M x V RAIL

Rolling Contact Fatigue (RCF) Characterization Using Electro-Magnetic Field Imaging (EMFI) Technology

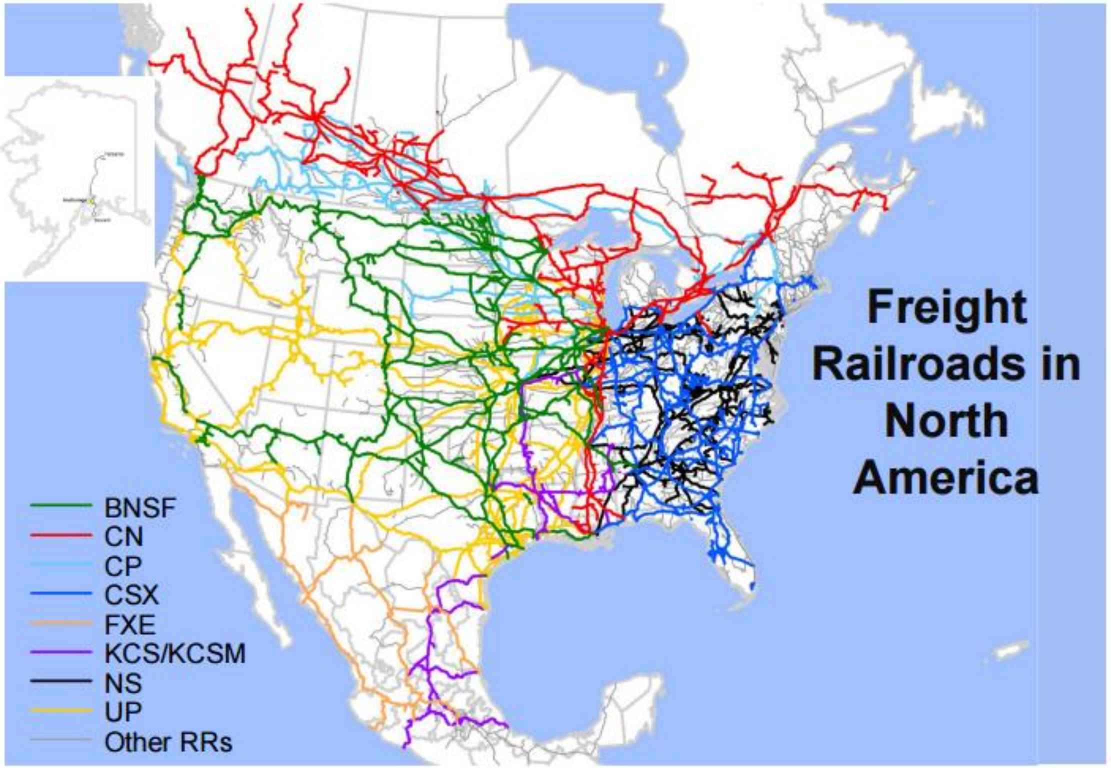
Anish Poudel, PhD

Principal Investigator II - NDE

M x V RAIL

North American Railroads

- How many miles of track? **289,682 km**
- How many locomotives are in service? **26,500 locomotives**
- How many freight cars are part of the system? **1.66 million cars**
- How many gallons of fuel do we use? **3.54 billion gallons**
- Tons of traffic hauled? **1,622 billion tons**
- Capital dollars invested? **$13 billion**
- What is the total revenue of the US railroads? **$70 billion**
- How many employees? **148,000 employees**



Source: *www.aar.org*

The AAR and its Subsidiaries

AAR

- Policy making
- Standard setting
- Industry data, reports & publications
- Research & technology initiatives

MxV Rail

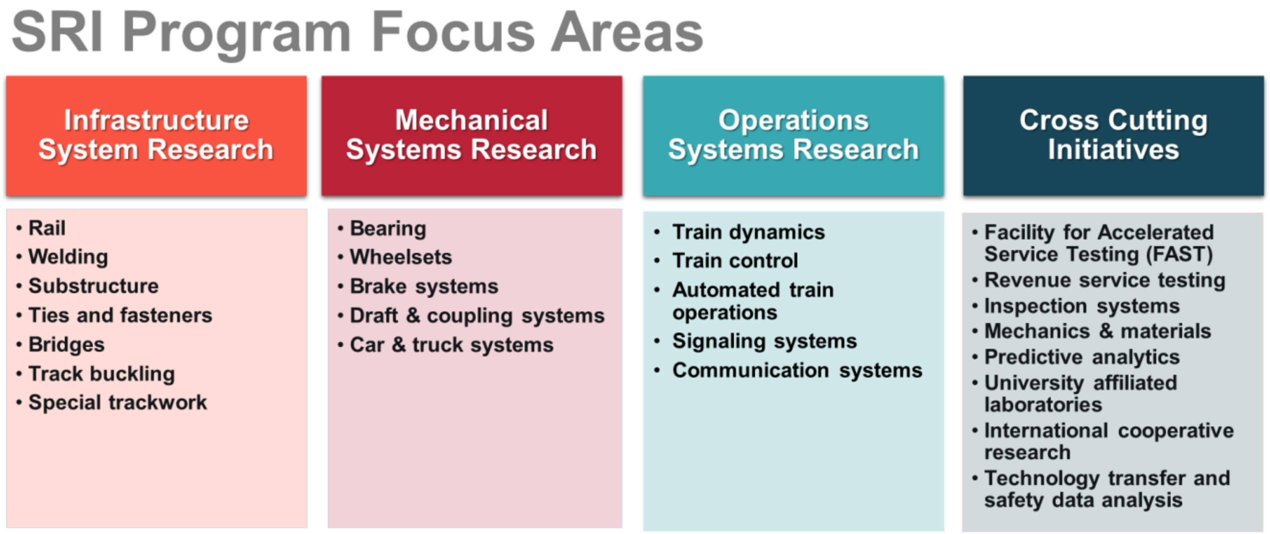
- For-profit AAR subsidiary
- Research, testing, and training for global rail industry
- Manages Strategic Research Initiatives (SRI) Program

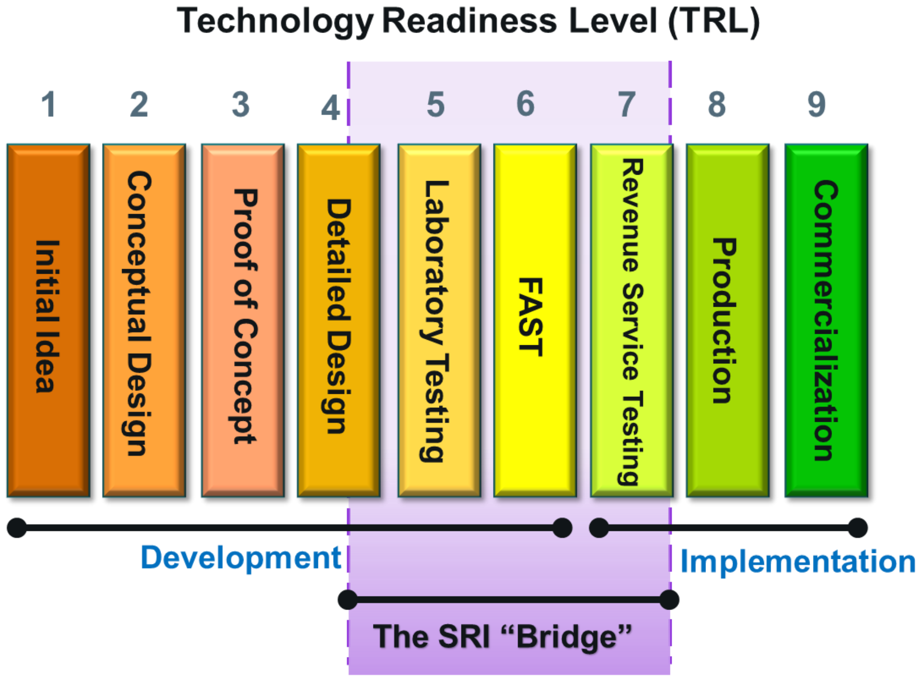
Railinc

- For-profit AAR subsidiary
- Rail data and messaging services to the NA freight railway industry.
- Railinc Committee:
  - Asset Health Strategic Initiative
  - Clear Path – Gateway Operations Visibility
  - PTC Support

The SRI Program

- **Improve safety, reliability, and efficiency**
- **Build exemplary teams and facilities**
- **Empower science-based solutions**
  - Identify and evaluate technologies
  - Demonstrate understanding of root causes
  - Support implementation
  - Communicate findings

