RAIL TRANSIT SEMINAR

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ENSCO, Inc.

August 26-28, 2025

WRI2025RT SEATTLE, WA

WRI2025 30th ANNIVERSARY
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INTEGRATION OF AUTONOUMOUS WAYSIDE AND VEHICLE BOUND MEASUREMENTS INTO DIGITAL TWIN SIMULATIONS FOR OPERATION RISK REDUCTION AND MAINTENANCE PLANNING

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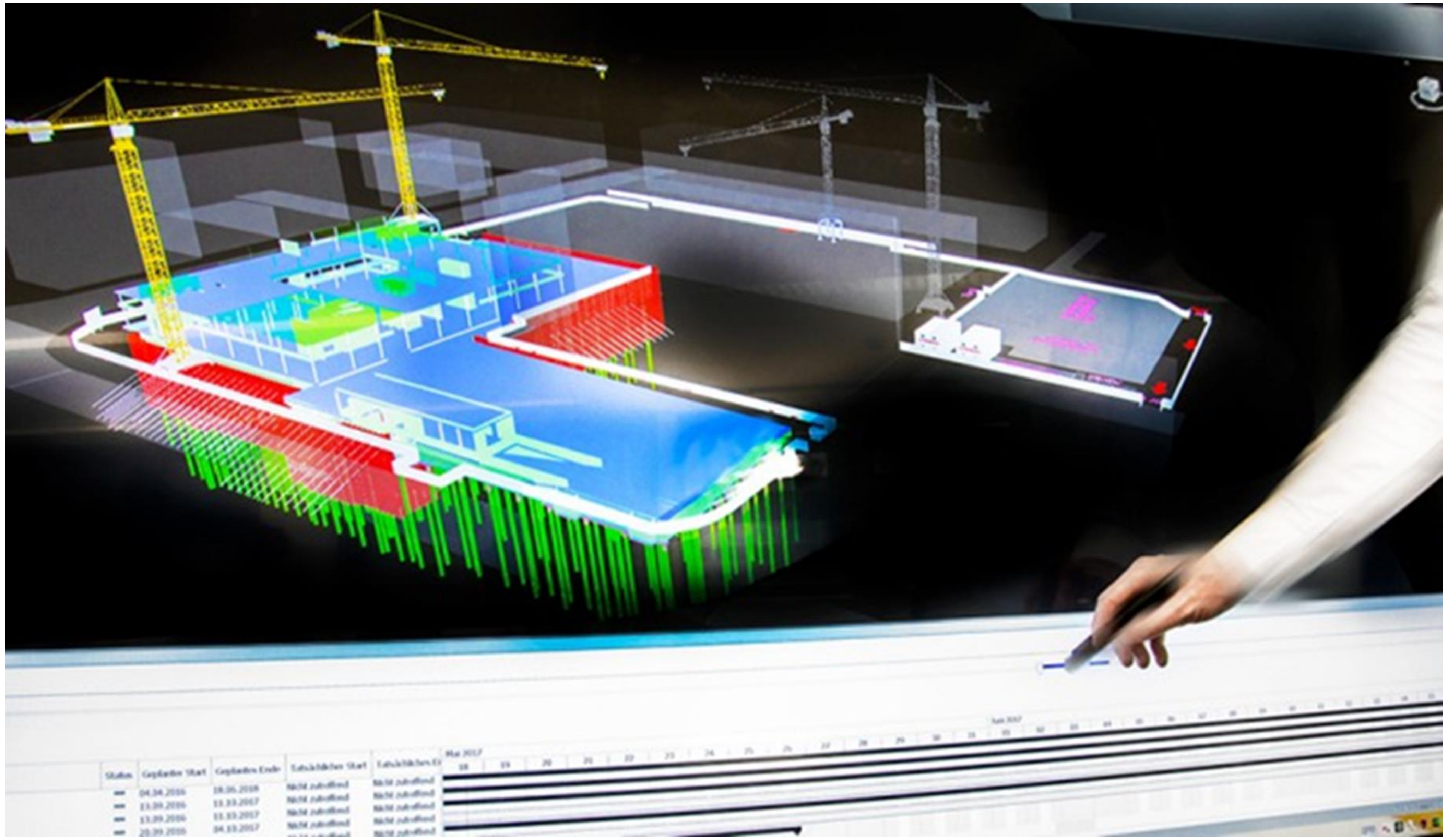
The Digital Twin Defined



“**A digital twin is a virtual model of a process, product or service.** This pairing of the virtual and physical worlds allows analysis of data and monitoring of systems to **head off problems before they even occur**, prevent downtime, develop new opportunities and even **plan for the future** by using simulations” - Marr, Bernard. "What Is Digital Twin Technology - And Why Is It So Important?." *Forbes*, 06 March 2017. Par. 2.

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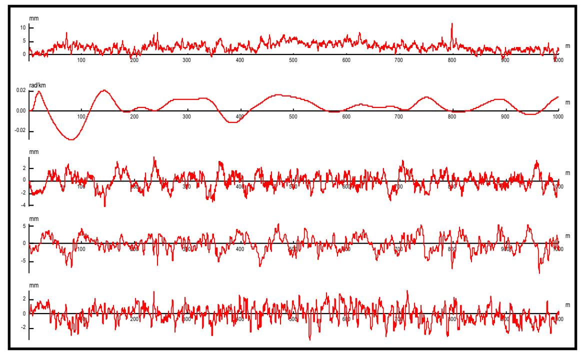
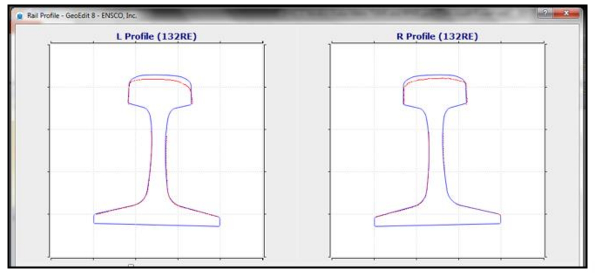
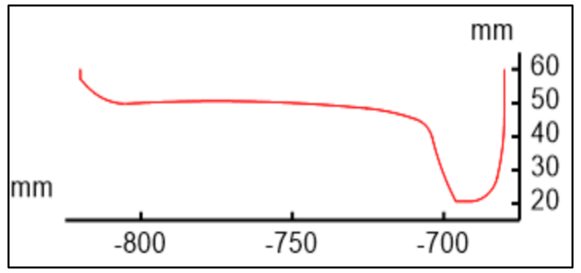
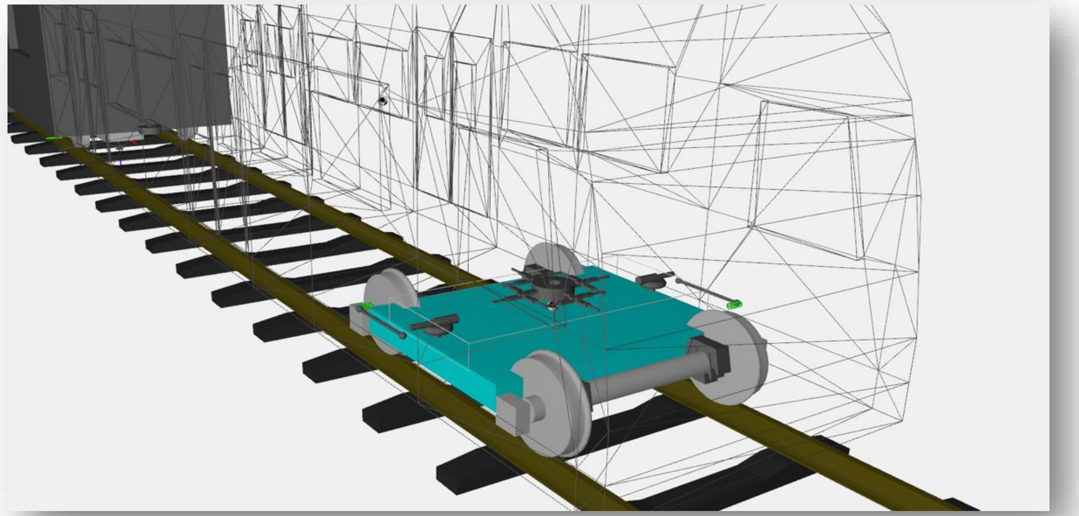
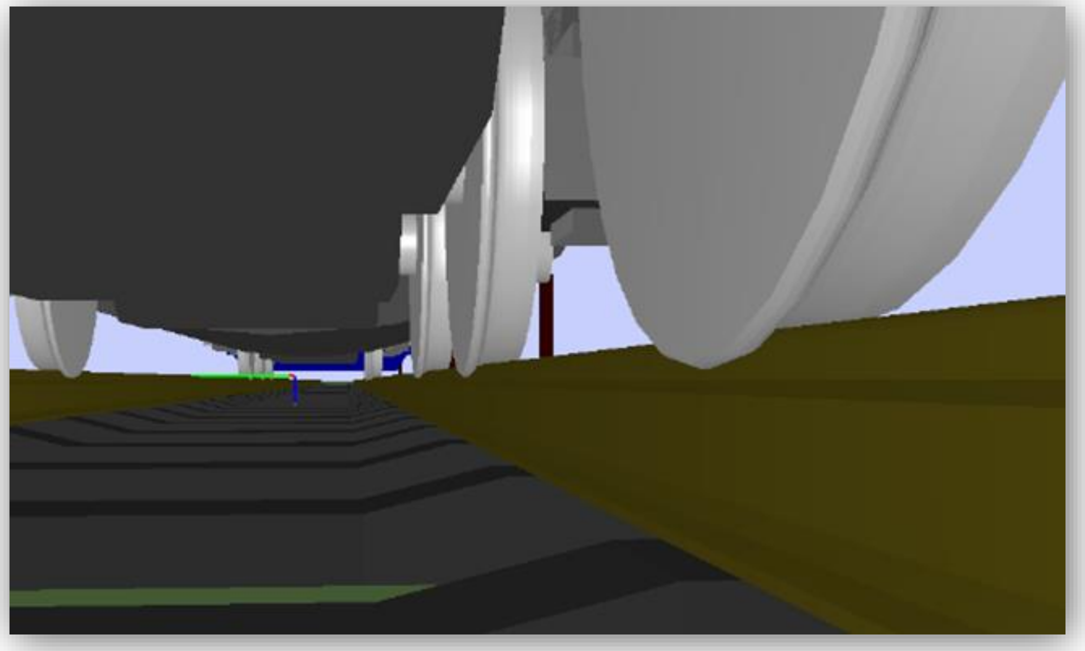
Measurements, Simulations, and The Digital Twin











- A digital twin is a virtual model of a physical process
- The virtual and physical worlds are paired via data (i.e., track geometry measurements)
- Data analytics and simulations can predict problems, evaluate alternatives, guide decision making and optimize operations.

Digital Twin Applied

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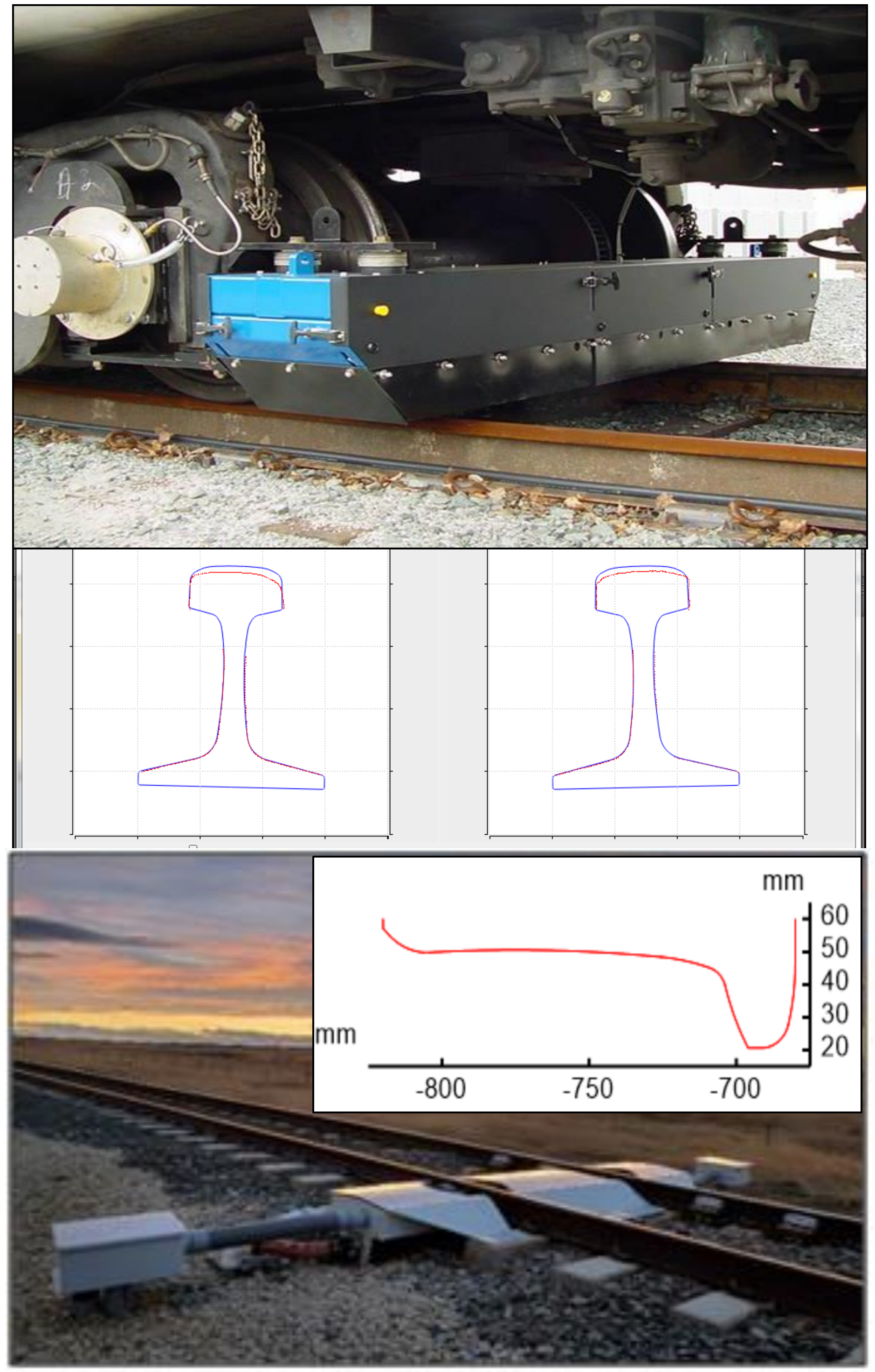

