ICRI workshop

Vancouver, June 22

Hyatt Regency Hotel

Agenda

- Reviews of some ongoing ICRI projects
- A presentation on “Principles and operations of Electromagnetic Field Imaging and its application to the wheel rail interface” – Paul Gies, Athena Industrial Services of Calgary
- 2:55 - 3:15 pm: coffee break.
- A presentation on “Analyzing Broken Rail Caused Derailments using a Risk Mapping Tool” – Yan Liu, National Research Council, Canada
- An outline of the “ICRI Broken Rails” project, including a summary of the six different elements.
  - Load Characterization – Alex Woelfle
  - Wear modeling - TBA
  - RCF modeling – TBA
  - Rail Resilience/Broken Rails – Chris Ladubec
  - Derailment modeling – Eric Magel
- (As time allows) A working session on how we practically go about understanding, predicting and monitoring risk associated with broken rails.

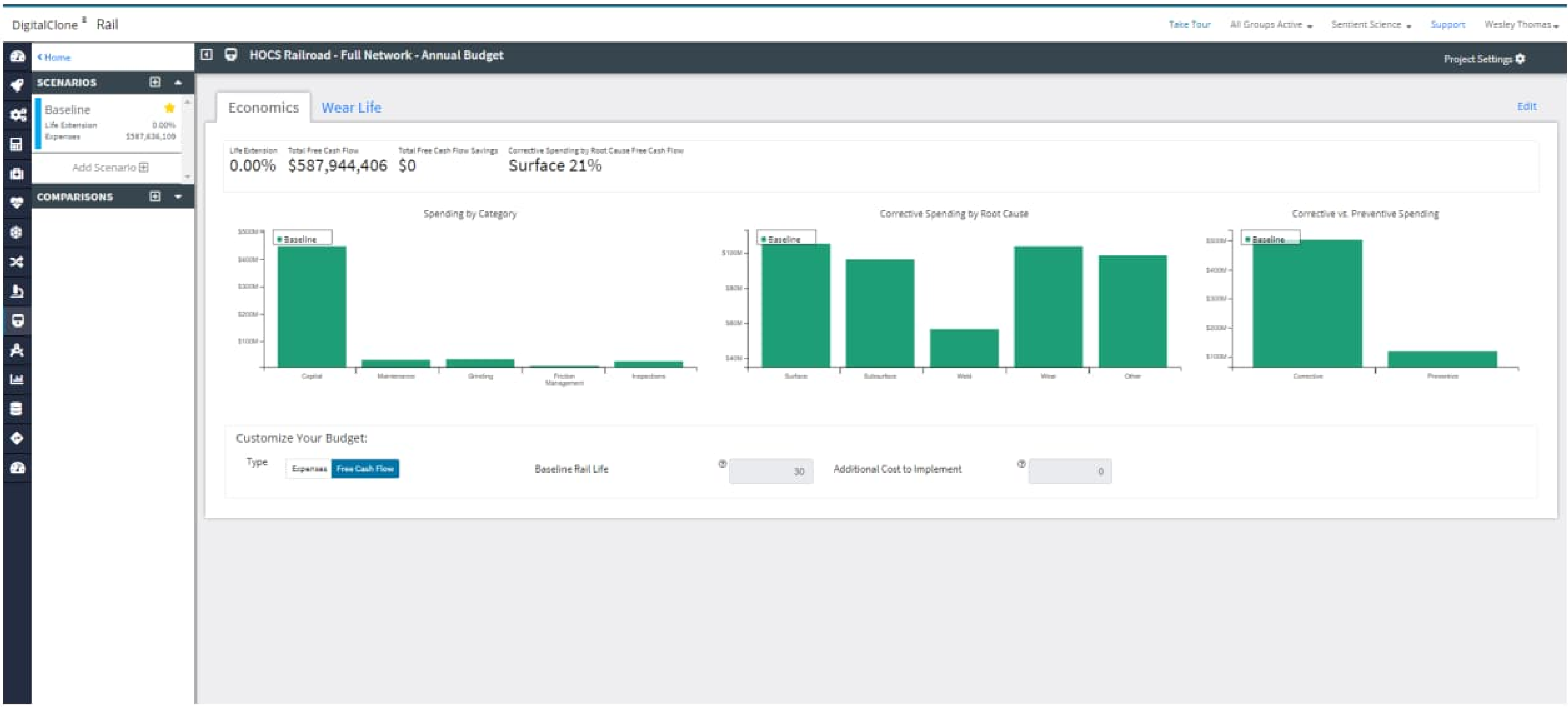
Reviews of some ongoing ICRI projects

- VTI-Economics – Wesley Thomas
- Friction Library – Davey Thomas
- Tribometer Continuity Plan – Robert Caldwell
- Quantifying Surface Damage – Daniel Szablewski

VTI Economics

1. Third Party “Open Source” Model, but built by Railroads
2. Data Available from Different Departments/Specialties
3. Decision Support Tool of Costs and Benefits
4. Find New Savings and Innovations
5. Compete and Protect Important Projects
6. Improve Partnerships of Railroad and Supplier