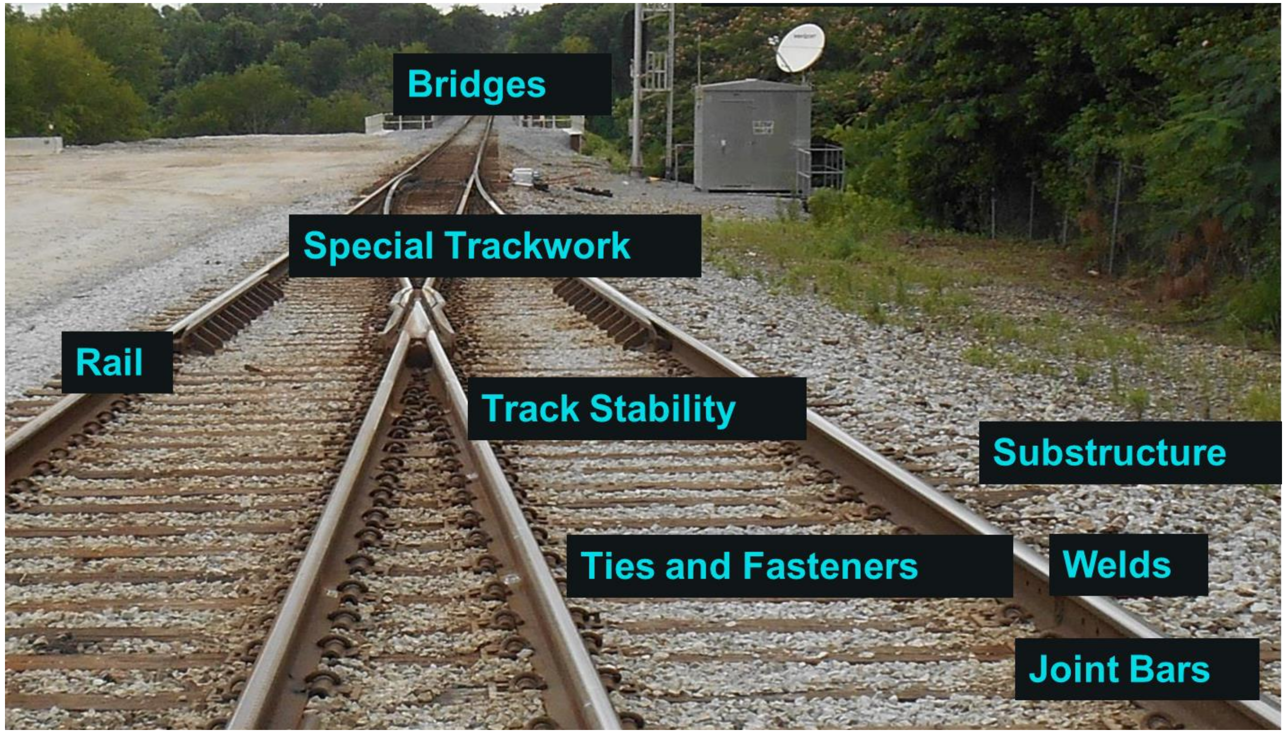




MxV

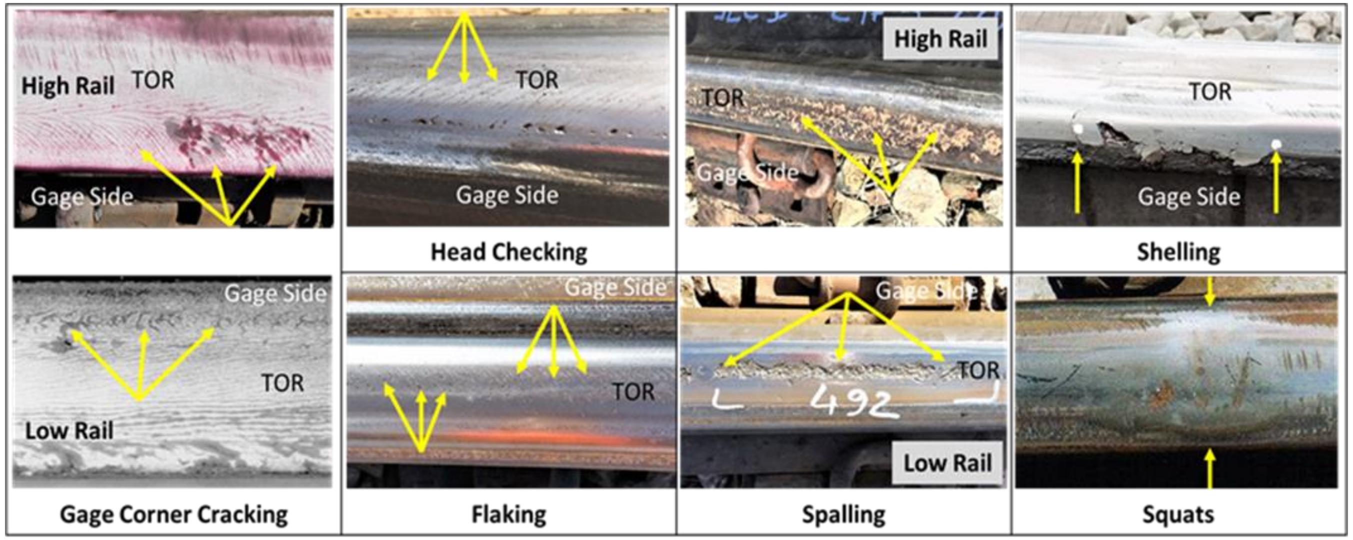
Why Rail Inspection Research?

- ***Safe, reliable, and efficient*** train operations without track interruption (**Origin to Destination**)
- **Challenges**
  - Reliable detection to prevent rail breaks
  - Defect detection over all conditions:
    - **Rolling Contact Fatigue (RCF)**
    - Weld Defects
    - Base Defects
    - Joint Bar Defects
    - Grade Crossing & Dark Territory
  - Improved speed and detection efficiency

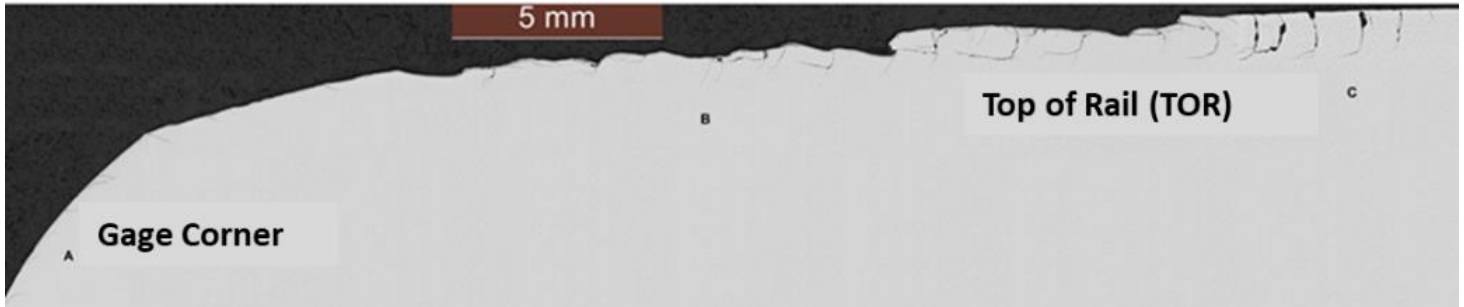


RCF Research Motivation

- Railway maintenance challenge
  - RCF damage (cracks and pits)
    - **Complicates rail inspection**
      - Remediated by rail grinding
    - **Material strength**
      - RCF reduces the life of the rail
- Focus
  - Accurate in-motion NDE measurement techniques
    - Crack depth
    - Material exhaustion



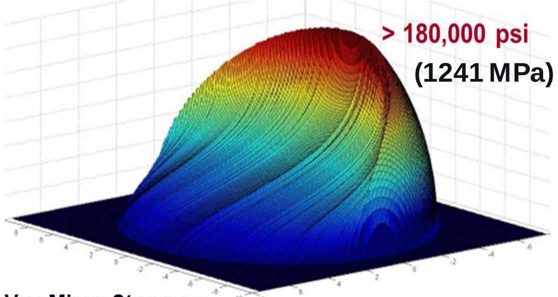
Examples of RCF Damages in Rail



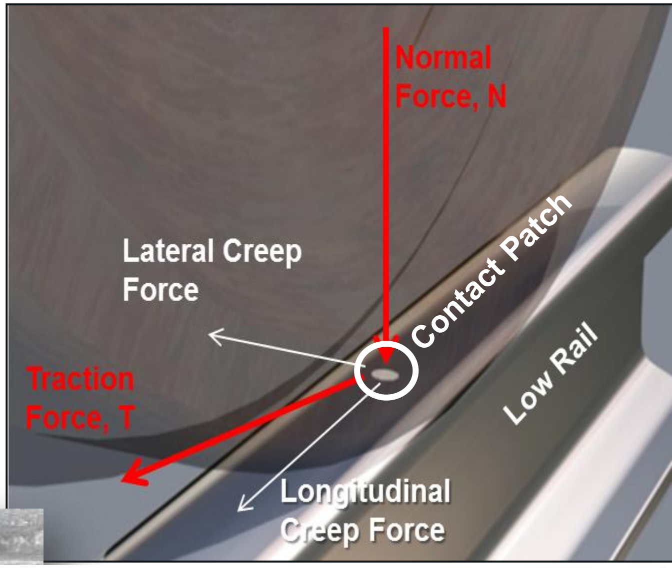
Micrograph of Severely Spalled High Rail

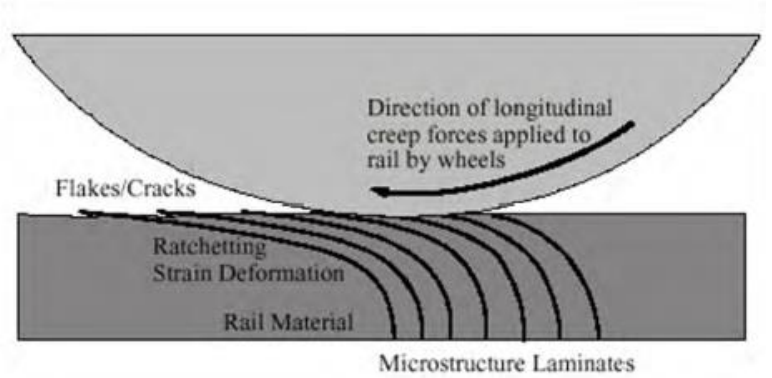
RCF Damage in Rails

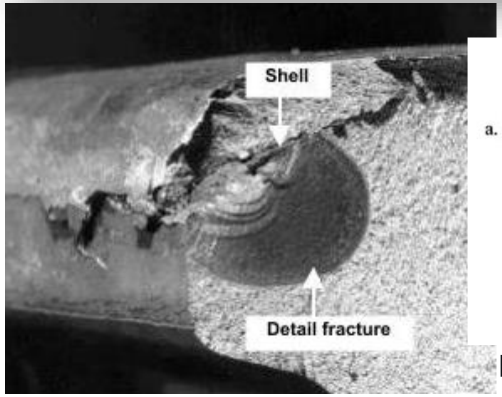
- Wheel/Rail Interface: Hertzian contact patch (CP)
  - CP is elliptical, ~10 mm major axis
- Fatigue induced in the CP between the wheel and the rail
  - Rail yield stress always exceeded
- Repeated heavy rolling contact can cause fatigue damage
  - Surface cracks
  - Subsurface cracks

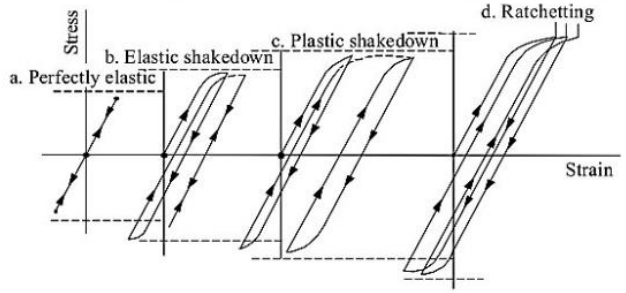


Von Mises Stress on surface of contact patch





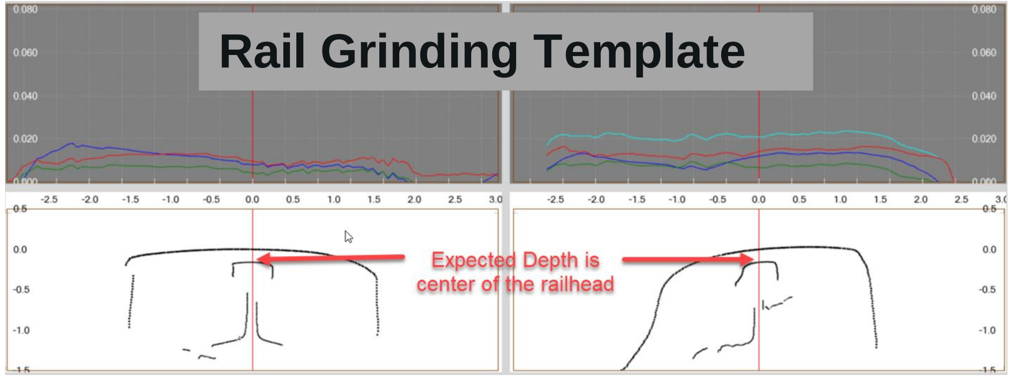




Material response to repeated loading

Rail Grinding – Current Best Practices

- **Preventative approach** for North American Freight Railroads
- Grind frequency is based on Million Gross Tons (MGT)* intervals
- Track segments are grouped based on the tangent and/or mild or sharp curves
- Additional grind passes for “out-of-normal” or “severe” situations
- Challenges:
  - Highly subjective and qualitative (dependent on visual analysis by the operator)
  - Removing too much metal on “good rail”
  - Not removing enough metal on “problem” locations



Rail Grinding Operation

MGT: Amount of weight the train carries

Pre-Grind Inspection – Future State

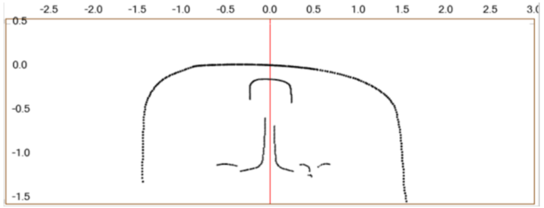
Profile Templates

Measured Profile

Automated Laser Profiler
Profiles collection every meter/foot
Forecasting using historical trending