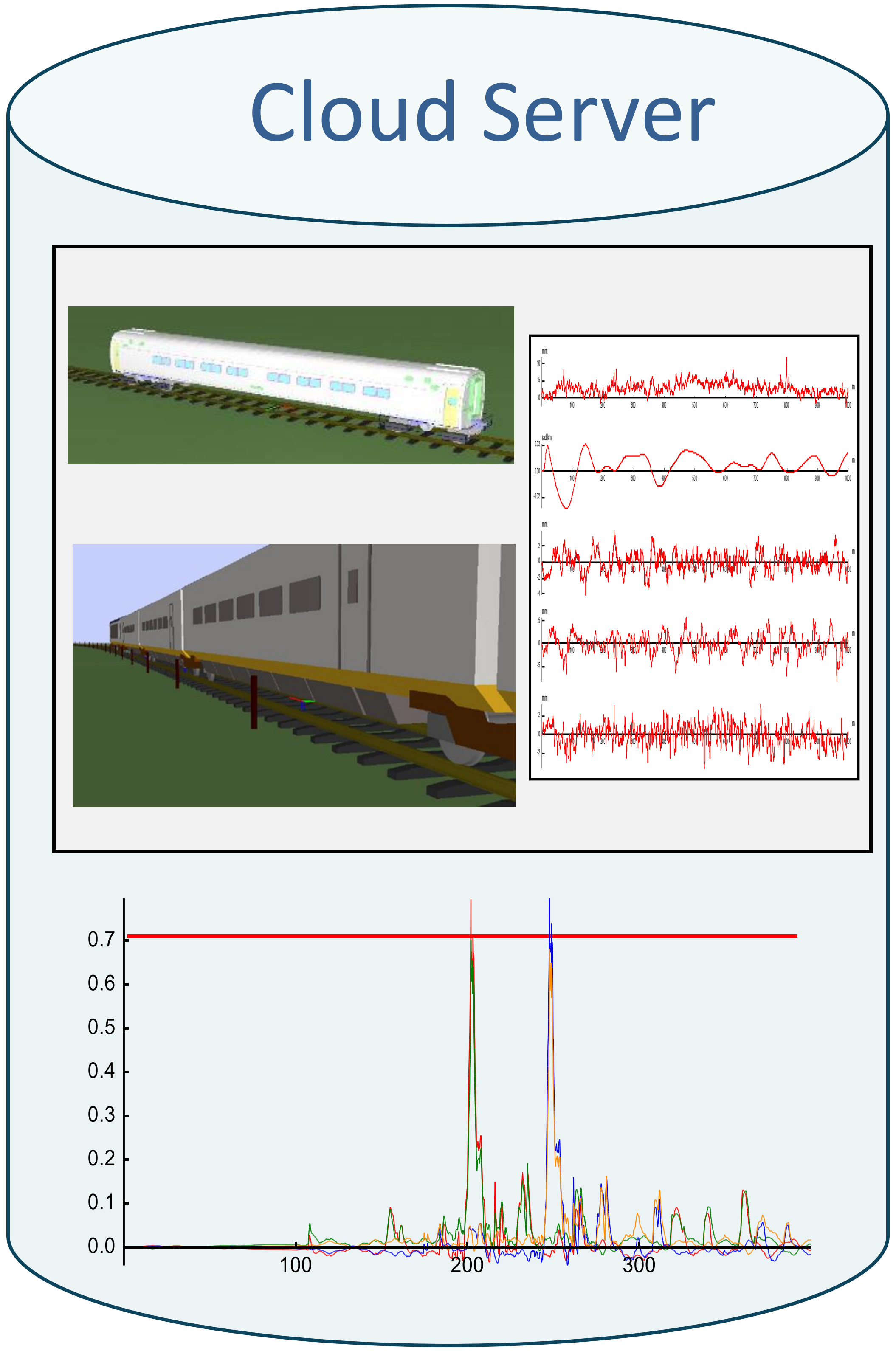

- **Identify and deal with high-risk/high-cost locations before they cause a problem**

- **Explore Alternatives**

  1. Frequent measurements with vehicle bound and in-track systems
  2. Automated data transfer via cellular
  3. Automated parallel processing on the Cloud

24	47	L Combined Wear	0.28	8	T	4	4	01
24	47	L Gage Side Wear	0.28	8	T	4	4	01
1	82	**L Face Angle**	27.60	2279	T	-1	3	01
25	39	**L Face Angle**	27.30	80	T	-1	4	01
25	67	**L Face Angle**	26.60	20	T	-1	4	01
25	93	L Face Angle	20.80	4	T	4	4	01
26	38	**Twist 31**	-0.79	5	E	2	4	01
26	51	R Vert Wear	0.22	6	T	4	4	01
26	75	R Vert Wear	0.23	12	T	4	4	01
22	74	**Lmt Speed 3**	39.00	990	C		4	01
27	60	**L Pwr Rail Low**	-0.57	11	T	0	4	01
28	21	R Vert Wear	0.17	8	T	4	4	01
28	43	**R Pwr Rail Low**	-0.75	26	T	0	4	01
29	98	**R Pwr Rail Low**	-0.89	52	T	0	4	01

Maintenance & Risk

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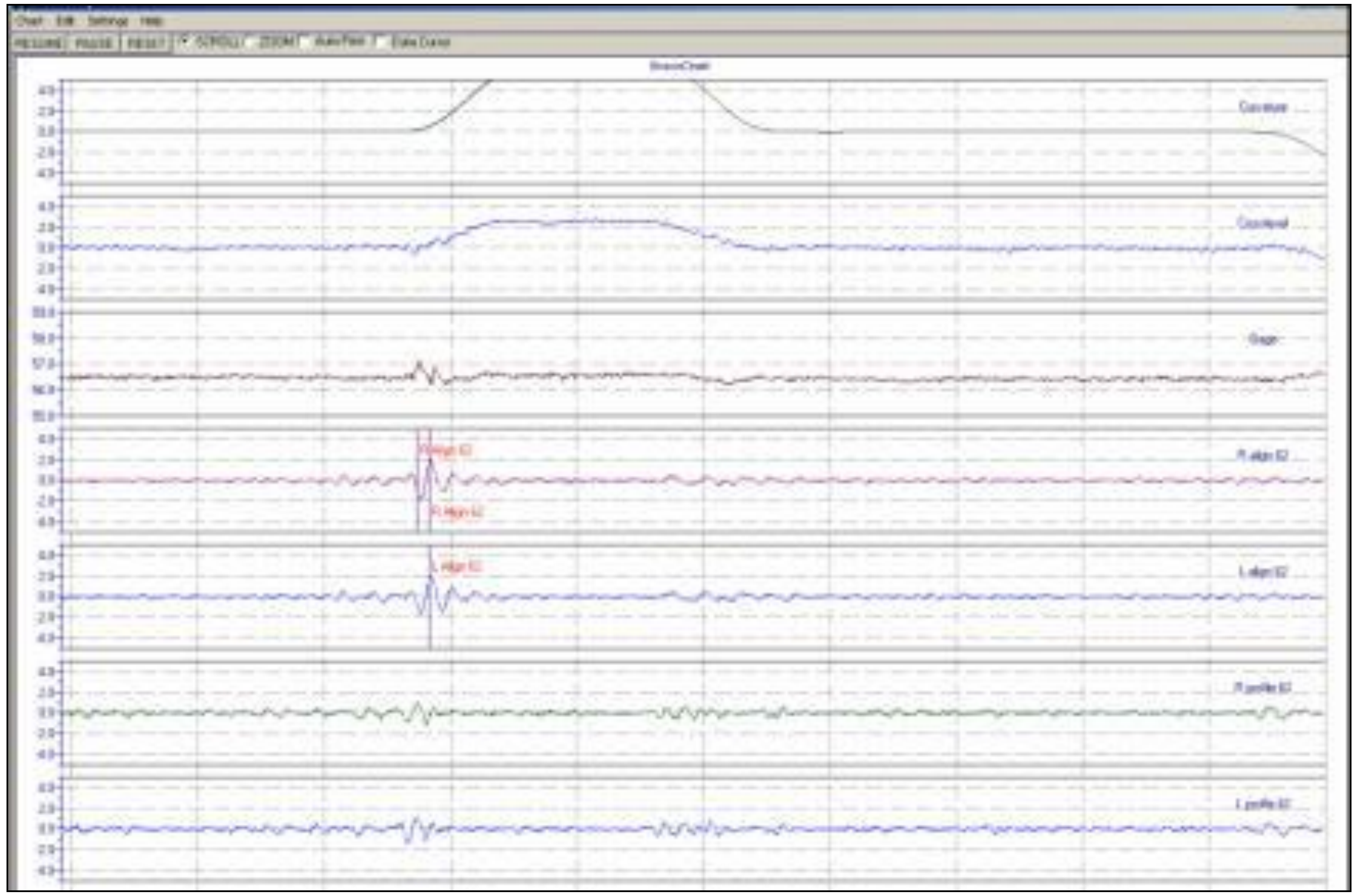
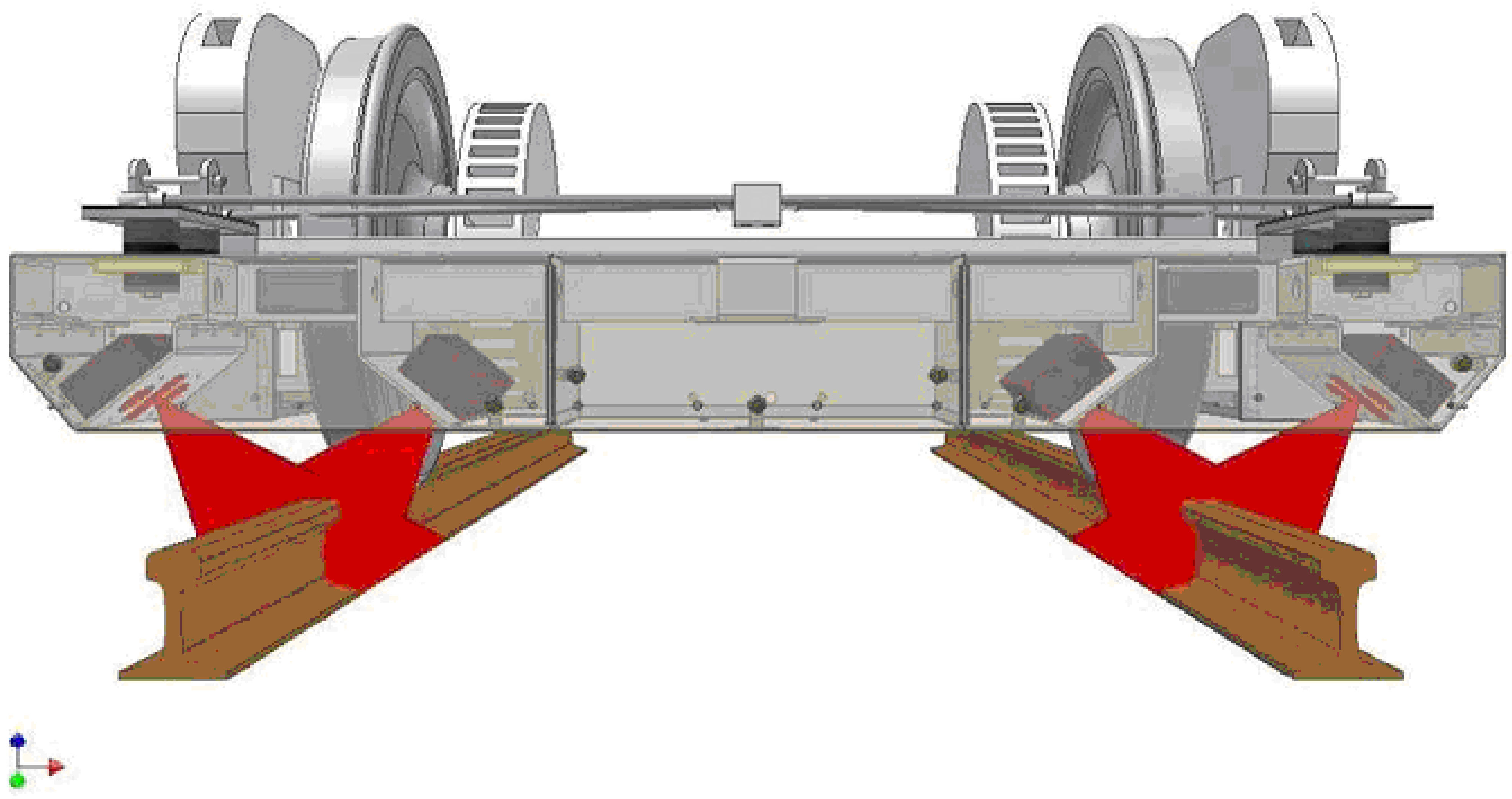
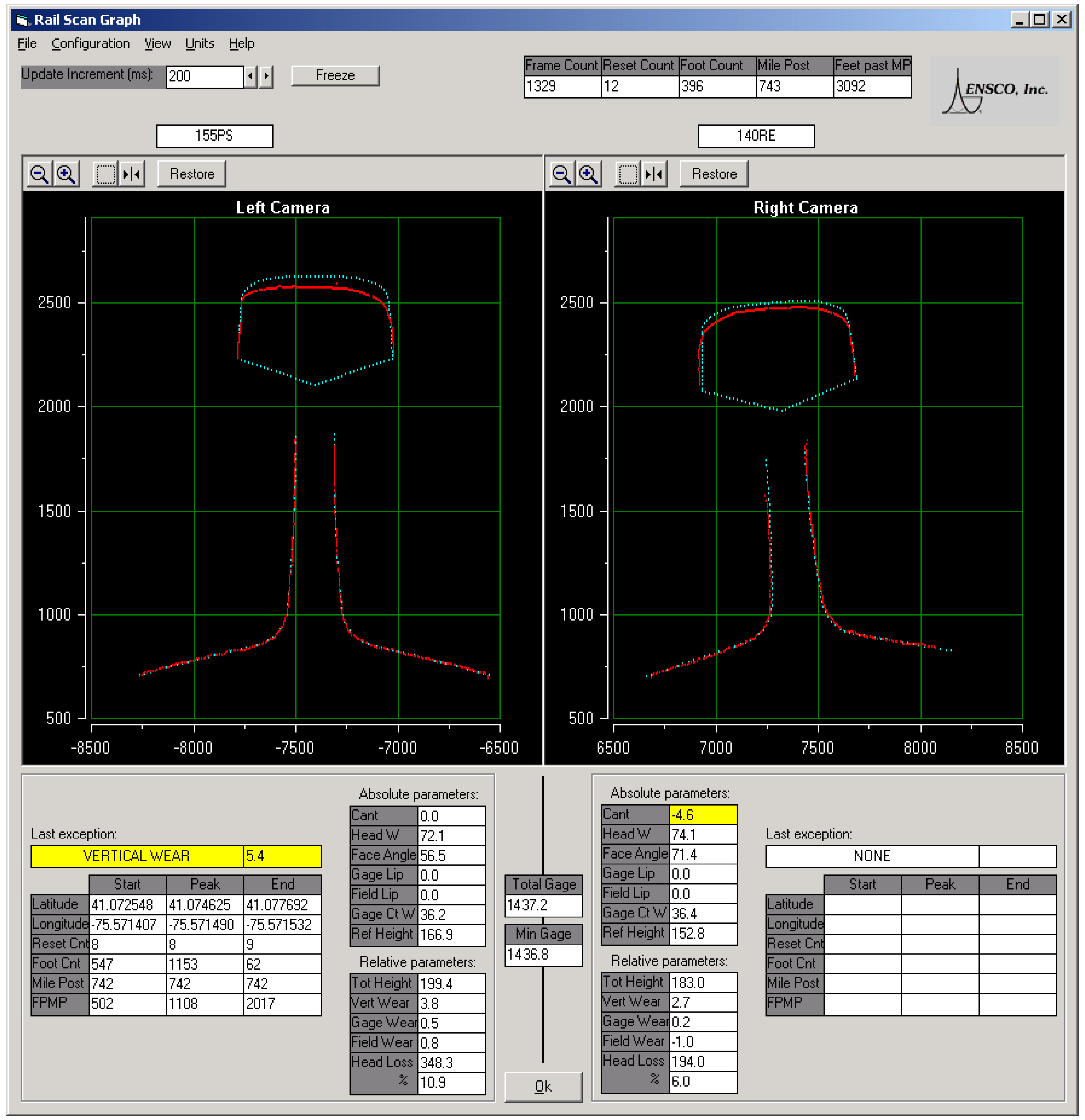
Track Geometry Measurement System



