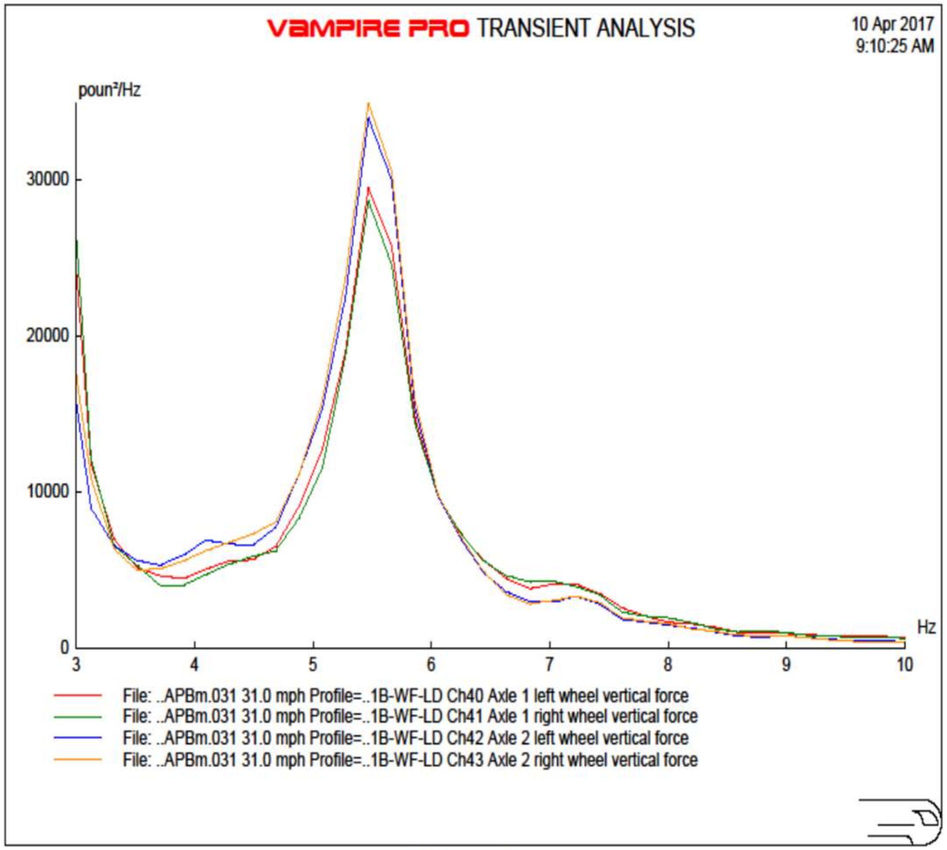
Measured data

FFT frequency
30 wagons
Config: 10 + 20
Date: 170216
Time: 17:23:06
Speed: 50,8 km/h
(51,0-50,5 km/h)
MP: MP 33 Spåret
Dir:

Simulation results

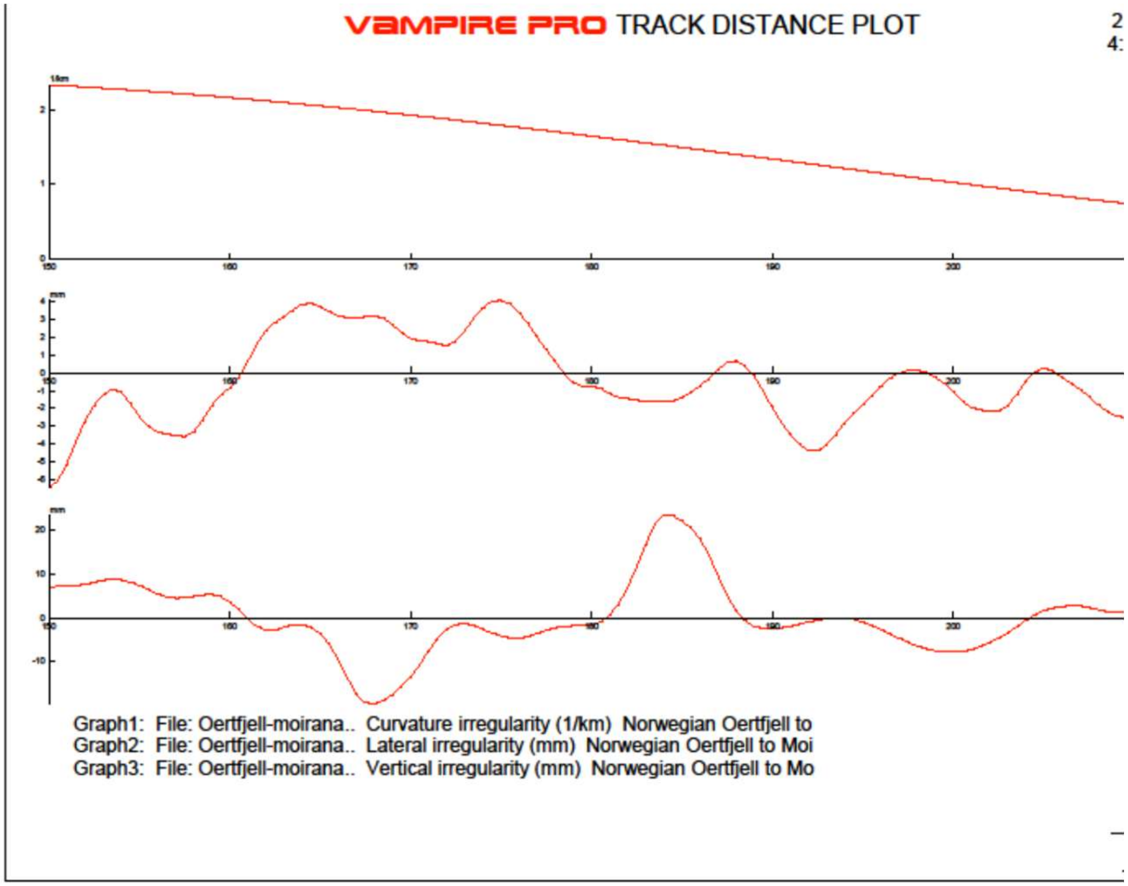
Natural frequency of the bogie suspension
~ 5.6 Hz at 50 km/hour