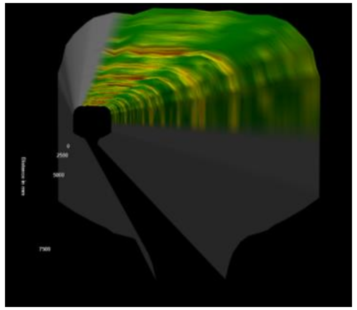
Surface Condition

Automated high-speed NDE
Maps RCF crack depths & density
Industry accepted scoring (SQI)



Where

How Dense & Deep



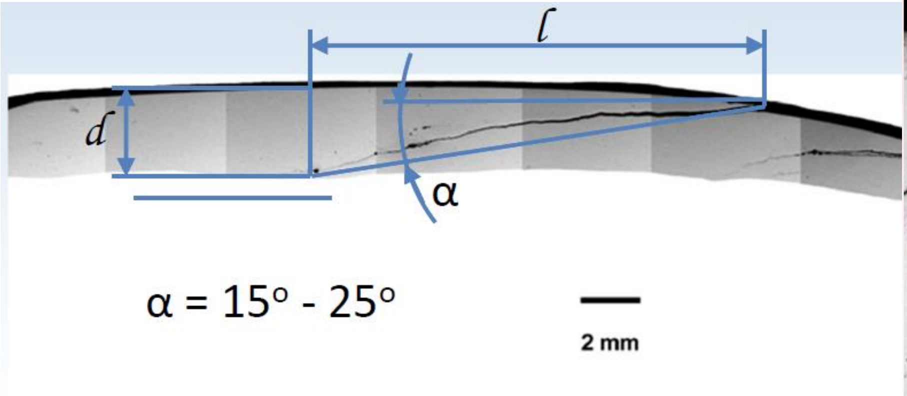
Future State – Predictive/CBM

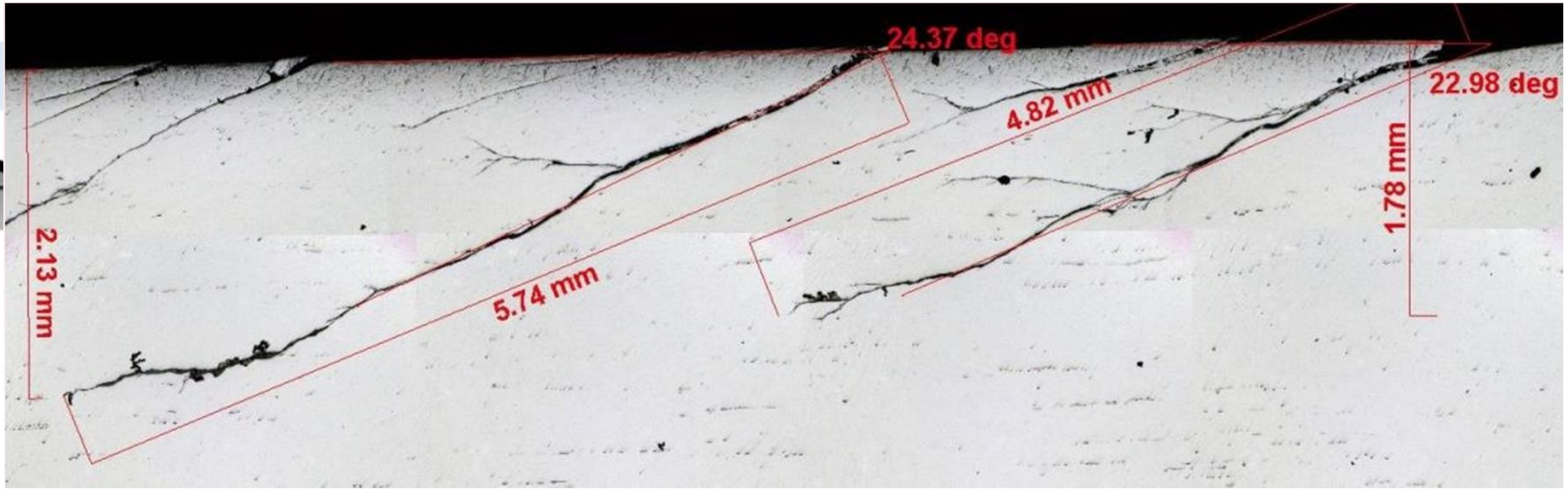
RCF Characterization – NDE Methods

- **Eddy current (EC)**
  1. Pohl, R., Krull R., and Meierhofer, R., 2006, “A New Eddy Current Instrument in a Grinding Train,” Proc. ECNDT, Berlin, Germany.
  2. Szugs, T., et al., 2016, “Combination of Ultrasonic and Eddy Current Testing with Imaging for Characterization of Rolling Contact Fatigue,” Proc. 19^{th} WCNDT, Munich, Germany.
- **Magnetic flux leakage (MFL)**
  1. Y. Jia, K. Liang, P. Wang, K. Ji, P. Xu, Enhancement method of magnetic flux leakage signals for rail track surface defect detection, IET Sci. Meas. Technol. 14(6) (2020) 711–717.
- **Alternating current field measurement (ACFM)**
  1. Papaelias, M., Lugg, M.C., Roberts, C., and Davis, C.L., 2009, “High-speed Inspection of Rails Using ACFM Techniques,” NDT & E International, Vol. 42 (4), pp. 328-335
  2. Nicholson, G.L., Kostryzhev, A.G., Hao, X.J., and Davis, C.L., 2011, “Modelling and Experimental Measurements of Idealised and Light-moderate RCF Cracks in Rails Using an ACFM Sensor,” NDT & E International, Vol. 44(5), pp. 427-437.
- **Pulsed eddy current thermography (PECT)**
  1. Wilson, J., Tian, G.Y., Mukriz, I., and Almond, D., 2011, “PEC Thermography for Imaging Multiple Cracks from Rolling Contact Fatigue,” NDT & E International, 2011, Vol. 44(6), pp. 505-512.
  2. Peng, J., Tian, G.Y., Wang, L., Zhang, Y., Li, K., and Gao, X, 2015, “Investigation into Eddy Current Pulsed Thermography for Rolling Contact Fatigue Detection and Characterization,” NDT & E International, Vol. 74, pp. 72-84
  3. Gao, Y., et al., 2017, “Electromagnetic Pulsed Thermography for Natural Cracks Inspection,” Nature Sci. Rep. 7, 42073, doi: 10.1038/srep42073.
- **Electromagnetic acoustic transducers (EMATs)**
  1. Edwards, R.S., Dixon, S., and Jian, X., 2006, “Characterization of Defects in the Railhead Using Ultrasonic Surface Waves,” NDT & E International, Vol. 39 (6), pp. 468-475.
  2. Witte, M., Poudel, A., and Fry, G., 2018, “Rolling Contact Fatigue Measurement Using EMATs,” AAR/TTCI Technology Digest TD 18-004.

Existing NDE Techniques - Limitations

- To determine crack depth, a crack angle must be assumed. Depth is then calculated using crack length and angle
- Existing NDE techniques tend to overestimate the depth; sometimes significantly





Kerchof, B., 2015, “Validation of Rail Crack Measurement Devices on NS,” *Proc. of WRI Conference.*

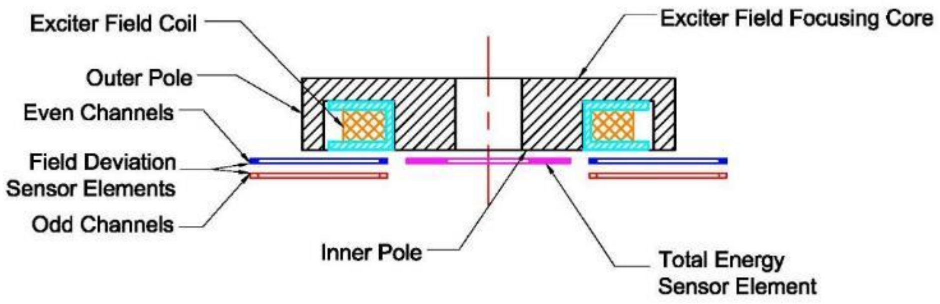
Electro-Magnetic Field Imaging (EMFI)

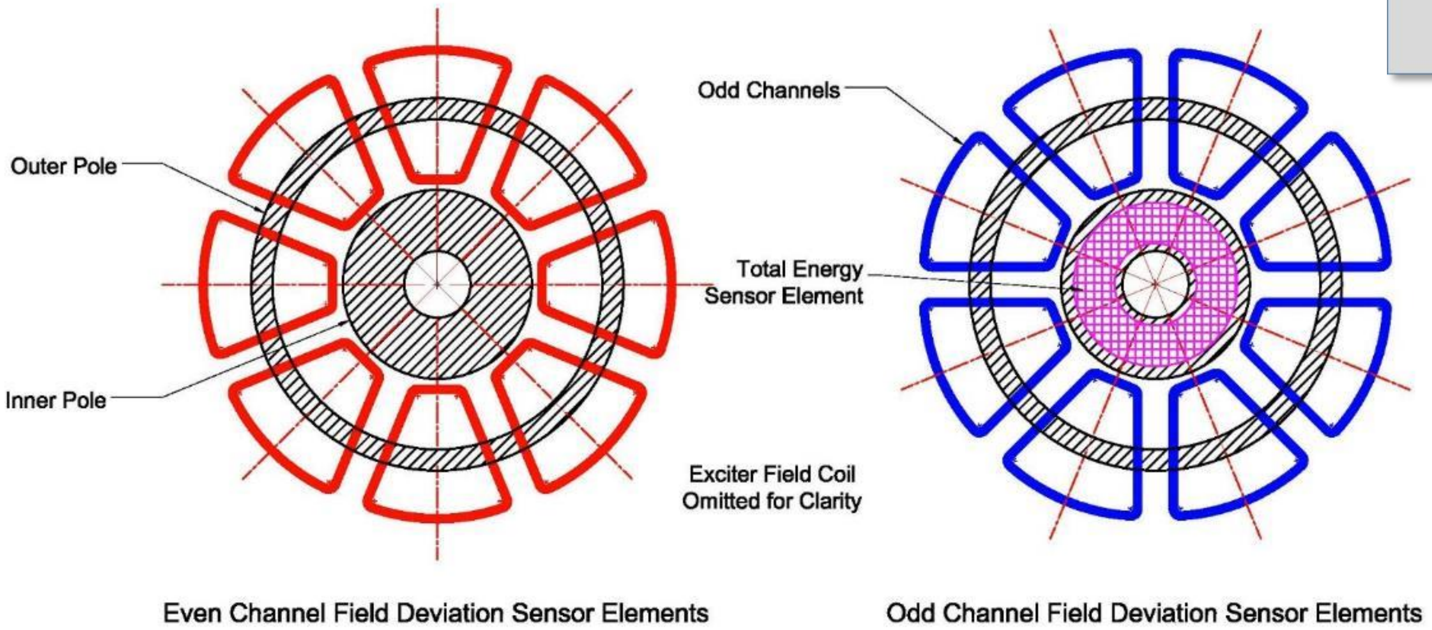
- Noncontact electromagnetic NDE technique
  - Designed to create a focus EMF to the shape of the object being inspected
  - Measures the position of the mean magnetic field point from the core (i.e., measures distortion of the mean field path)
- Detects surface/ near-surface defects
  - Maps the location and colony or field sizes
  - Measures/analyzes the depth of the defects