- Continuous geometry can be ingested to represent the effects of track inputs to the vehicle/track - wheel/rail system

Rail Profile Measurements

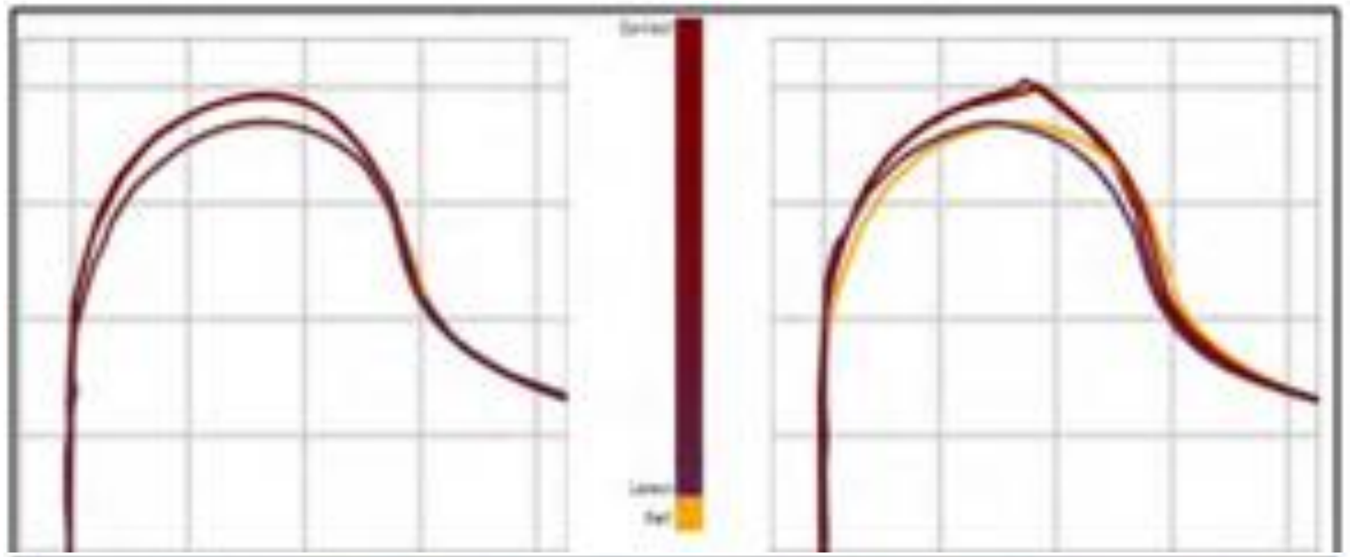




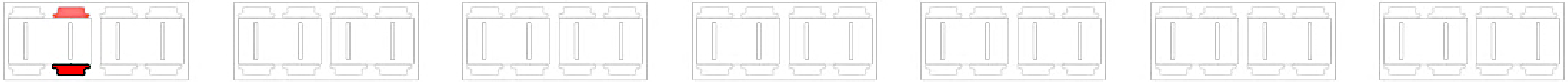
- Continuously varying rail profiles can be aligned with track geometry data

Wheel Measurement System

- With the acquisition of KLD labs, ENSCO is in a unique position to combine wheel and rail profile measurements to enhance the Digital Twin



Wheel Measurements of Entire Train Sets



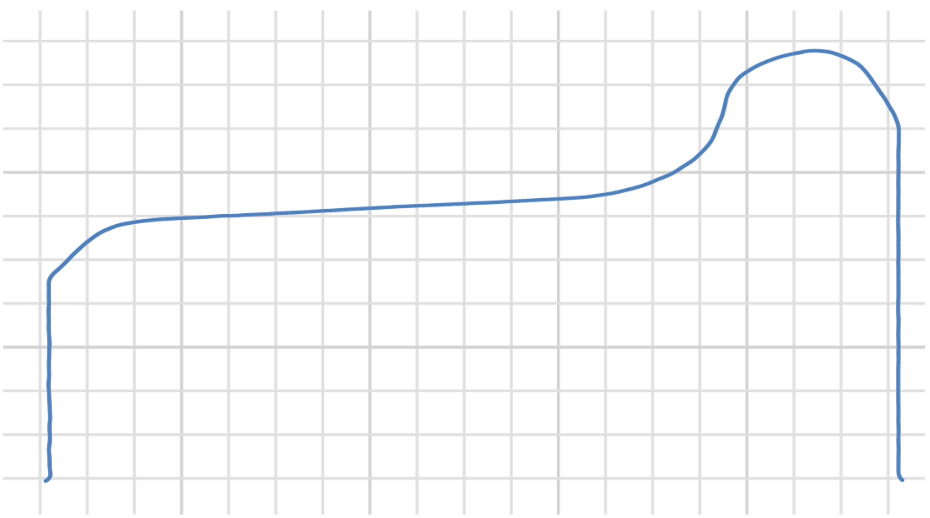
- Wheel profiles from entire vehicles, trains, and fleets can be evaluated