- Spring stiffness changes had little affect
- Slower speeds reduced the frequency
- Slower speeds also reduced forces at rail



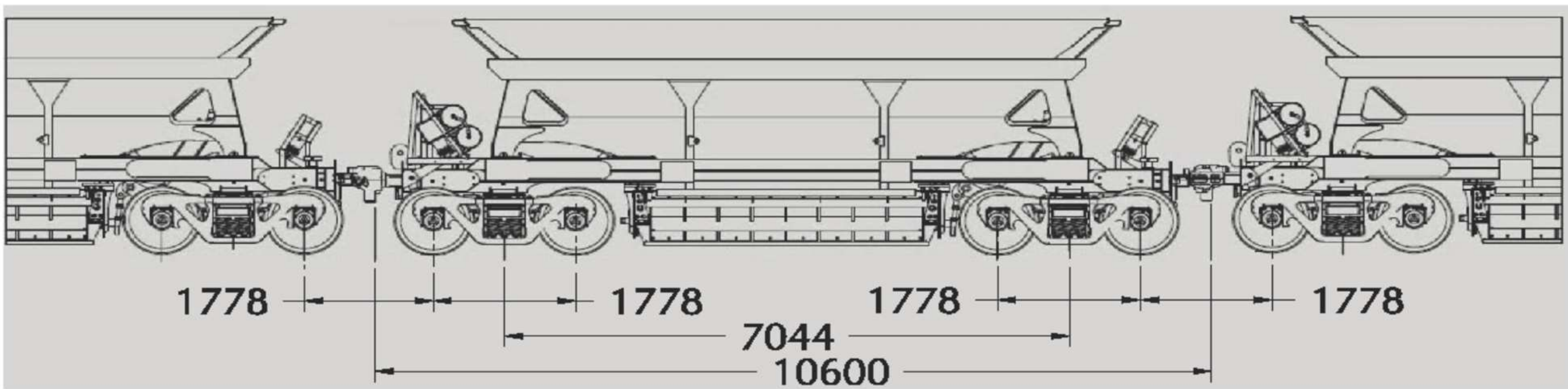
VAMPIRE Plot

Track file vertical irregularity



VAMPIRE Plot

Geometric influence



Bogie spacing of 7044 mm is about 2 times spacing wagon-to-wagon
Conclusion the bogie spacing causes all the track inputs to match the natural frequency at 50 km/hour

Potential options for resolution

1. Slower speeds to reduce severity and frequency
2. Intersperse different length wagons in train
3. Build ground vibrations barriers
4. Apply longer couplers
5. Re-work the track geometry at/near cabin

Preferred action: re-work the track

Dynamic Simulation results

40 t/axle bogie for Ore wagon (353k lbs)

- SSRC → SSRM
- New design Spring
- Optimized suspension
- High Speed Stability
- New Wheel profile – ENSCO

- Passed track test in Australia

Benefits of vehicle-track simulations

- All modeling parameters can be studied
- No danger of derailments, damage or costly on-track tests
- Repeatability is assured

- Provides insight into significant influencers
- Provides understanding of complex interactions
- Parametric studies for optimization

Acknowledgements

UM

“The Laws of Physics apply to every place in the world” Eric Magel at WRI-2013

Questions?