In-motion EMFI System

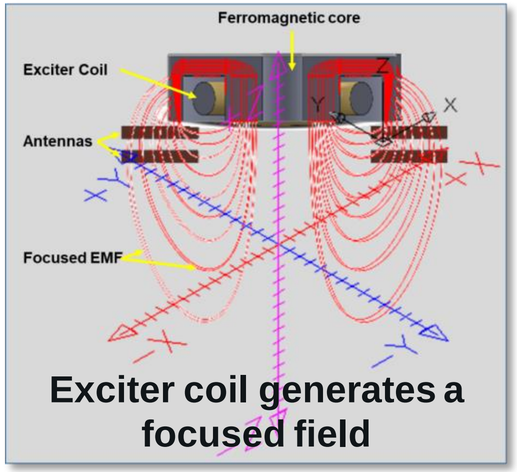
This technology belongs to Athena Industrial Services Inc., Calgary, Canada

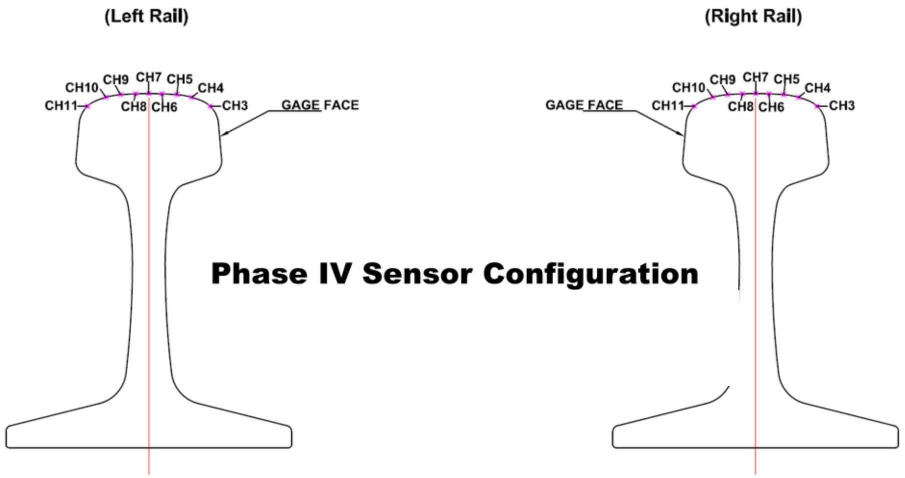
EMFI Sensor Architecture





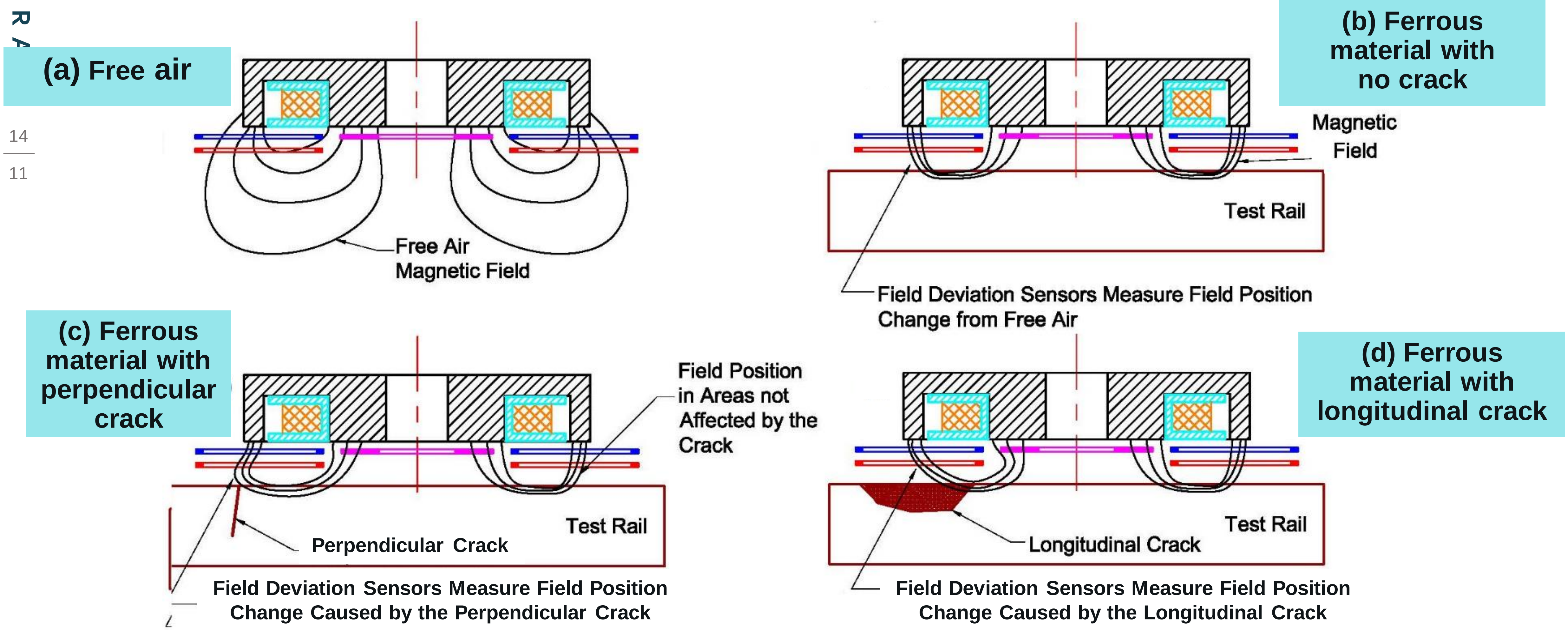
Top-down view of the even and odd channel field deviation sensor elements