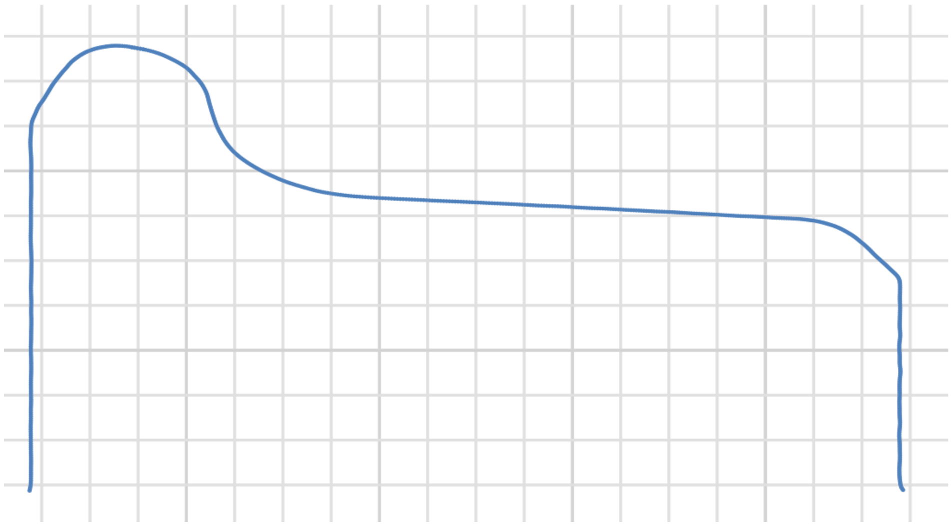
Wheel Measurements of Entire Train Sets

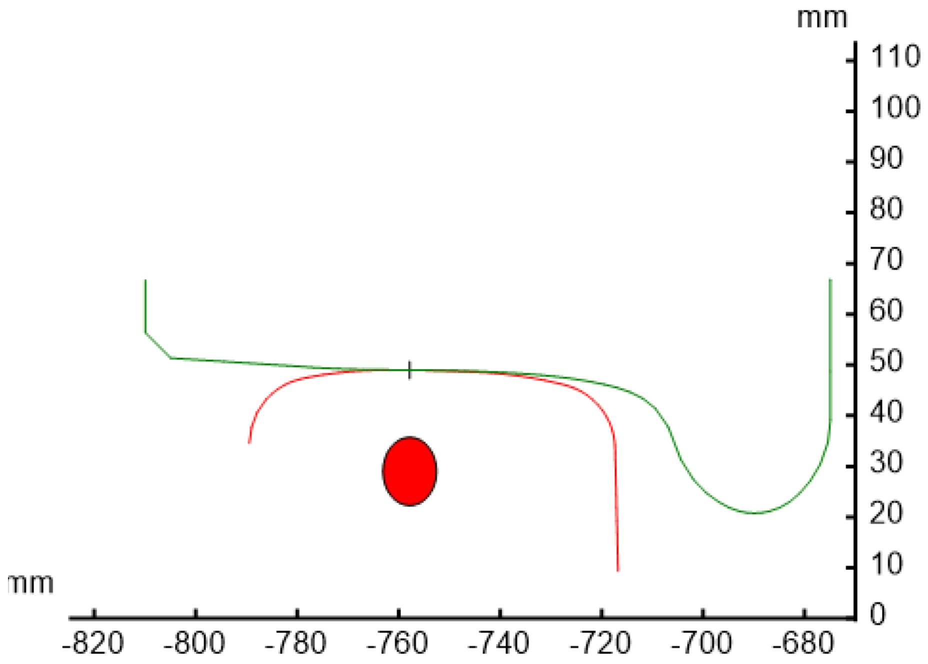
B2B Gauge	Hollow tread	Flange width	Flange height	Rim thickness (sel.)	Wheel width	Flange angle
Inches	Inches	Inches	Inches	Inches	Inches	Degrees
53.22	0.00	1.32	1.10	1.55	5.57	63.83
53.24	0.00	1.27	1.10	1.44	5.64	61.99
53.24	0.00	1.30	1.09	1.42	5.65	63.44
53.37	0.00	1.28	1.09	1.99	5.49	66.45
53.37	0.00	1.22	1.10	1.98	5.49	65.64
53.34	0.00	1.29	1.09	2.08	5.49	63.93
53.34	0.00	1.23	1.10	2.09	5.49	66.12
53.33	0.00	1.27	1.09	2.09	5.50	65.50
53.33	0.00	1.24	1.10	2.07	5.49	65.92
53.34	0.00	1.27	1.11	1.99	5.49	63.47
53.34	0.00	1.24	1.10	1.99	5.48	64.69
53.34	0.00	1.24	1.07	2.50	5.49	64.03
53.34	0.00	1.23	1.07	2.54	5.49	66.48
53.32	0.00	1.23	1.08	2.62	5.47	64.79
53.32	0.00	1.25	1.08	2.67	5.48	65.06
53.31	0.00	1.24	1.08	2.71	5.49	64.92
53.31	0.00	1.24	1.08	2.75	5.50	67.17
53.32	0.00	1.24	1.08	2.50	5.49	64.76
53.32	0.00	1.26	1.07	2.55	5.50	65.03
53.33	0.00	1.28	1.10	2.80	5.50	63.71
53.33	0.00	1.29	1.10	2.74	5.49	64.28
53.33	0.00	1.28	1.10	2.80	5.50	64.68
53.33	0.00	1.28	1.10	2.75	5.49	64.43

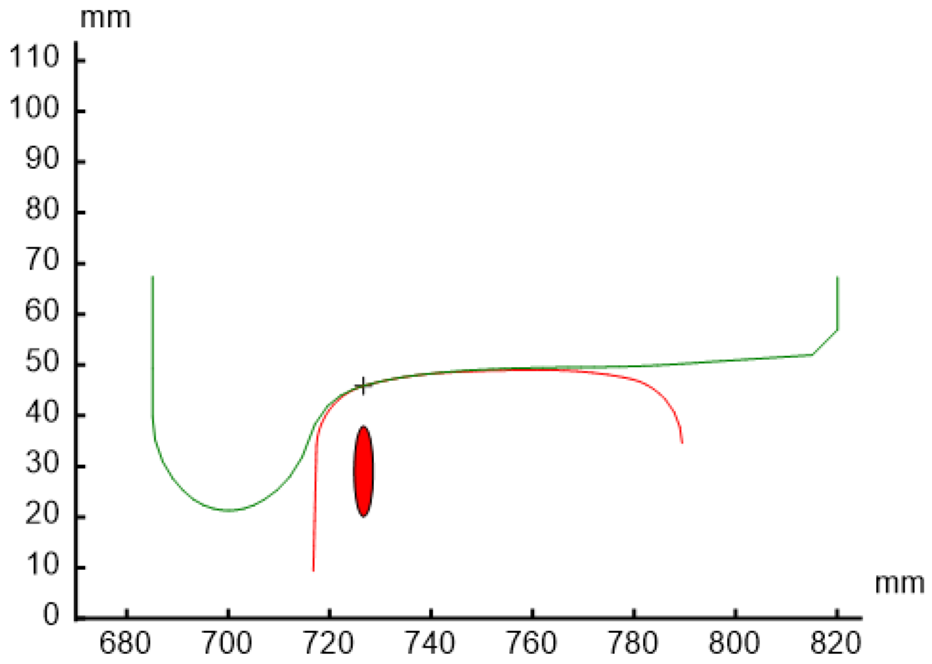
- Critical features of wheel profiles can be evaluated and reported

Wheel Measurements









- Continuous measured wheel profiles can be integrated with continuous rail profiles within VAMPIRE
- Key wheel/rail contact metrics can be calculated

VAMPIRE® Vehicle Dynamics Modeling Software

Vehicle

analysis

Modeling

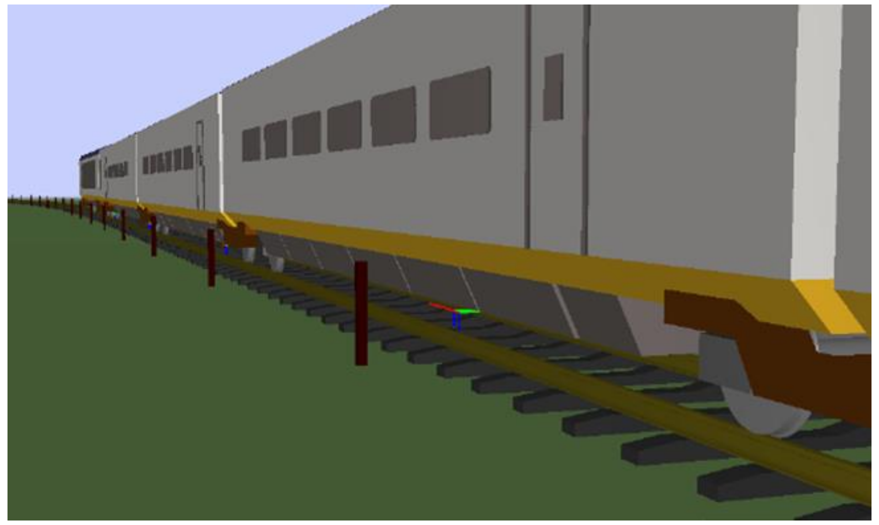
Package

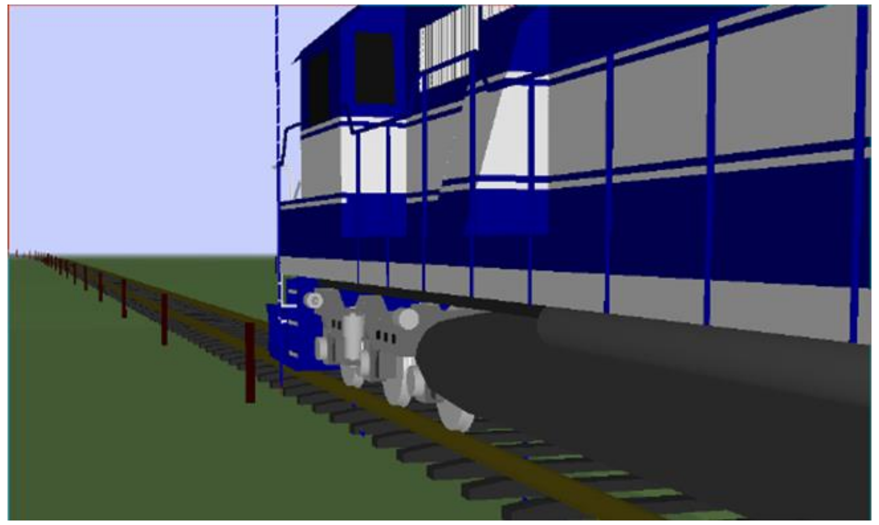
In the

Railway

environment

- VAMPIRE® is a multi-body rail vehicle dynamics modeling package developed by Resonate. Resonate was formed from its predecessors, Delta Rail, AEA Technology Rail and British Rail Research.
- Since around the late 1970's, routines have been written to describe and predict rail vehicle behavior primarily for the purposes of design evaluation and optimization, accident investigation and safe operations setting.
- ENSCO, Inc. has used VAMPIRE for many years and has recently obtained the source code to VAMPIRE to continue developments specific to our customer needs





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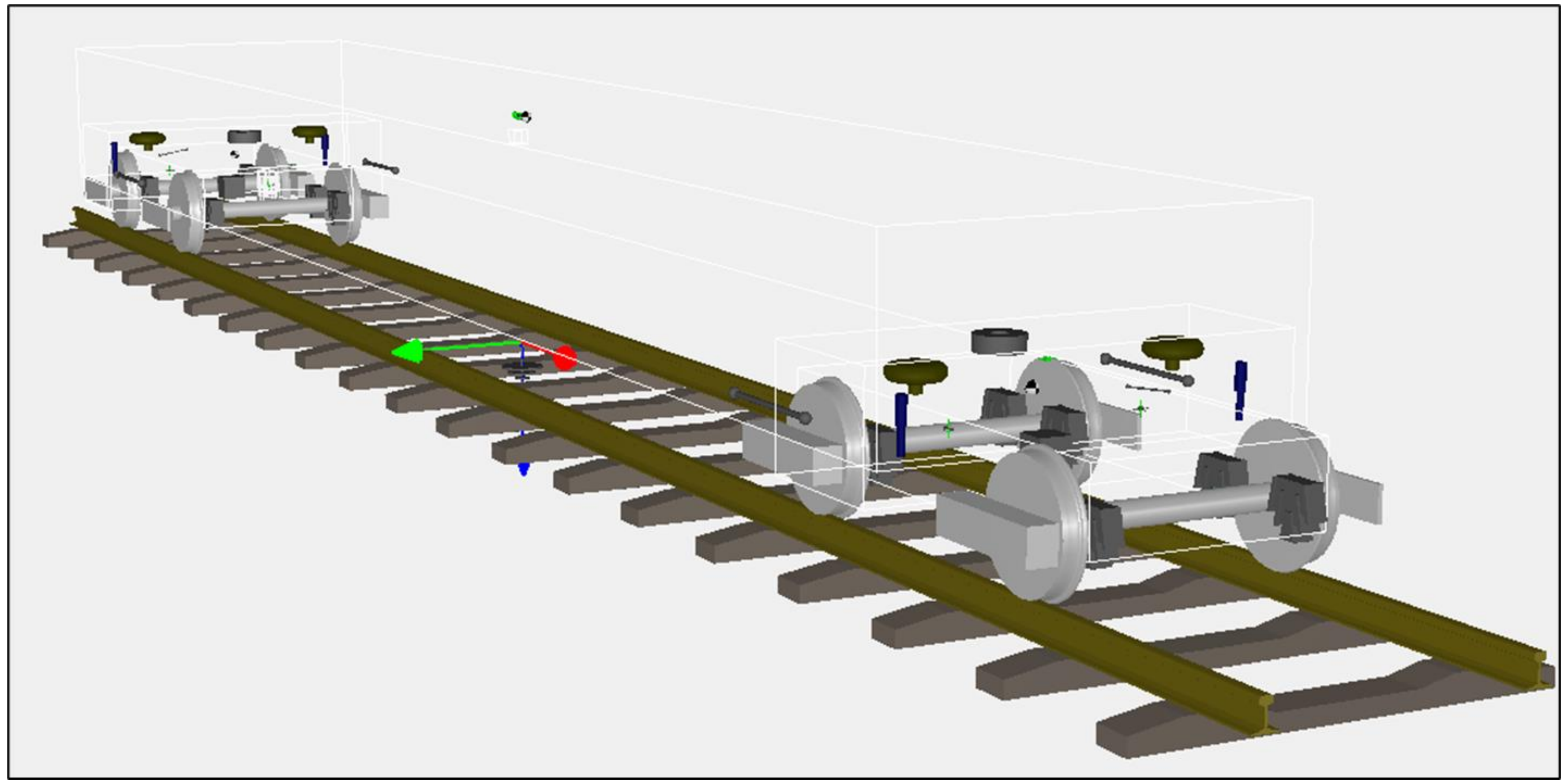
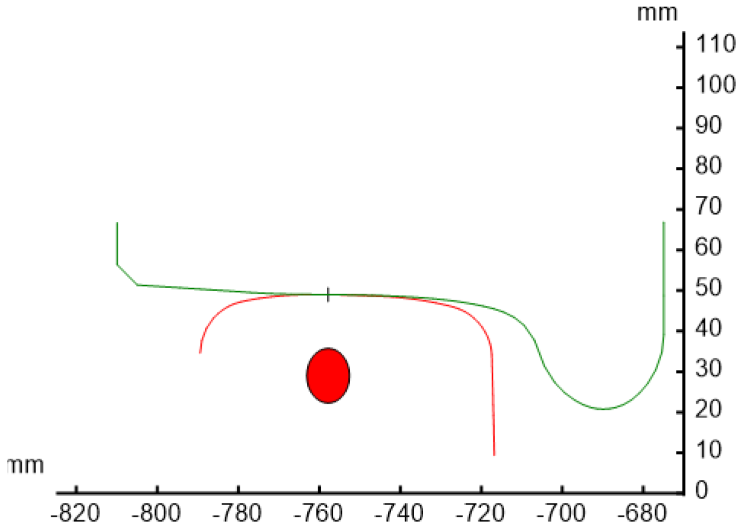
VAMPIRE® Vehicle Dynamics Modeling Software

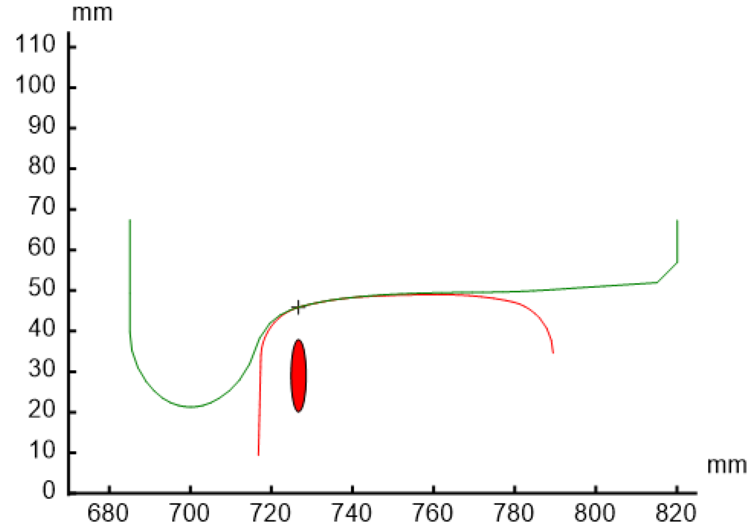
VAMPIRE® is a vehicle – track interaction computer simulation software.