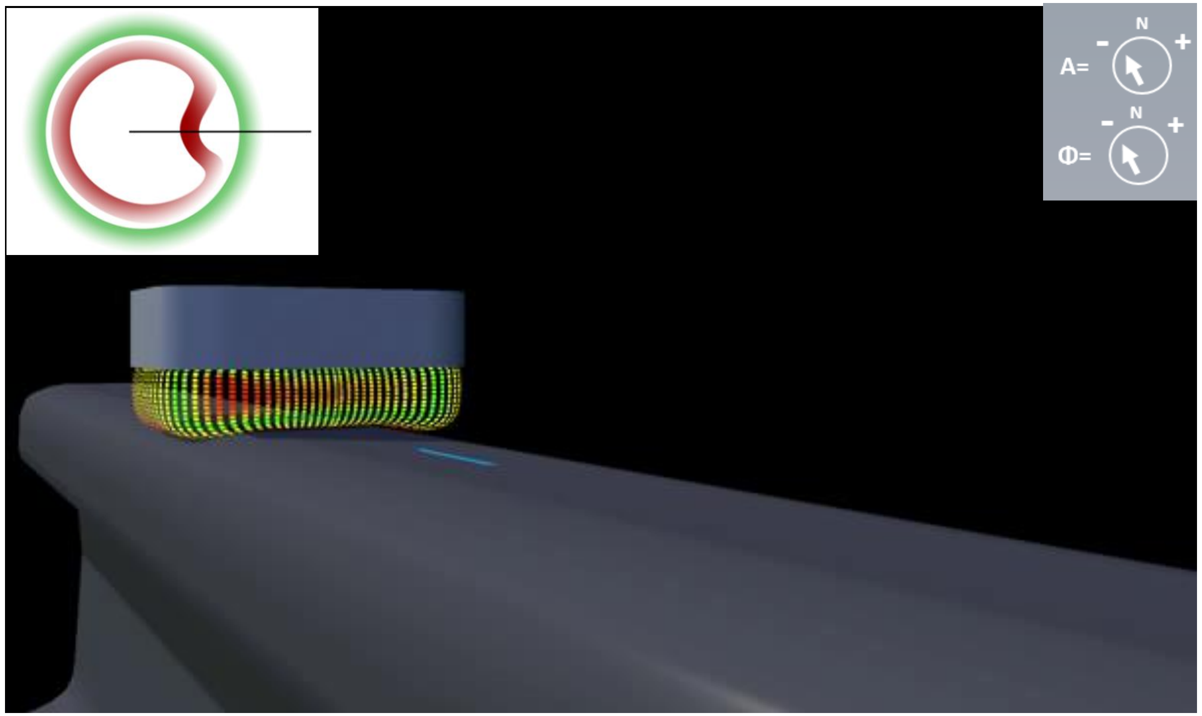
EMFI Sensor Antenna Positioning

EMF Shape Changes

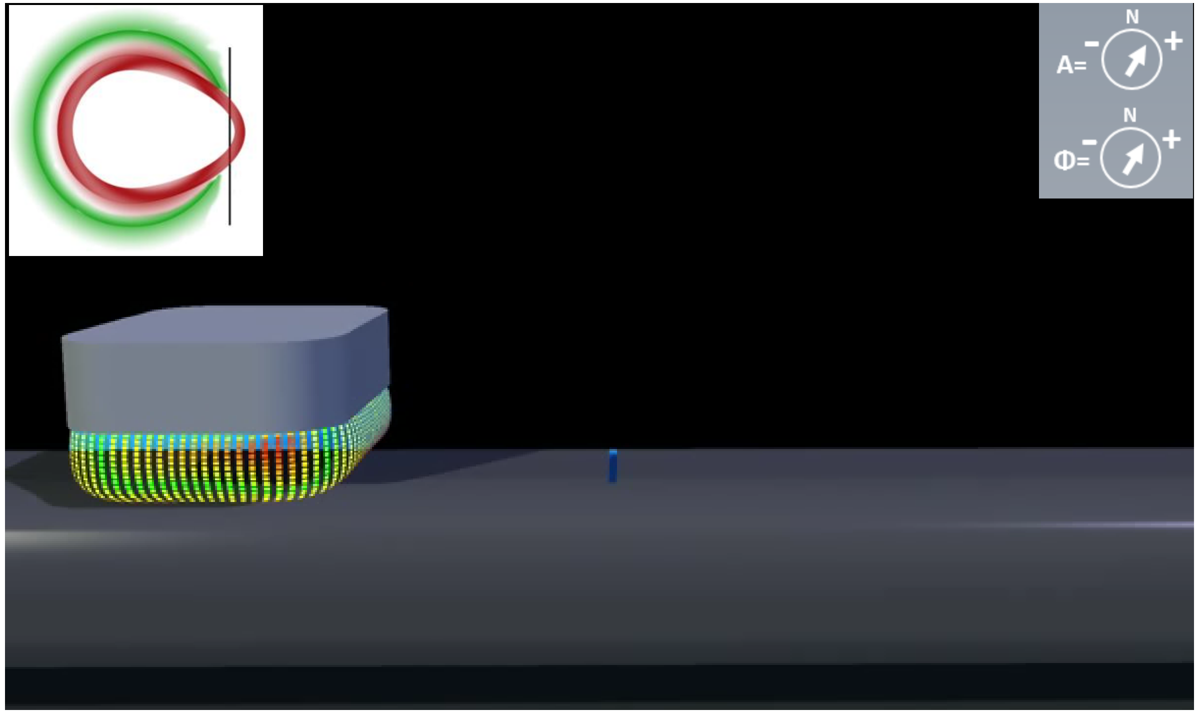


Schematic of EMF Shapes

EMF Shape Changes Visulaization



EMF in presence of longitudinal cracks

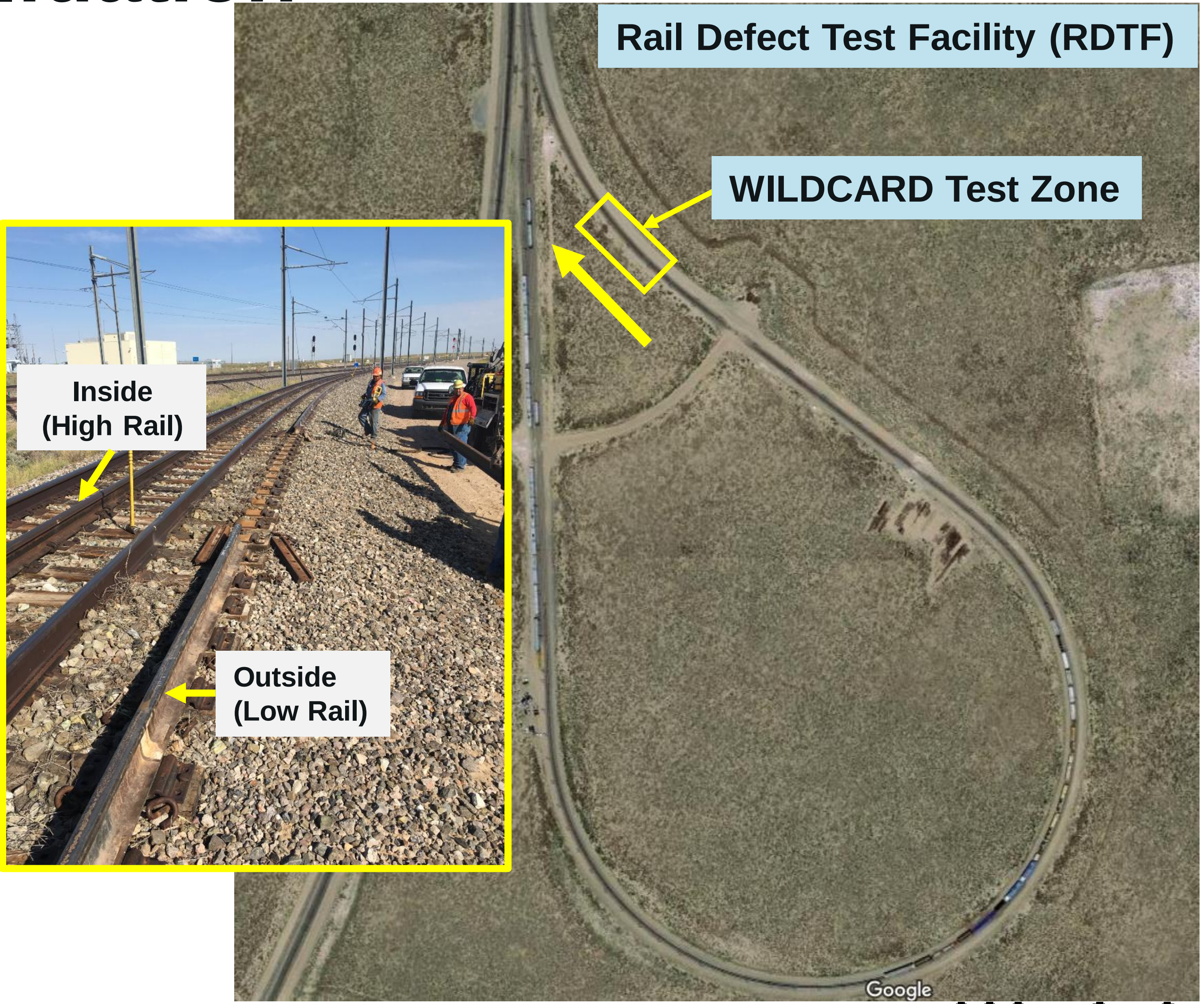


EMF in presence of transverse cracks

- EMF shifts are measured with customized antennas inside the sensor
- Algorithms designed correlates EMF shifts to crack depths

MxV Rail On-Track Validation

- Two test rails were installed on the inside/outside loop of the RDTF WILD CARD test zone
- Outside (low) rail was 52-foot long
  - Visual Rating: 0.0 – 2.0
  - 14-foot rail plug was installed
- Inside (high) rail was 66-foot long
  - Visual rating: 0.0 – 2.0
- 9 measurement locations were determined for both rails for pre- and post- grind measurements
  - MiniProf
  - Liquid Penetrant Testing (PT)
  - EMFI



Test Results

- Test runs were made at speeds of crawling, 5, 10, and 15 mph, and data was analyzed immediately after all the runs
  - Runs at each speed were repeated five times
- Based on the aggregate data, a grind depth was determined, and the rails were ground accordingly. The goal was not to remove the RCF cracks completely during the grinding, but to leave the cracks behind for comparison and validation of the post-grind EMFI measurements with the destructive analysis
- Repeatability and reproducibility of the EMFI system at different speeds was determined using Pearson's correlation coefficient (PCC)

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}}$$

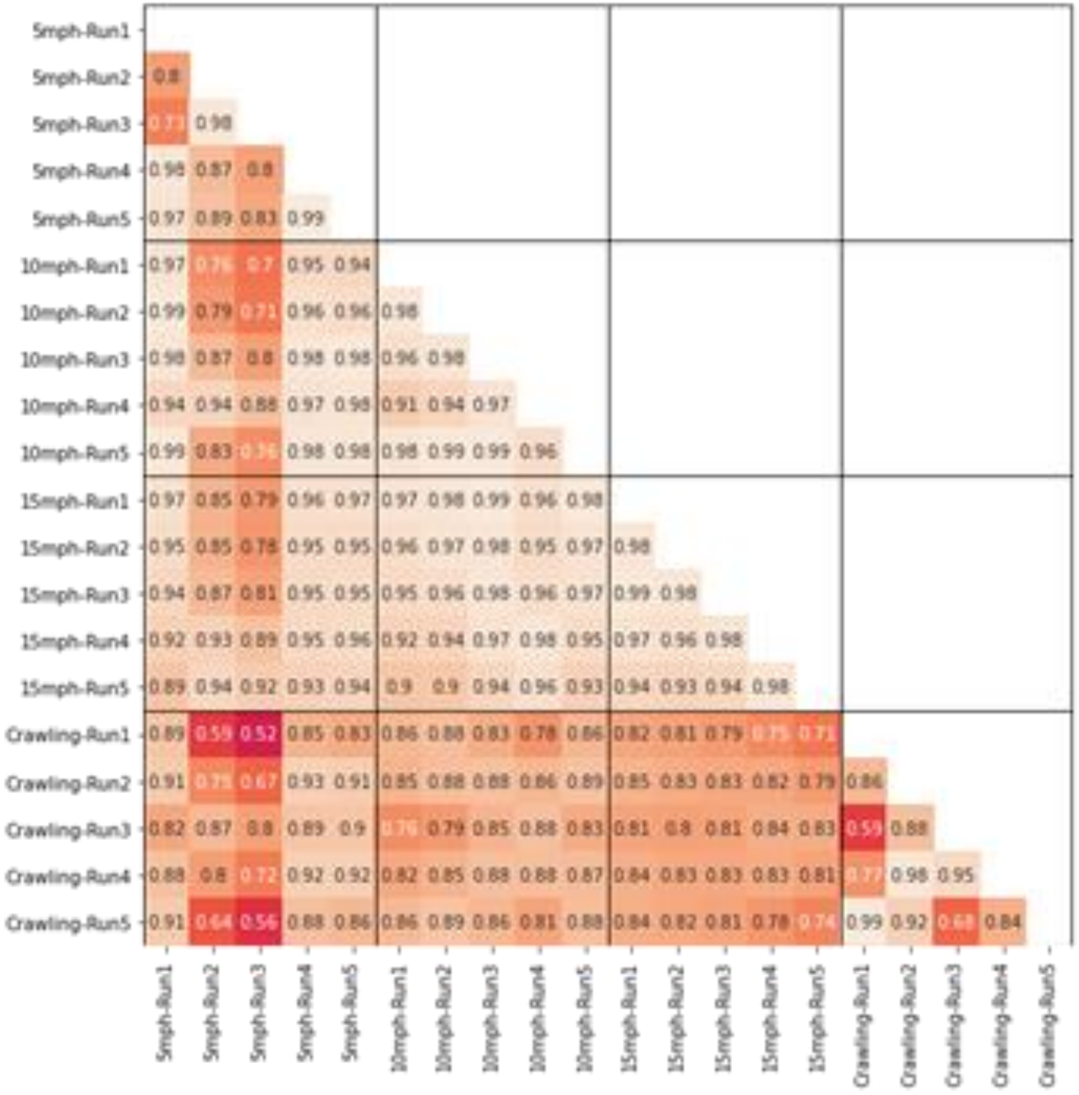
r = correlation coefficient

x_i = values of the x-variable in a sample

$\bar{x}$ = mean of the values of the x-variable

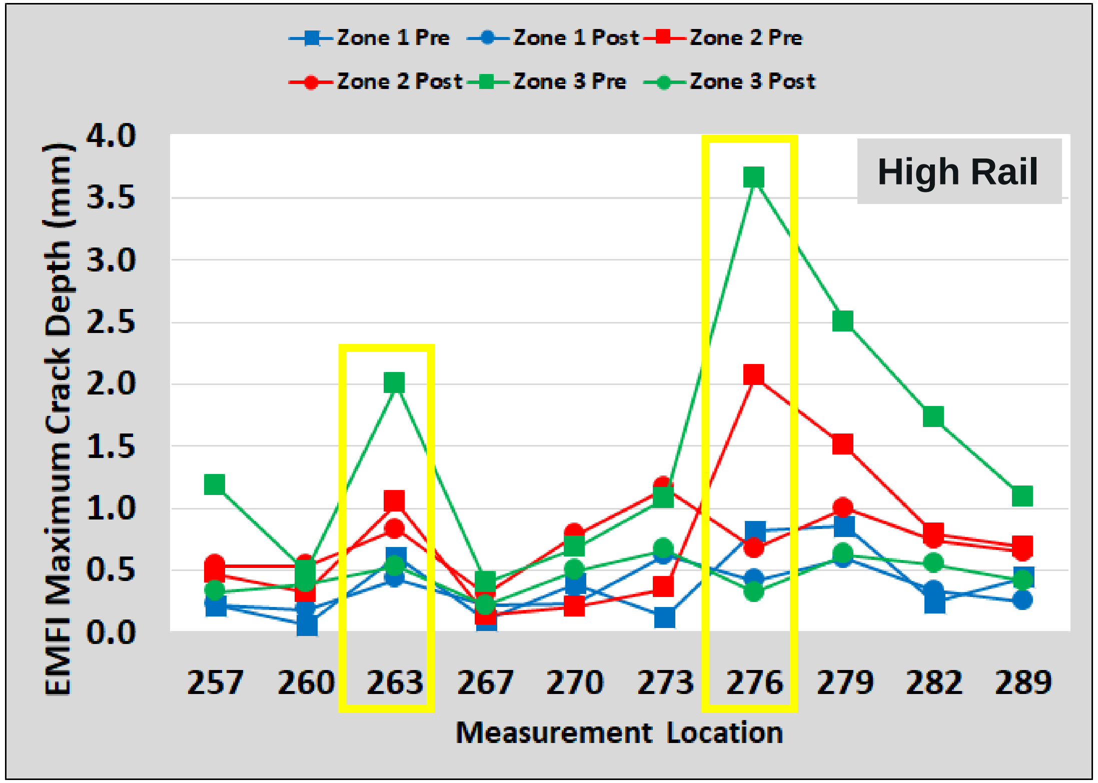
y_i = values of the y-variable in a sample