- It is a useful tool to predict the following:
  - Derailment Risk
  - Ride Quality
  - Forces Imparted to Track from Vehicle
  - Forces into vehicle components (wear and life cycle)
  - Wear and damage at the wheel/rail contact

➢ VAMPIRE lends itself well to automation and is fast







Benefits of Adding Wheel and Rail Profiles

1. Create more accurate simulations of vehicle/track interaction behavior (e.g., hunting, effects of hollow worn wheels, etc.)

2. Capture the effects of wheel/rail profile geometry at the wheel/rail interface to enhance wear, damage, and derailment predictions

3. More measurements added to the simulations eliminate assumptions increase accuracy

Wait! Why Use Simulations at All?

- Aren't measurements enough by themselves?
- Can't we just make predictions by trending measurements?
- Isn't everything okay as long as we comply with the maintenance limits?

Why MBS Simulations Add Value Over Trending and Compliance Checks Alone

- Simulations predict hidden system risks beyond maintenance limits
- Simulations can calculate important parameters that are harder to measure
  a) Derailment Risk
  b) Passenger comfort (ISO 2631)
- Simulations are able to evaluate "what if" scenarios and point you in the optimal direction for safety and cost savings
  a) Extension of wheel reprofiling interval
  b) Rail grinding cycle length extension
  c) RCF mitigation evaluation
- Simulations can evaluate and explore the effects of a very large number of variables above and beyond measurement systems and measurement trending

Maintenance Limits vs Simulation Insight

Maintenance Limits:

- Track geometry, wheel, and rail profiles checked individually and does not necessarily anticipate system interaction issues
- Each parameter may be within tolerance but interact unfavorably

Simulation Insight:

- Integrates measured geometry + wheel + rail profiles
- Reveals combined effects: high equivalent conicity, reduced hunting speed
- Quantifies forces, L/V ratios, RCF & wear indices
- Predicts poor performance even when all inputs are within limits

Trending of Measurements vs Simulation: Key Differences

Limitations of Trending of Measured Data:

- Only projects future outcomes based on past data
- Predicts effects of traditional maintenance actions (e.g., reprofiling, grinding) with respect to maintenance limits
- Cannot anticipate impacts of new features, designs, or strategies

Advantages of MBS Simulations:

- Converts measured data into system-level dynamic responses
- Predictive capability: reveals consequences, not just compliance
- Scenario testing: quantifies 'what if' changes, including new actions
- Optimizes timing for safety, cost, and comfort
- Can calculate important hard to measure parameters like derailment risk

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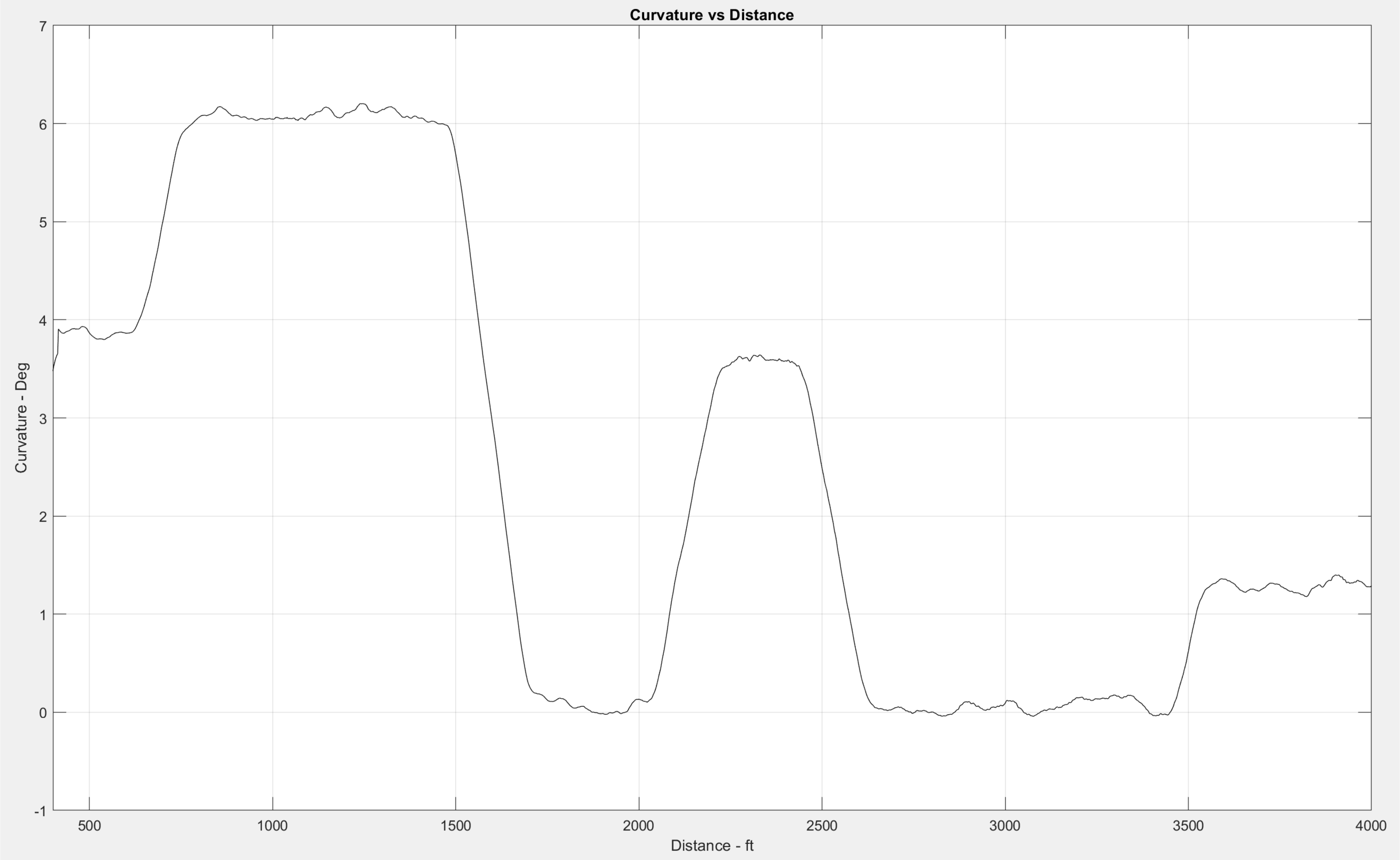
Example 1 – Comfort and Safety

Example 1 - Background



- Transit operation
- Succession of 3 curves
- Everything is within maintenance specs
- Evaluating the system with measurements integrated with simulations

➢ Key Metrics:
  – Ride Quality
  – Equivalent Conicity
  – Single Wheel L/V Ratio

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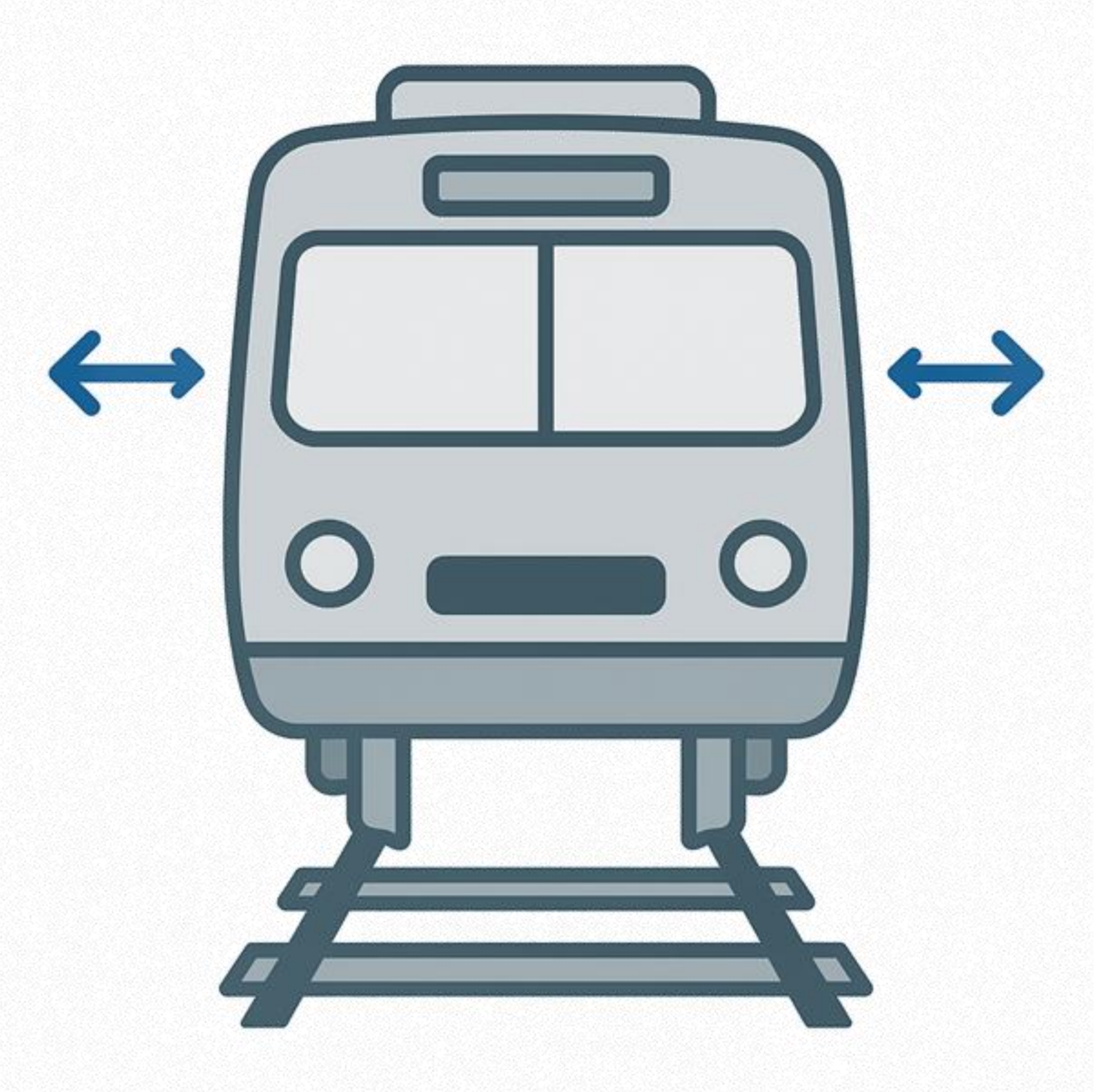
Ride Quality

- Some studies of ride comfort show that passengers are sensitive to sustained accelerations over short periods (~ 1 to 5 seconds).
- ISO 2631 and transit ride comfort research indicate that lateral RMS accelerations above **~1 m/s^2** correspond to the onset of "uncomfortable" ride quality.
- Below this threshold, most passengers perceive vibrations as tolerable.
- Using **1 m/s^2** as the cutoff provides a conservative but realistic indicator of when ride quality deteriorates.



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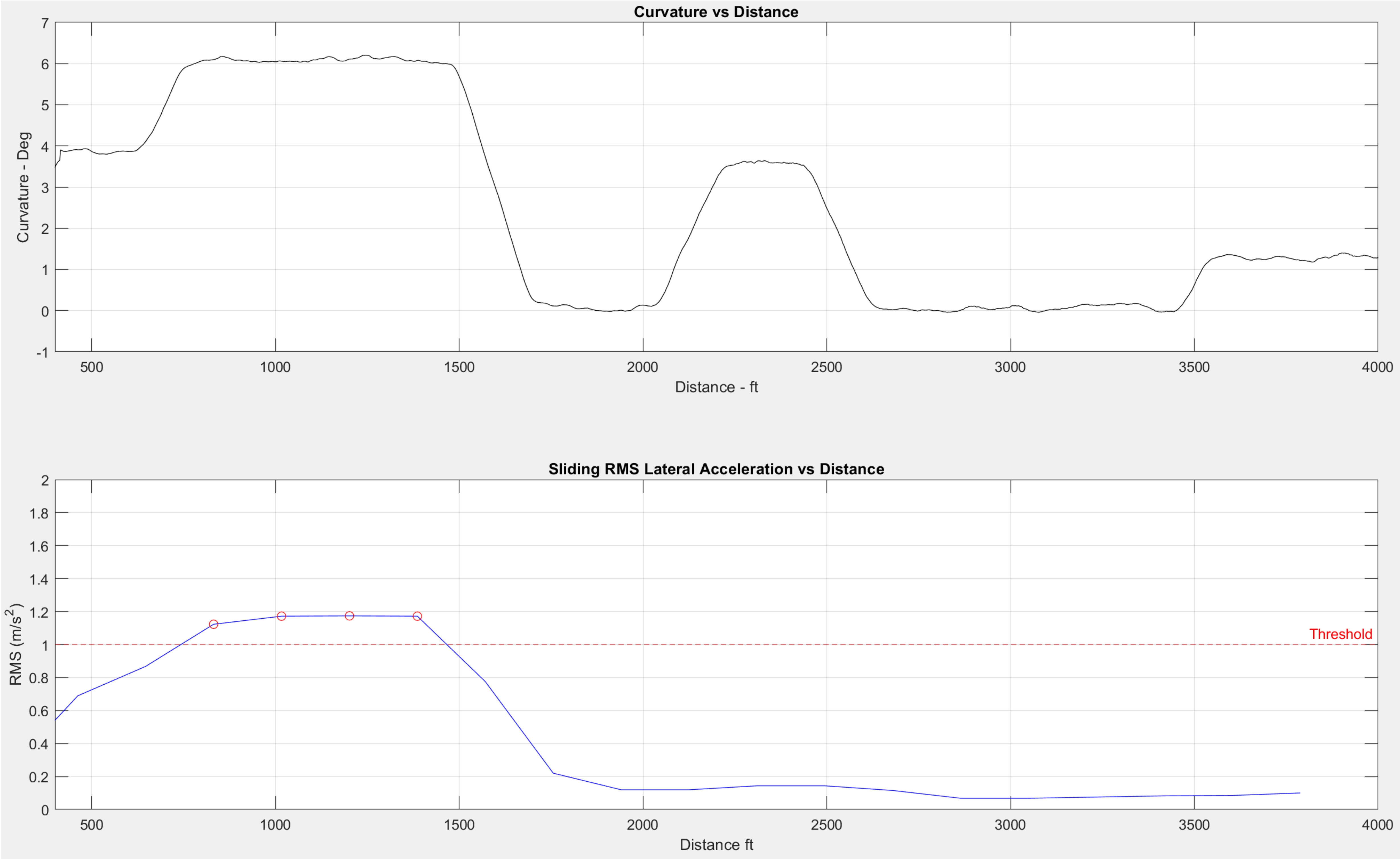
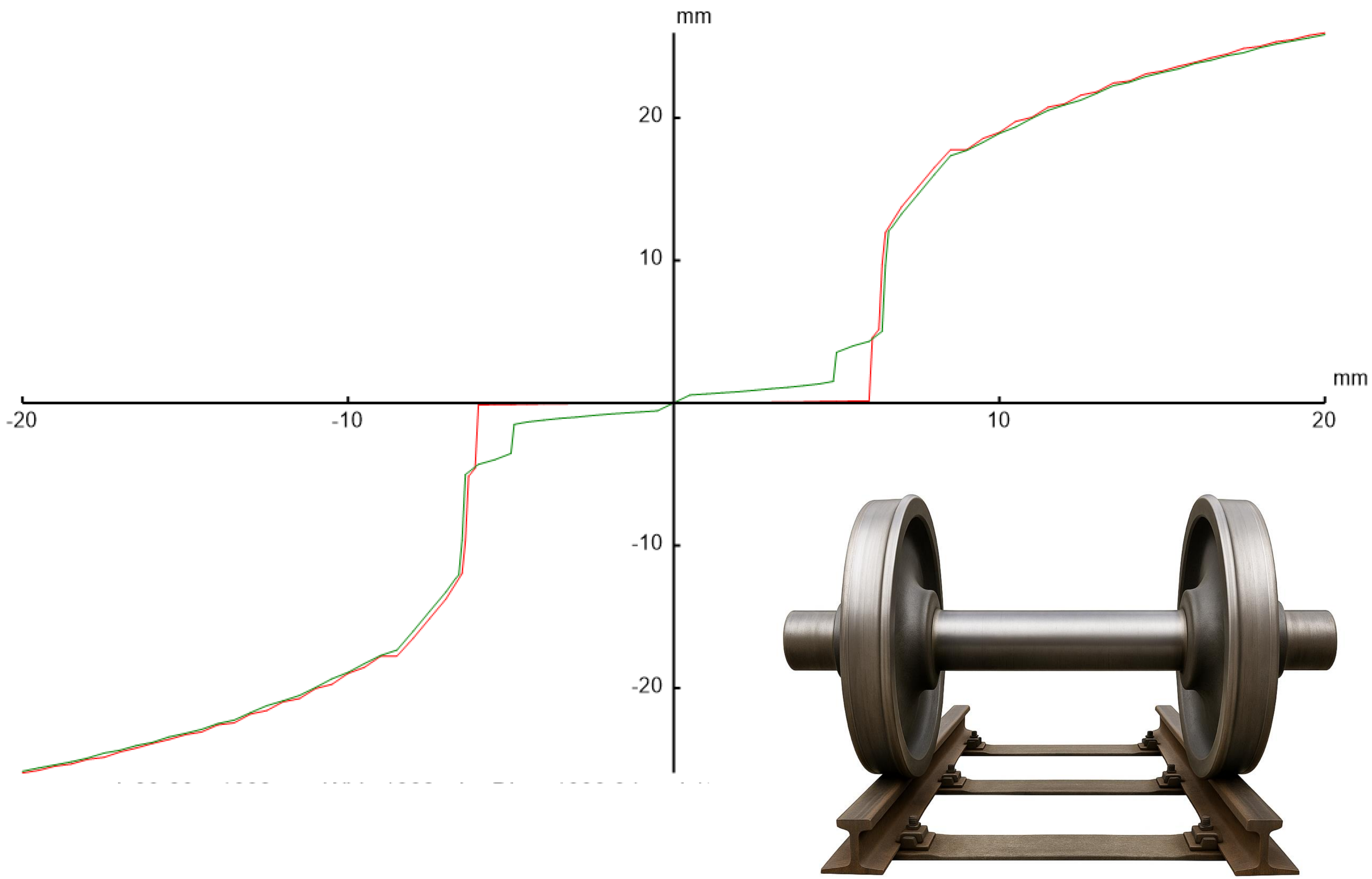
Ride Quality - Results



- A few slight exceedances of the conservative comfort threshold are calculated from the vehicle model moving through the ~ 6-degree curve

Equivalent Conicity



- Equivalent conicity quantifies how "conical" the effective wheel–rail contact is.
- It tells us how much the rolling radii of the left and right wheels differ when the wheelset shifts laterally on the rails.
- This difference drives the wheelset's tendency to self-steer.

Why Equivalent Conicity Matters

- Equivalent conicity is a measure of how wheel and rail profile combinations affect **vehicle stability and curving performance**.

- It reflects how quickly a wheelset will self-steer laterally on the rails.
  - **Too low** → poor steering in curves, high flange forces, and accelerated wear.
  - **Too high** → unstable hunting at speed, uncomfortable ride, and potential safety issues.

Recommended Range

- Industry practice (UIC, APTA, and others) typically recommends **0.1 – 0.4**:
  - **~0.1–0.2** → good for high-speed stability.
  - **~0.3–0.4** → good for urban/transit operations requiring better curving ability.

- Values **outside this range** increase risk of either **instability** (if >0.4) or **excessive wear and poor curving** (if <0.1).

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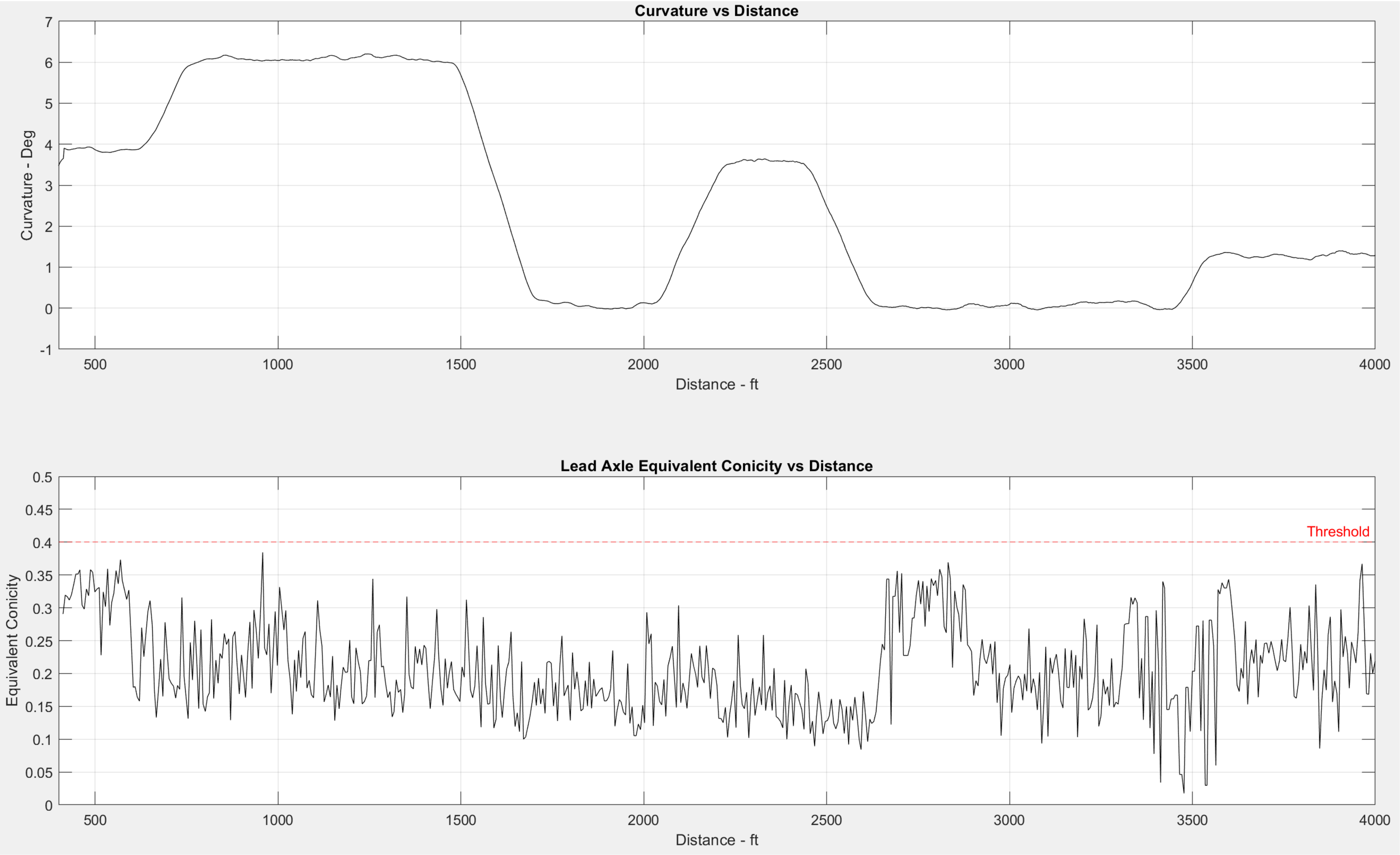
Equivalent Conicity – Lead Axle



- We are able to evaluate equivalent conicity throughout the route with measured wheel and rail profiles
- For the most part, the EC is within the recommended range
- One location is nearing the maximum threshold within the ~ 6-degree curve