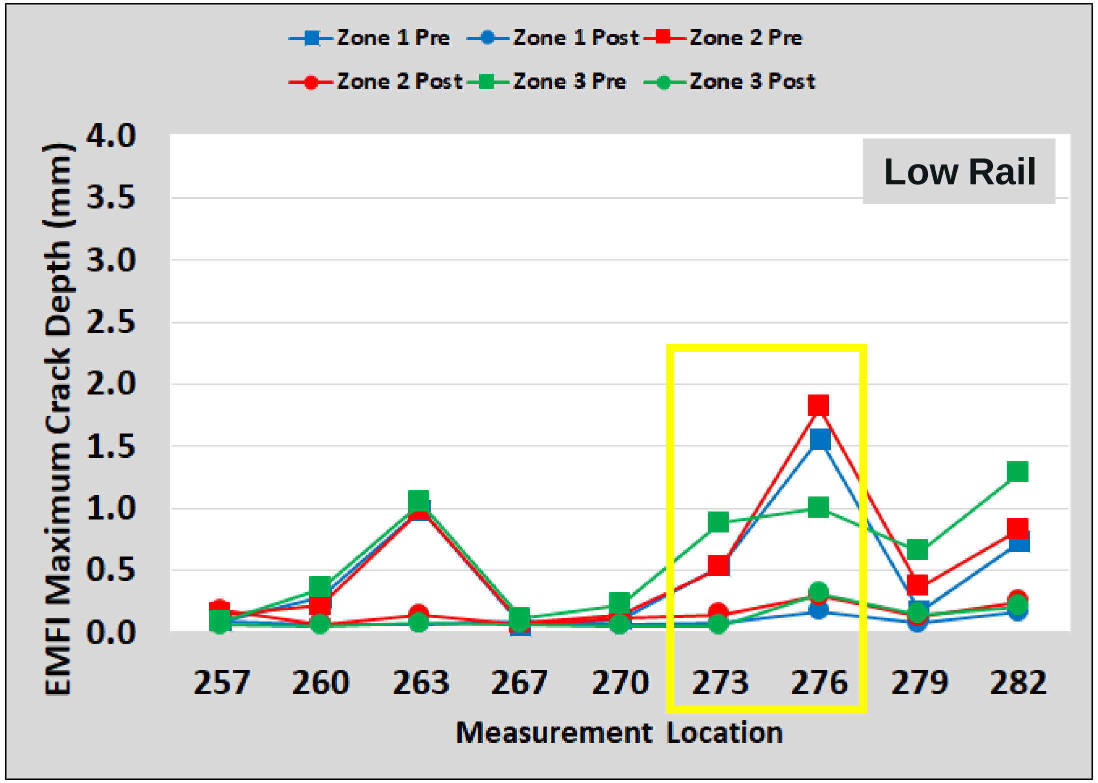
$\bar{y}$ = mean of the values of the y-variable



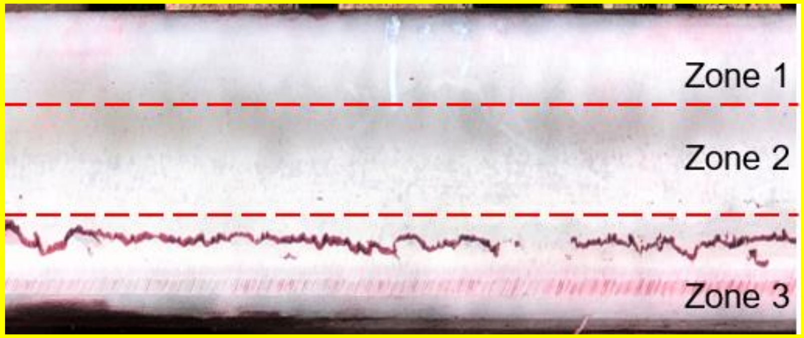
Correlation Matrix results for the post-grind

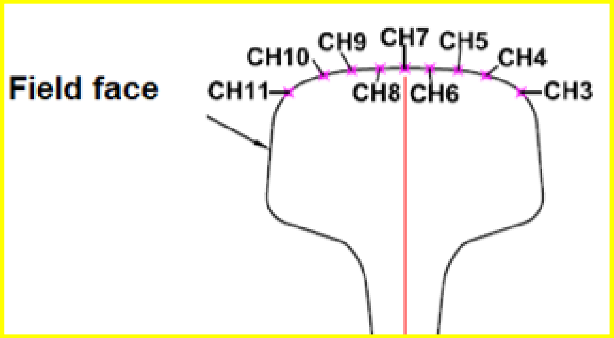
EMFI Crack Depth Analysis





Rails	Zone 1 (Ch. 4, 5)	Zone 2 (Ch. 6,7,8)	Zone 3 (Ch. 9, 10)
High Rail	Field	Center	Gage
Low Rail	Gage	Center	Field

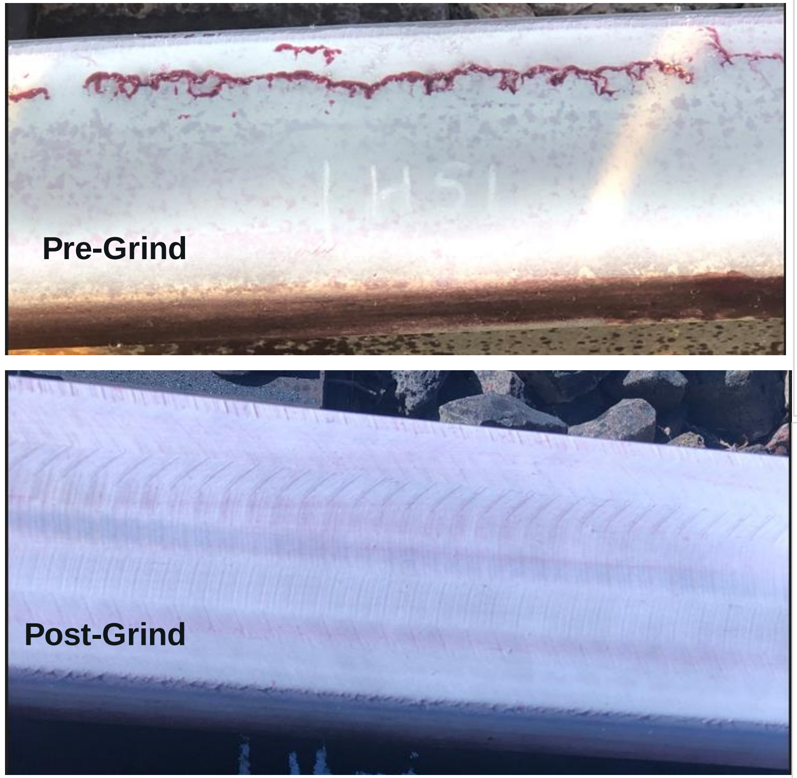




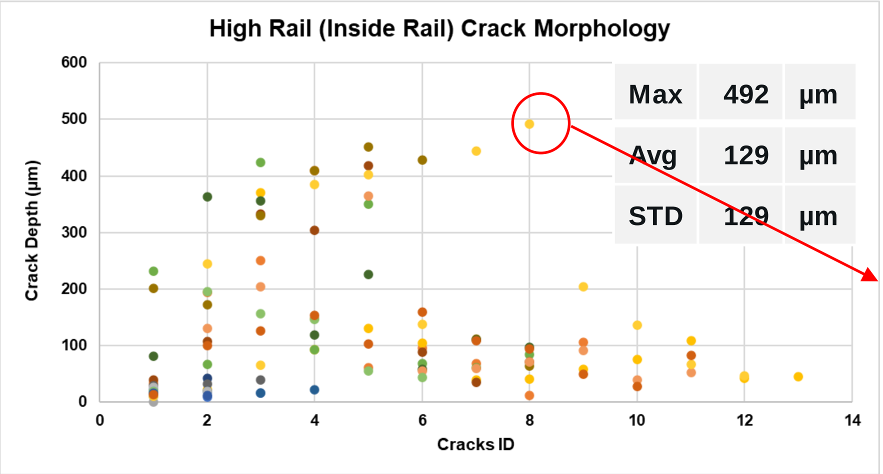
EMFI sensor zones relative to the rail head

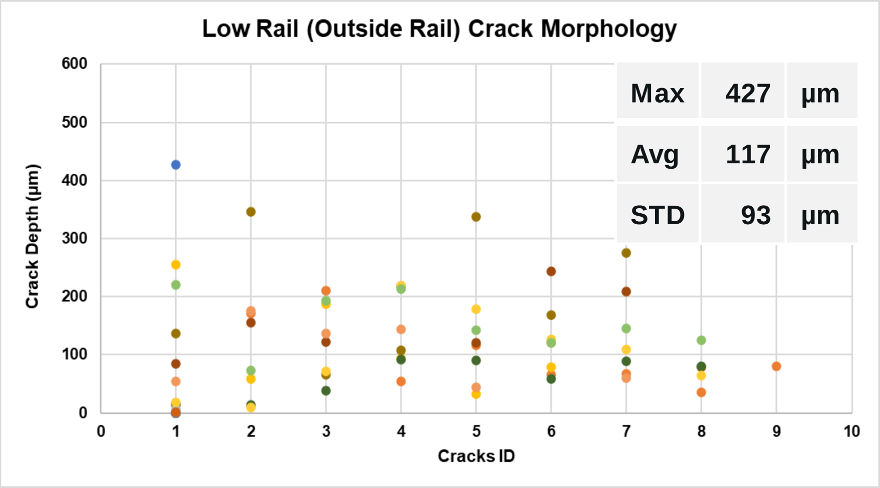
EMFI Verification - High rail tie location 263

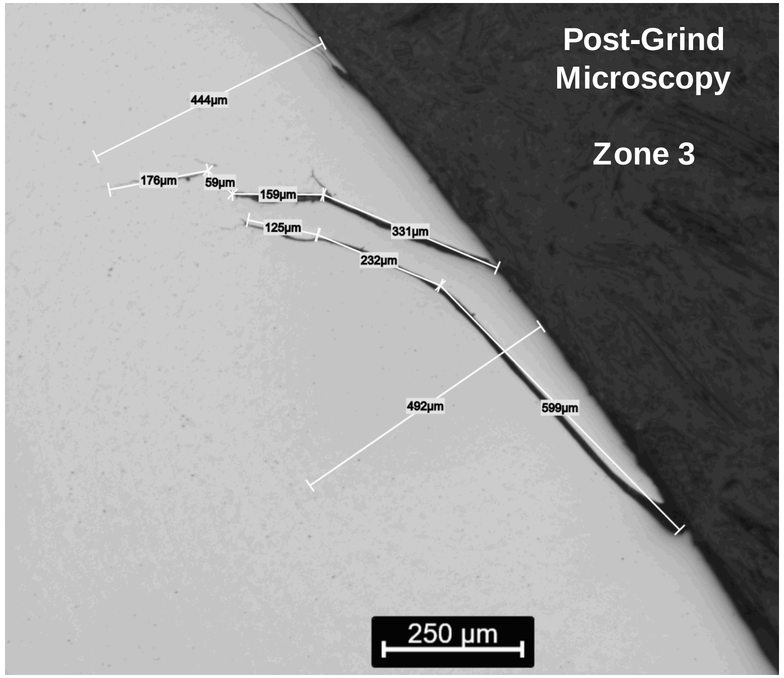
- Residual crack depths were measured using microscope after post-grind
  - Deepest crack remaining for the high rail tie location 263 after grinding was approx. 0.5 mm