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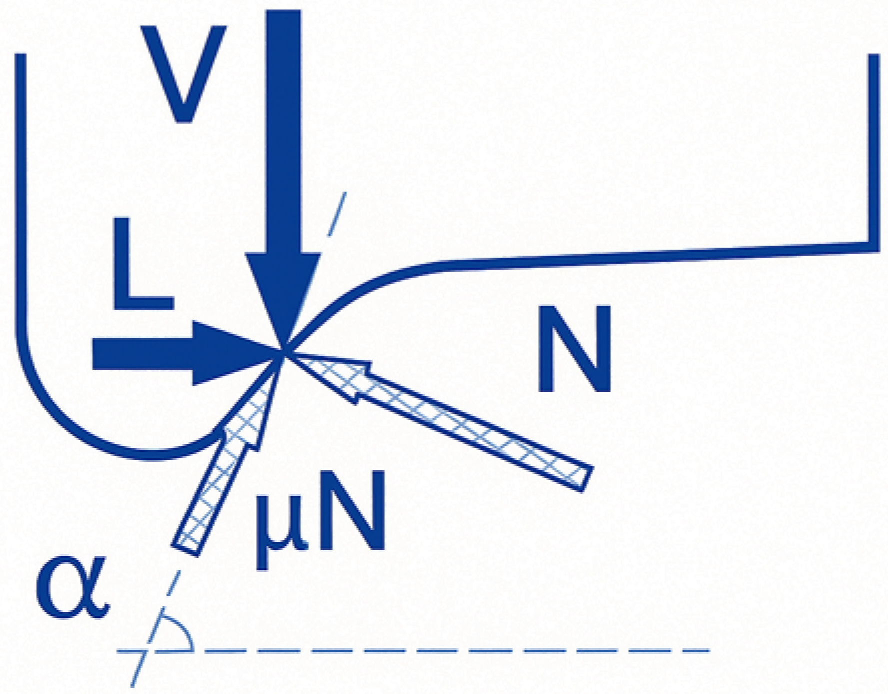
Derailment Risk – Determined by The Interaction of the System

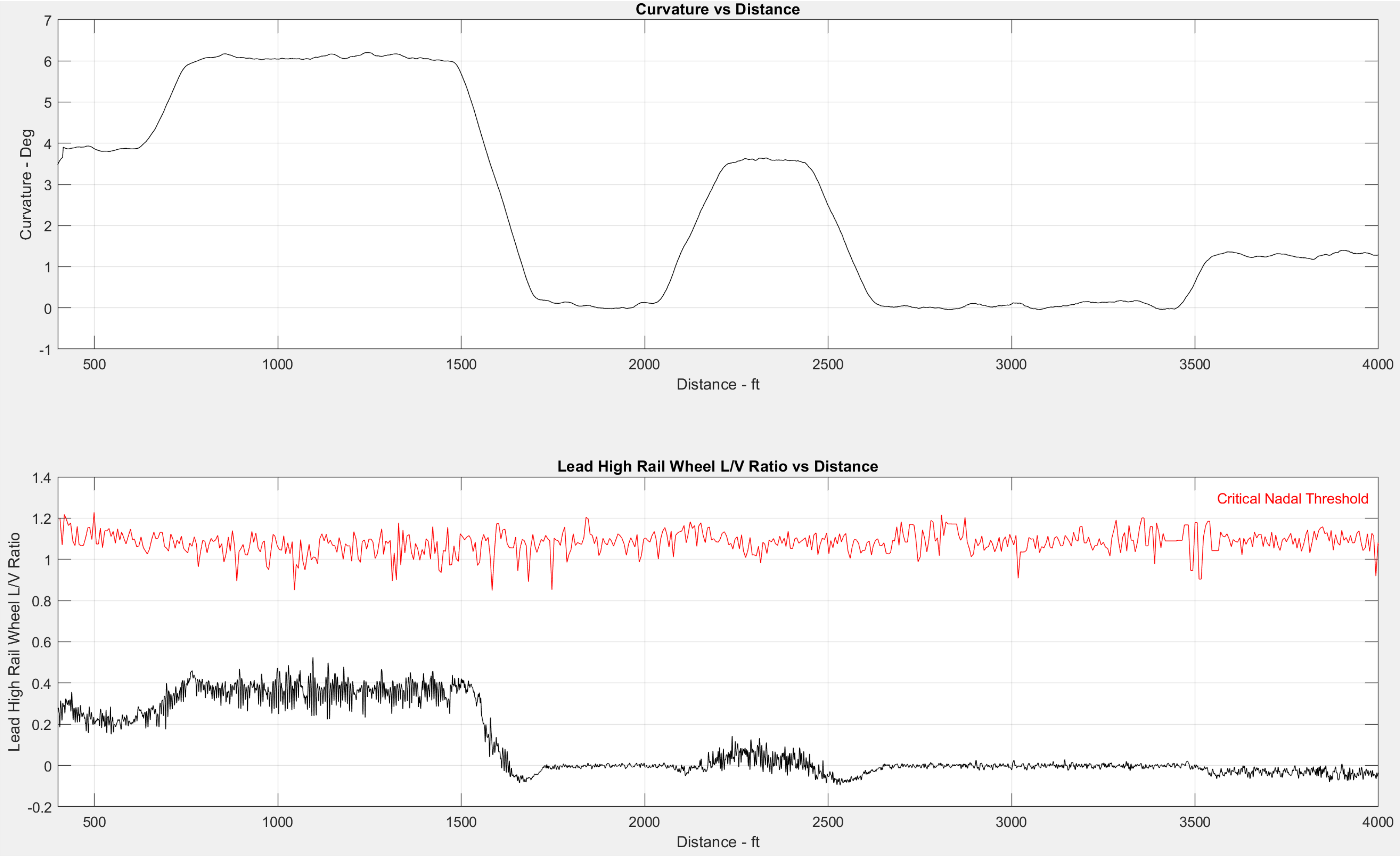
Nadal's Critical Wheel L/V Ratio



$$\frac{L}{V_{crit}} = \frac{\tan\alpha - \mu}{1 + \mu \tan\alpha}$$

1. **Wheel Flange Contact Angle (α)**
   a) The steeper (larger) the flange angle, the harder it is for the wheel to climb. A shallower angle lowers the threshold, making wheel climb more likely at lower L/V ratios.
2. **Coefficient of Friction (μ)**
   a) Higher friction increases the wheel's ability to "grip" the rail and climb, which lowers the critical L/V ratio. Lower friction (e.g., wet or lubricated rail) reduces climbing ability, raising the critical limit.
3. **Wheel/Rail Contact Conditions**
   a) Profile wear: worn wheel or rail shapes can alter the effective flange angle.
   b) Rail inclination: changes how forces resolve at the flange.
   c) Lateral geometry defects (misalignment, gauge issues) can amplify lateral forces.
4. **Vehicle/Track Dynamics**
   a) Suspension stiffness and damping affect how lateral forces build up.
   b) Curvature, crosslevel, lateral alignment, vertical alignment, cant deficiency, and hunting oscillations all influence the applied L/V.
   c) High speeds may amplify dynamic forces, reducing effective safety margins.

Derailment Risk – High Rail Wheel of Lead Axle



- We are able to evaluate and show the critical Nadal threshold for this wheel throughout the entire route using the measured wheel and rail profiles
- Everything is below the critical limit (for this wheel)
- There is a relatively elevated L/V ratio with respect to the calculated critical Nadal in the ~ 6-degree curve

Integrating and Cross Referencing

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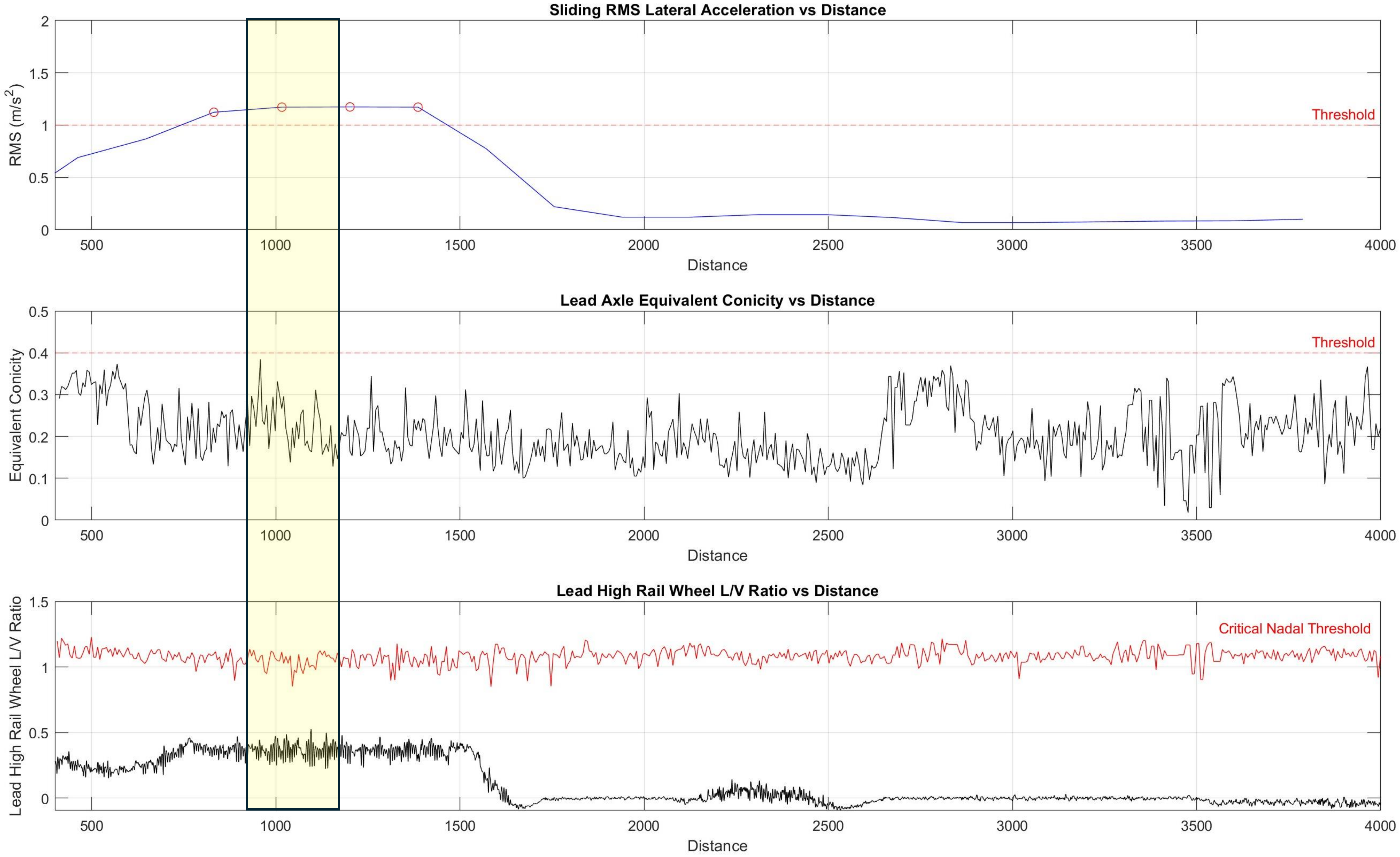
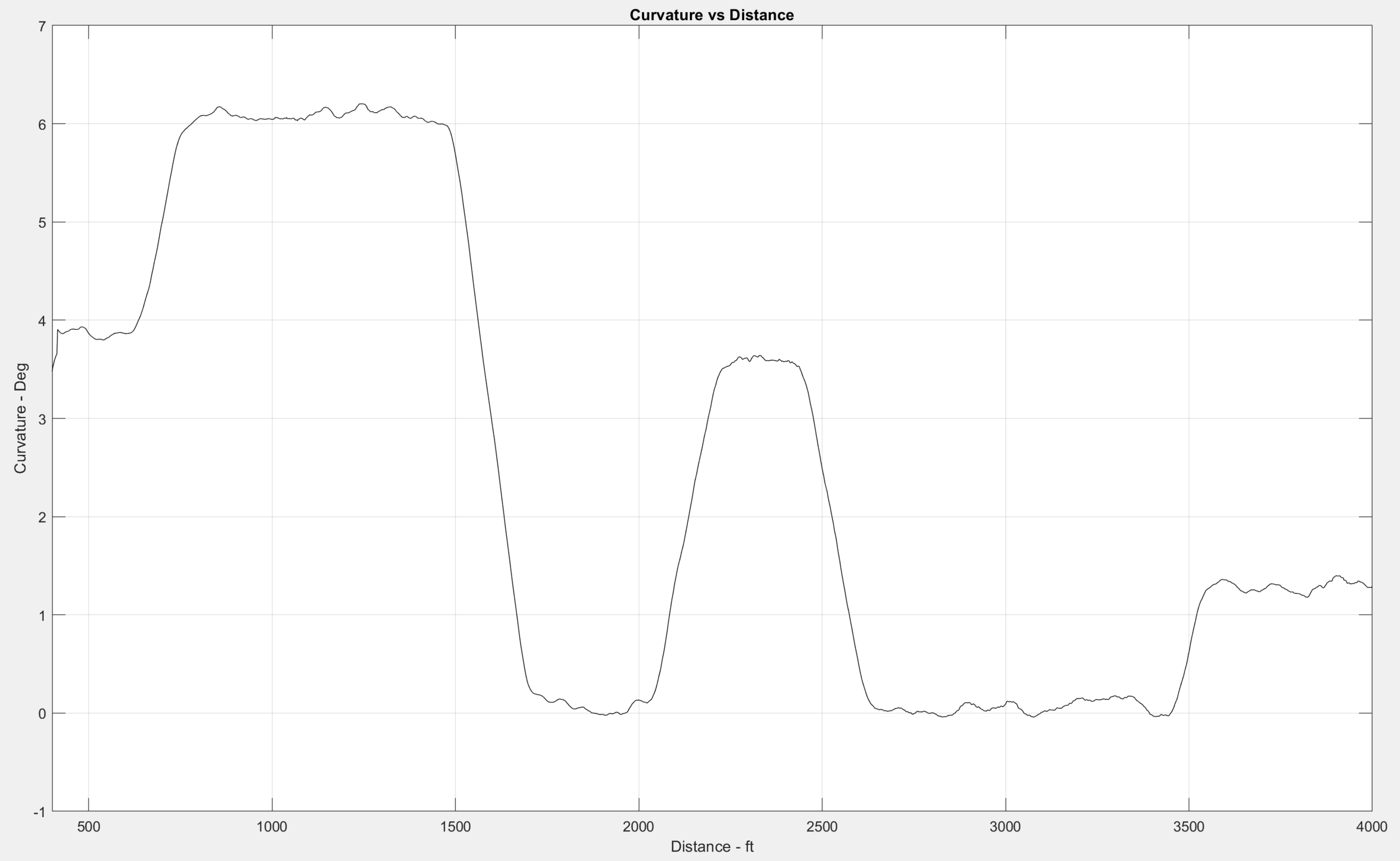


- By integrating and cross-referencing these metrics, the band shown contains a comfort issue, the highest equivalent conicity, and the highest derailment indication.