PT results for the high rail tie location 263







High rail tie location 263

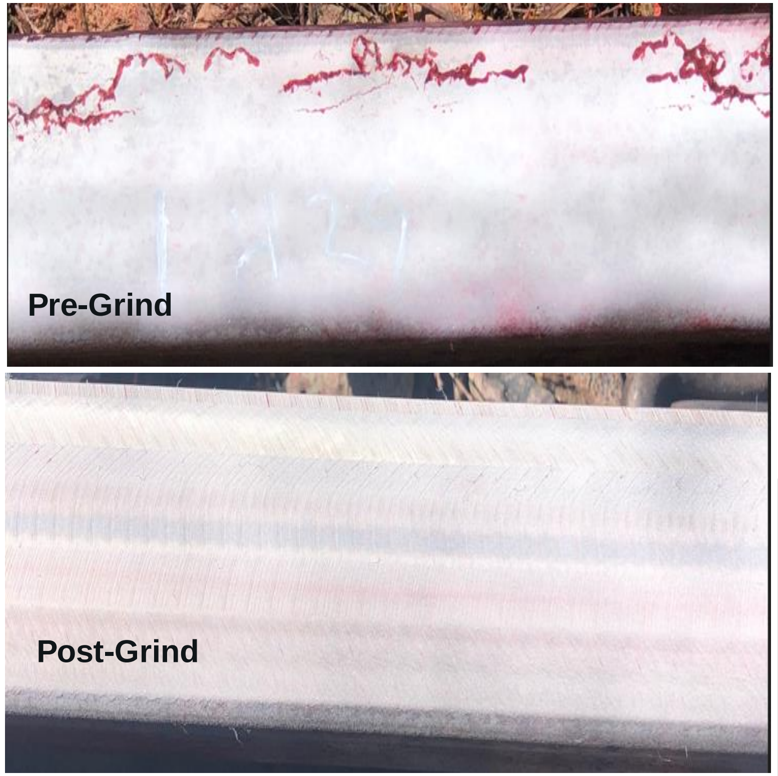
M x V R A I L

20

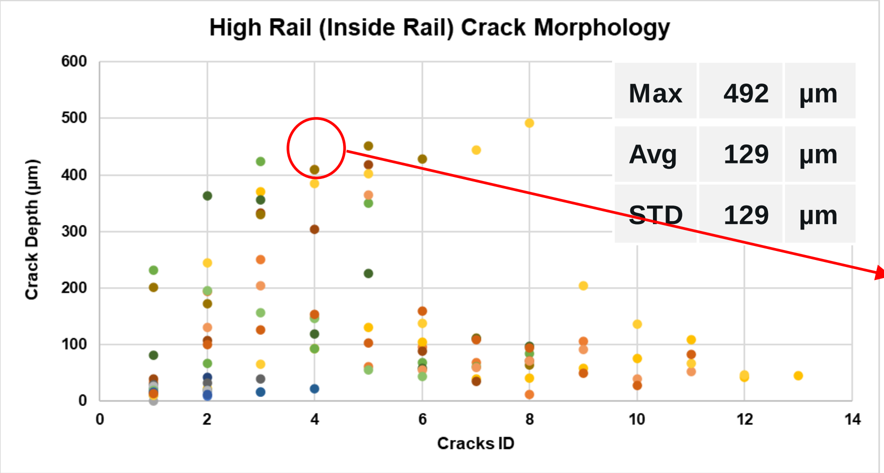
11

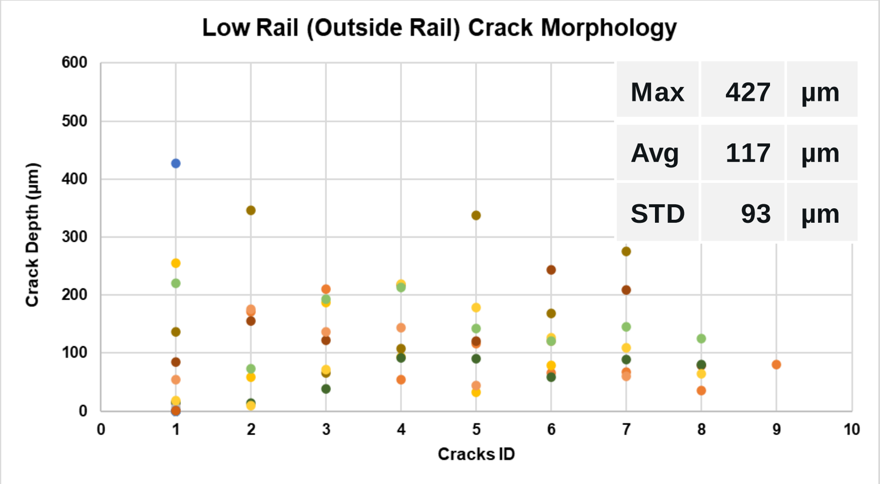
EMFI Verification - High rail tie location 276

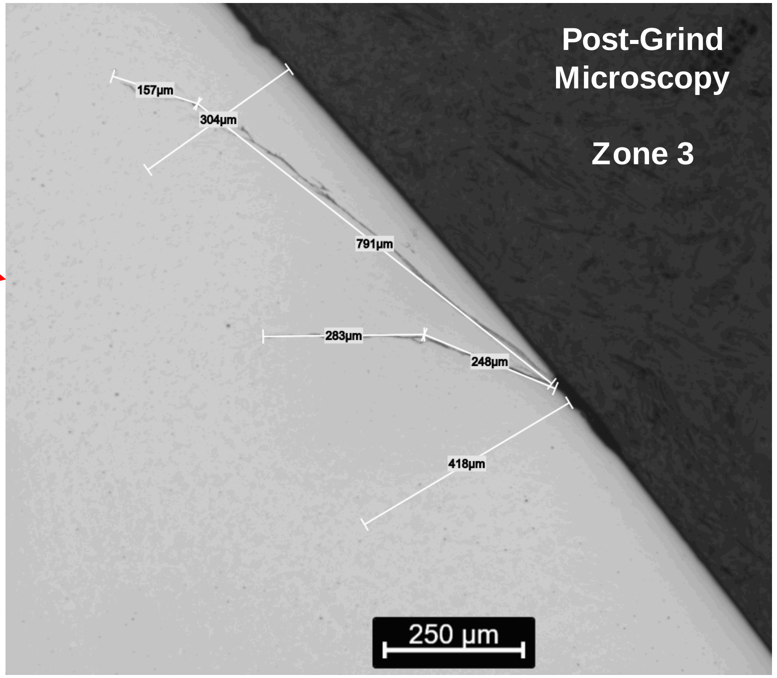
- Deepest crack remaining for the high rail tie location 276 after grinding was approx. 0.4 mm



PT results for the high rail tie location 276



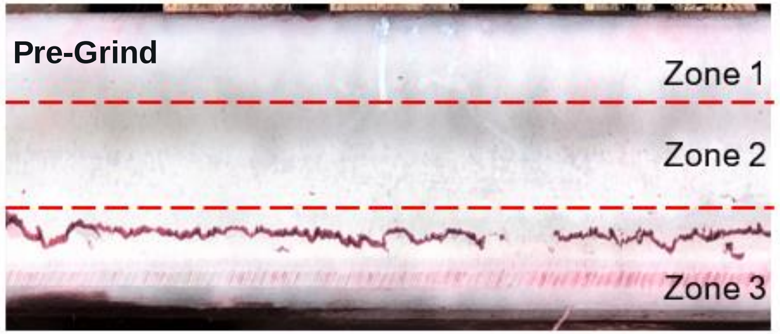


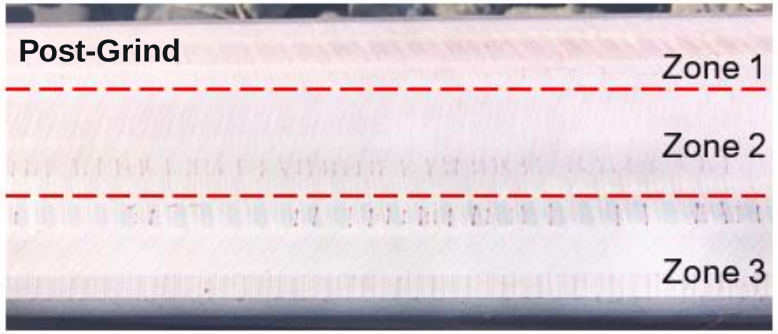


High rail tie location 276

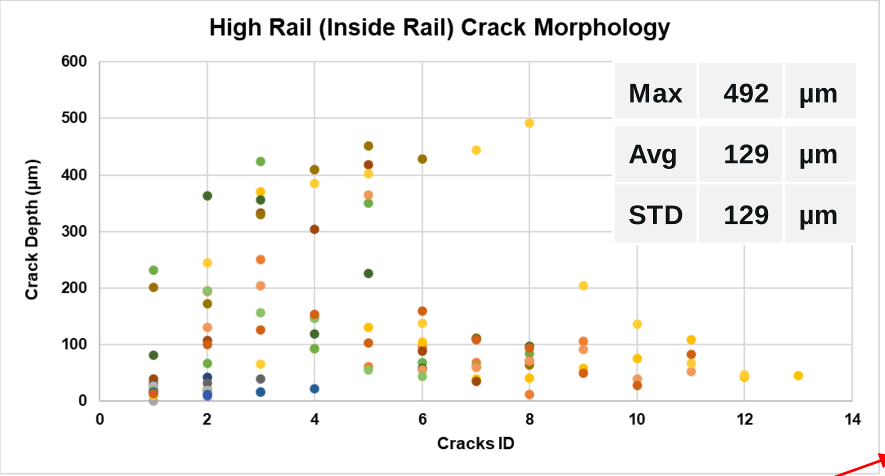
EMFI Verification - Low rail tie location 273

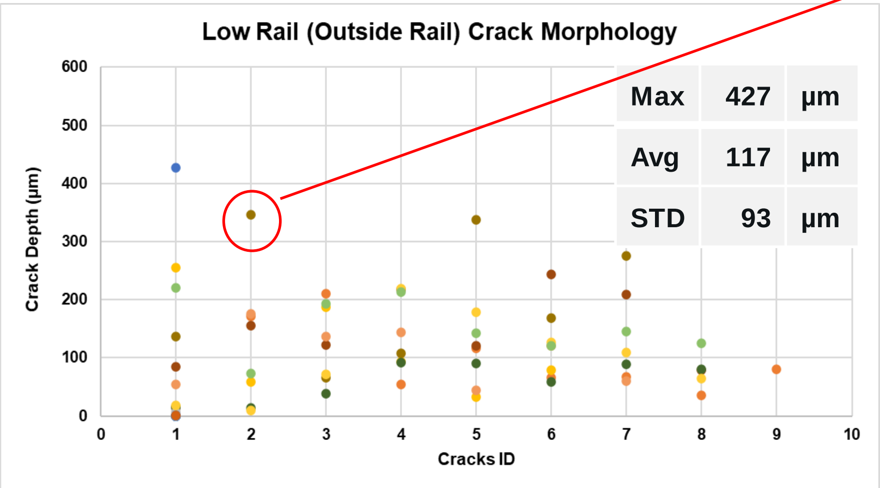
- Residual crack depths were measured using microscope after post-grind
  - Deepest crack remaining for the low rail tie location 273 after grinding was approx. 0.3 mm

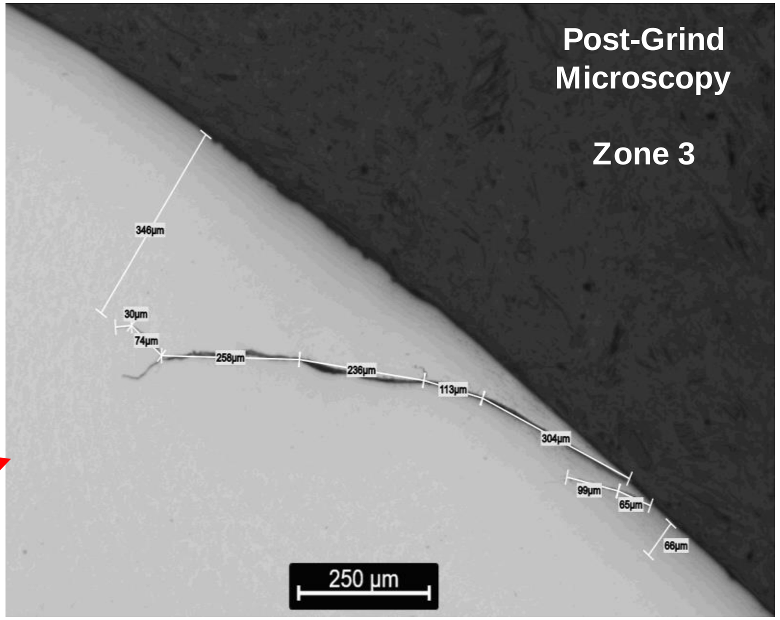




PT results for the low rail tie location 273



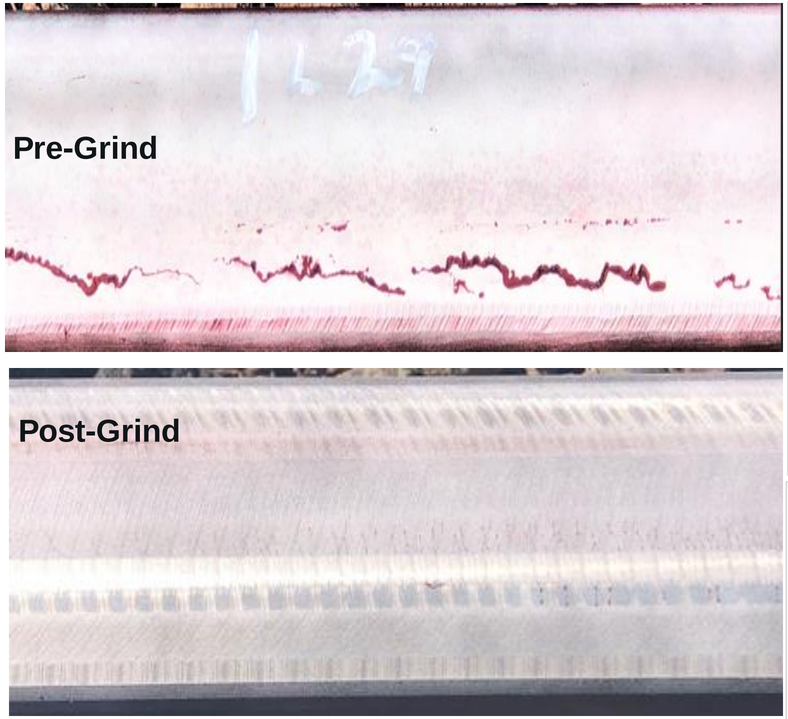




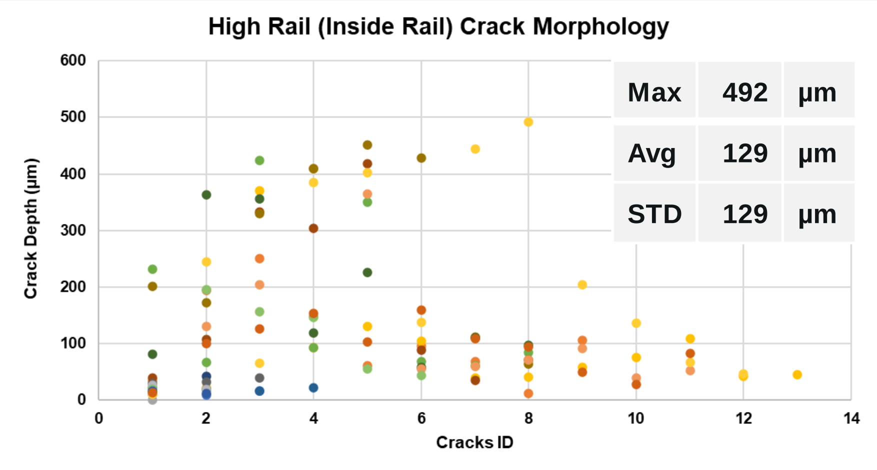
Low rail tie location 273

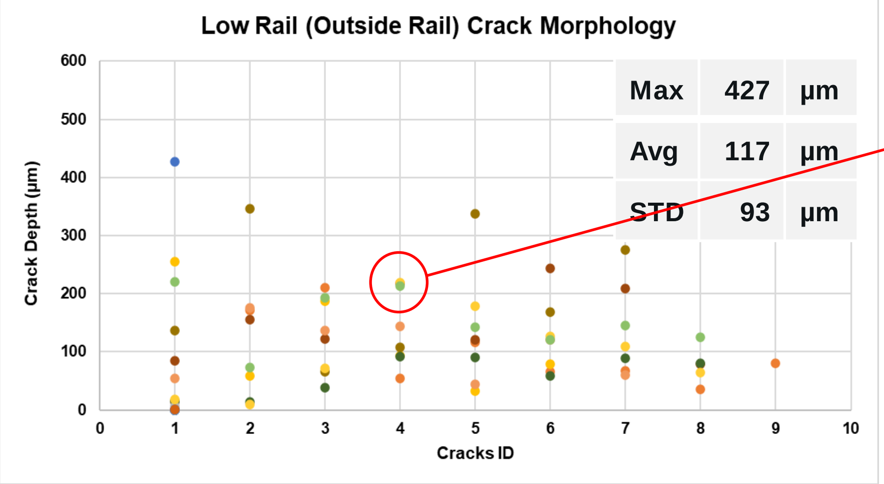
EMFI Verification - Low rail tie location 276

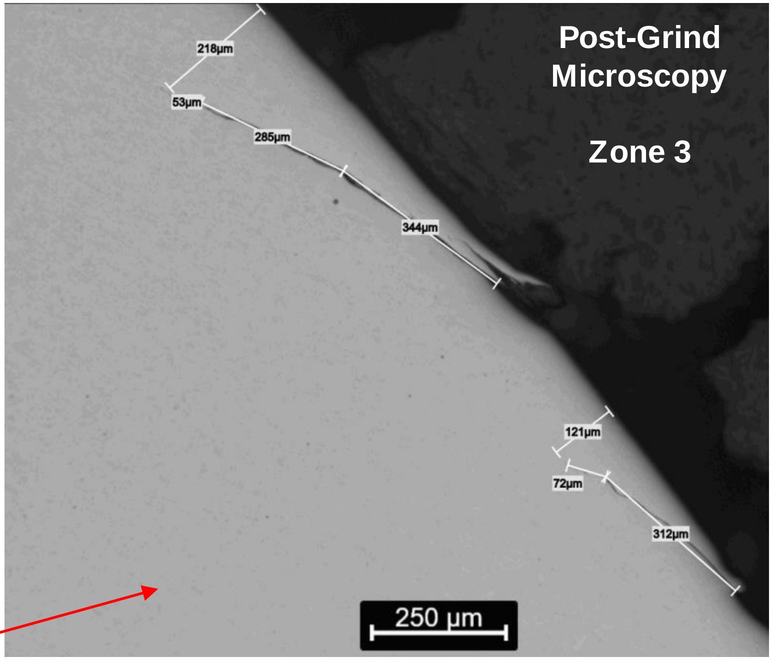
- Residual crack depths were measured using microscope after post-grind
  - Deepest crack remaining for the low rail tie location 276 after grinding was approx. 0.2 mm



PT results for the low rail tie location 276





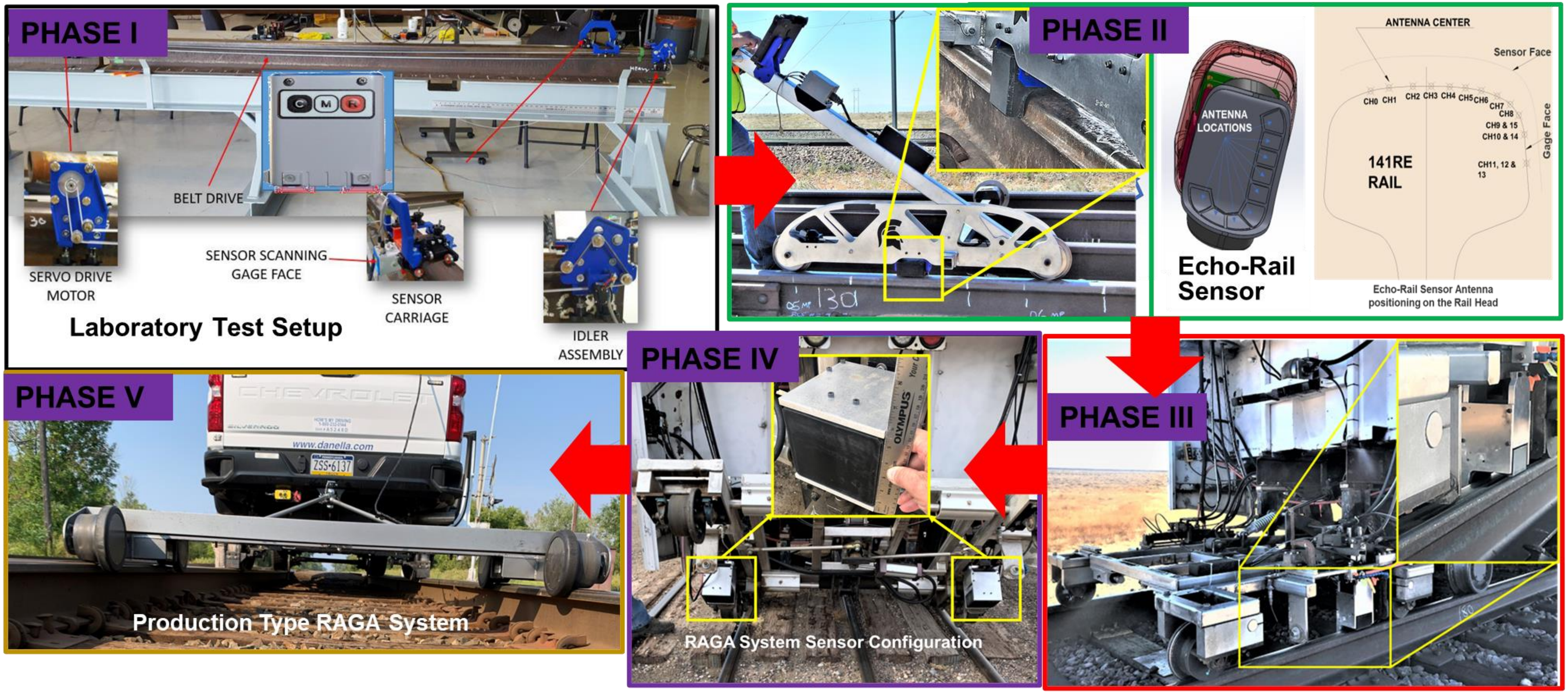


Low rail tie location 276

Conclusions

- Destructive microscopy findings match well with the EMFI post-grind measurements
- RCF crack depth measurements below 0.3 mm are found to be insignificant at the lift-off where the sensor is currently operating. The crack depths within the 0.3 mm regime can be affected by grinding marks and is within the error band of the EMFI sensor
- MxV Rail has recently completed the revenue service trial of the production-type EMFI system
- EMFI technology is ready for implementation in North American Railroads
- This research demonstrated the design, development, testing, and validation of EMFI technology for RCF characterization (TRL 2-7)

EMFI Technology Roadmap (TRL 2-7)



Acknowledgement

- MxV Rail Team
- AAR Rail Inspection TAG members
- AAR Members

M x V RAIL

Thank you!

M x V RAIL