➢ This location that occurs within the ~ 6-degree curve may be worth noting and tracking despite being within maintenance specs

Example 2 – Optimal Maintenance Action and Cost

Example 2 - Background



- Same transit operation
- Everything is within maintenance specs
- RCF clusters have been found spaced along the longer tangent section
- Primary driver of the RCF is sought
- Some have suggested redesigning the wheel/rail profiles may be warranted
- Evaluate the system performing a “what if” parametric study of potential drivers of damage with **pummeling**

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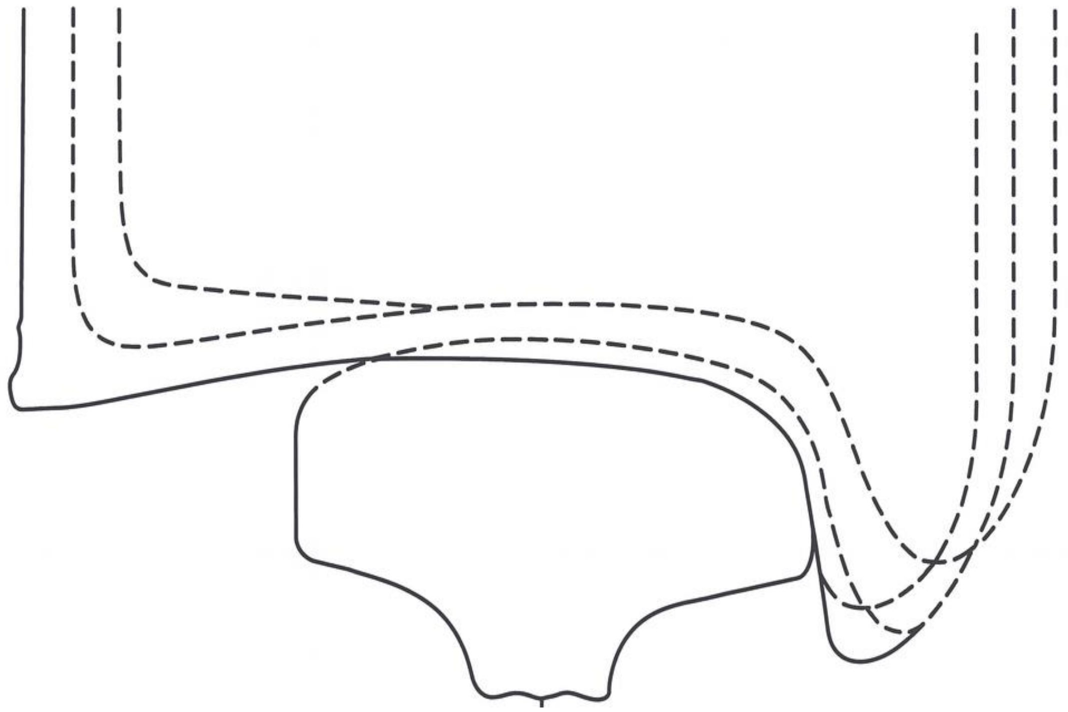
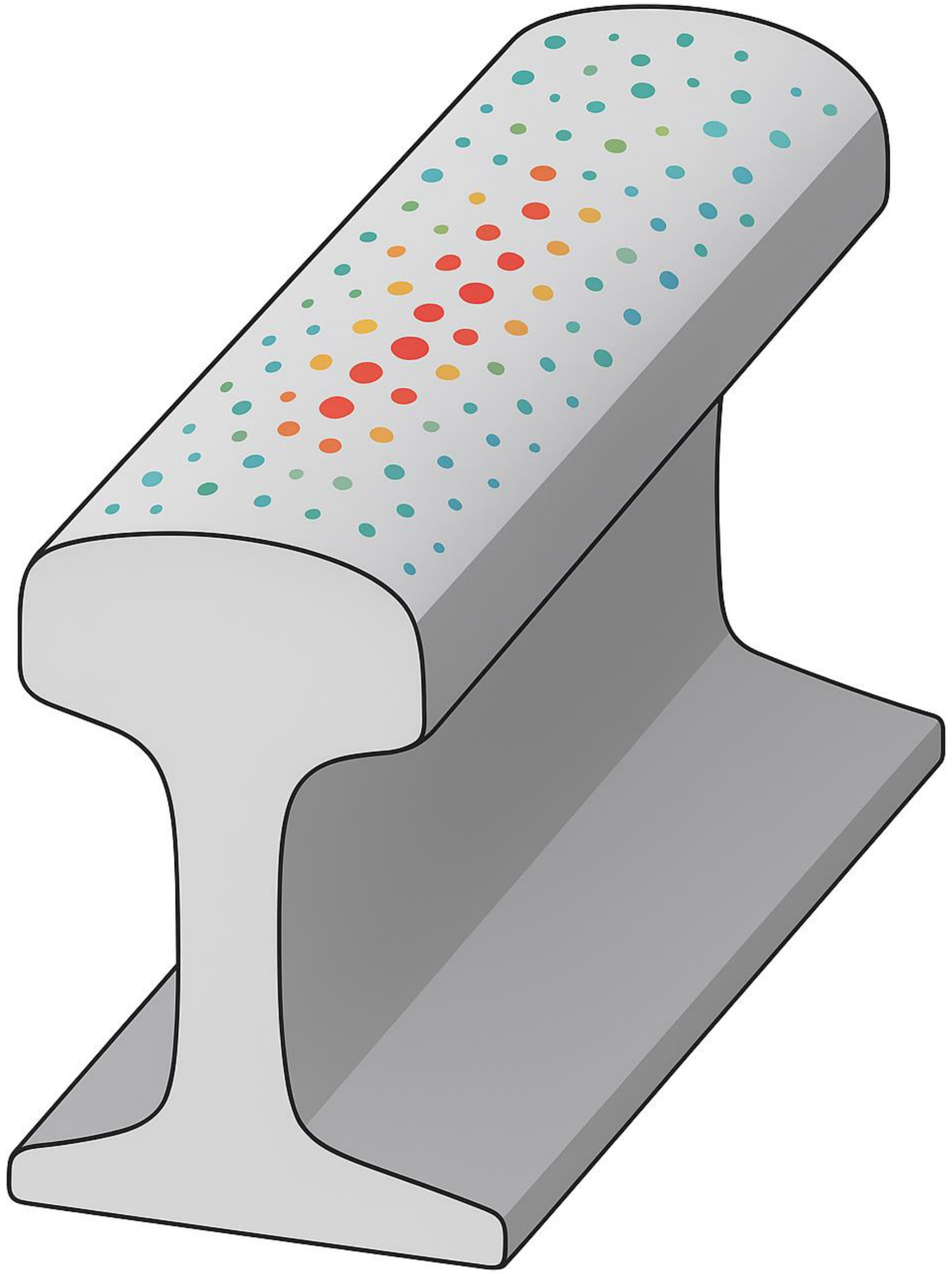
What is a Pummeling Analysis?





- Simulates repeated wheel/rail contact cycles to assess progressive damage
- Applies measured profiles with vehicle static and dynamic loading
- Tracks how wear and rolling contact fatigue (RCF) accumulate over iterations
- Reveals potential issues even when wheels, rails, and geometry are individually within limits
- Supports decisions on rail grinding, wheel reprofiling, profile redesign, improvement in geometry or operational changes

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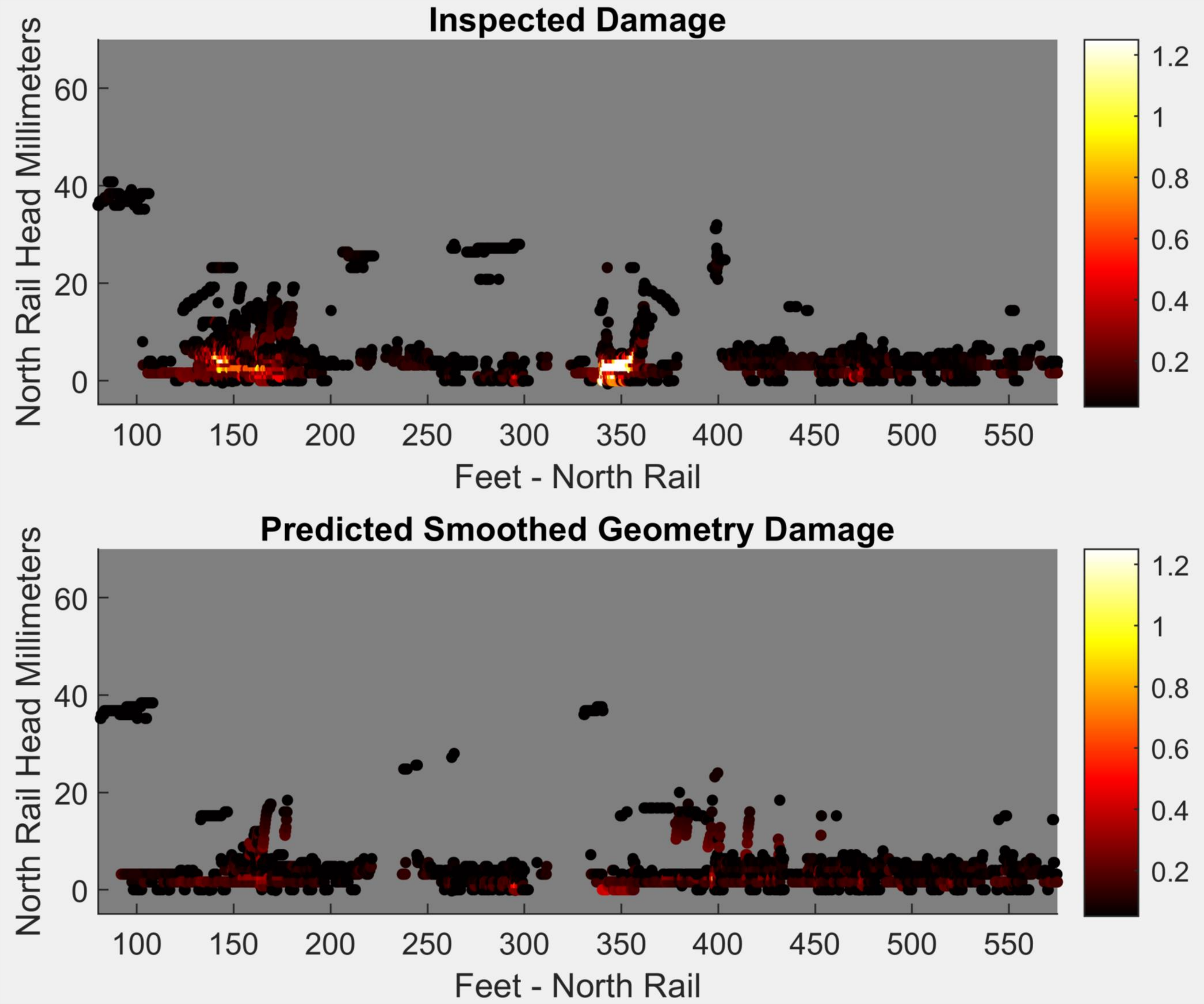
Pummeling Results



- Multiple potential options were evaluated
  - ❖ Different wheel profile
  - ❖ Different rail profile
  - ❖ Improvements in geometry perturbations driving dynamic loading

➢ Smoothing the geometry perturbations driving dynamic loading was most effective in reducing damage

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Targeted Future Developments and Additions

Replacing Assumptions with Data

- Hypothetical "Fixes" based on before and after measurements
- Integrate vehicle/bogie evaluation data (e.g., TPD or L/V monitor)
- Variable friction based on measured data and more sophisticated contact models

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Questions?