ICRI Economics Model



ICRI Friction Library

Project Overview & Update

ICRI 2022 Workshop, Vancouver

June 22nd, 2022

Davey Mitchell, P.Eng.
Commercial Manager, Friction Management

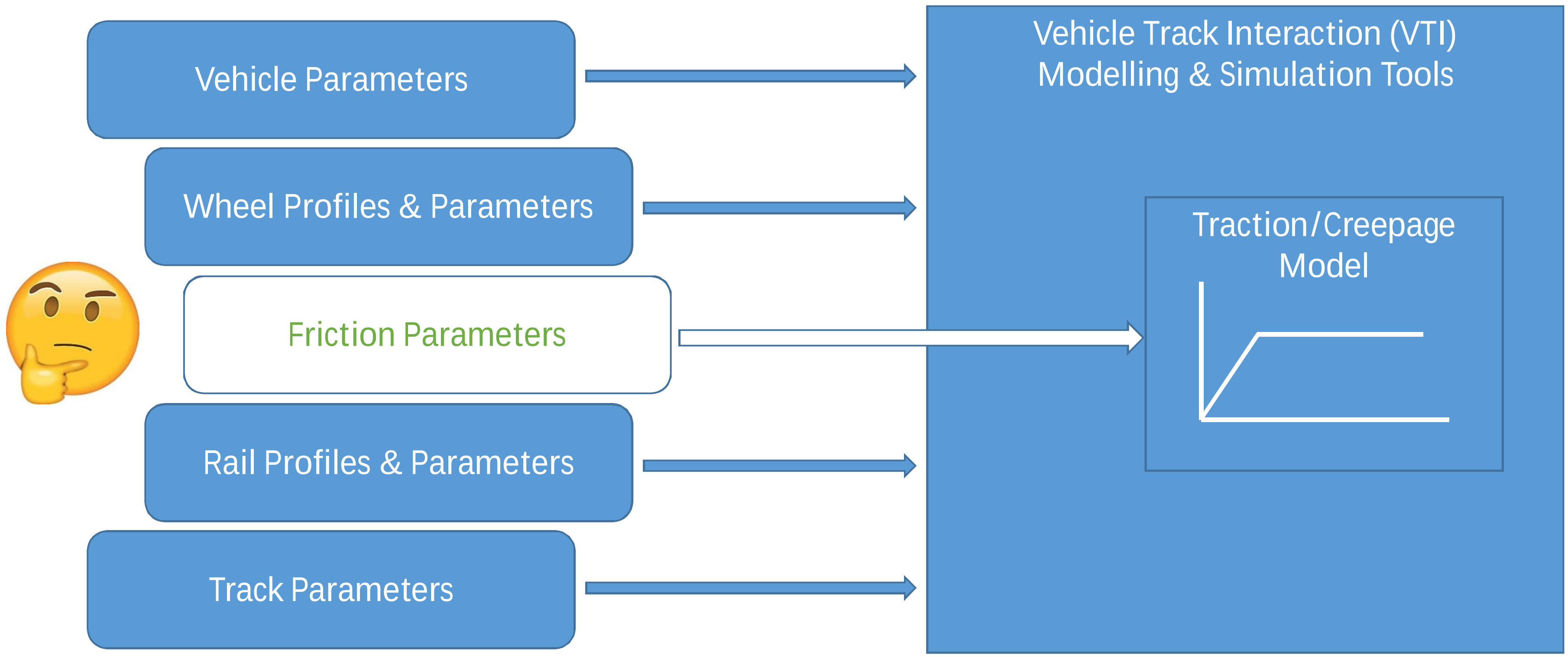
Overview

- Project Leads
- Motivation
- Objectives / Roadmap
- Status & Next Steps

Project Leads

- Davey Mitchell (LB Foster Rail Technologies): DMitchell@lbfoster.com
- Rob Caldwell (National Research Council): Robert.Caldwell@nrc-cnrc.gc.ca
- Kevin Oldknow (Simon Fraser University): koldknow@sfu.ca
- Marco Santoro (LB Foster Rail Technologies): MSantoro@lbfoster.com
- Sylvie Chenier (National Research Council): Sylvie.Chenier@nrc-cnrc.gc.ca

Motivation



Vehicle Parameters
Wheel Profiles & Parameters
Friction Parameters
Rail Profiles & Parameters
Track Parameters
Vehicle Track Interaction (VTI) Modelling & Simulation Tools
Traction/Creepage Model

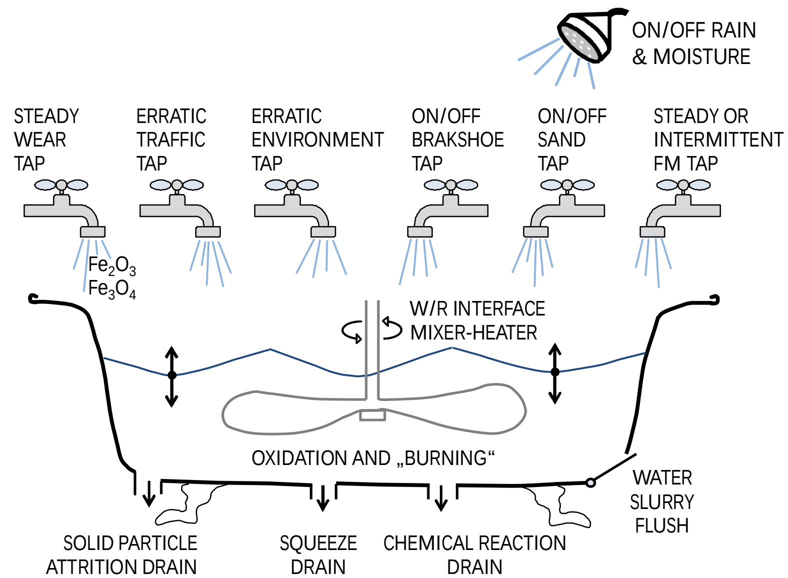
Motivation

1. We do not have any way to directly measure detailed friction characteristics between wheel/rail surfaces for arbitrary train wheels, at arbitrary track locations, at arbitrary points in time.

2. Wheel/rail friction characteristics can vary through wide ranges (e.g. COF < 0.1 to > 0.7), over relatively short distances and relatively small time scales.

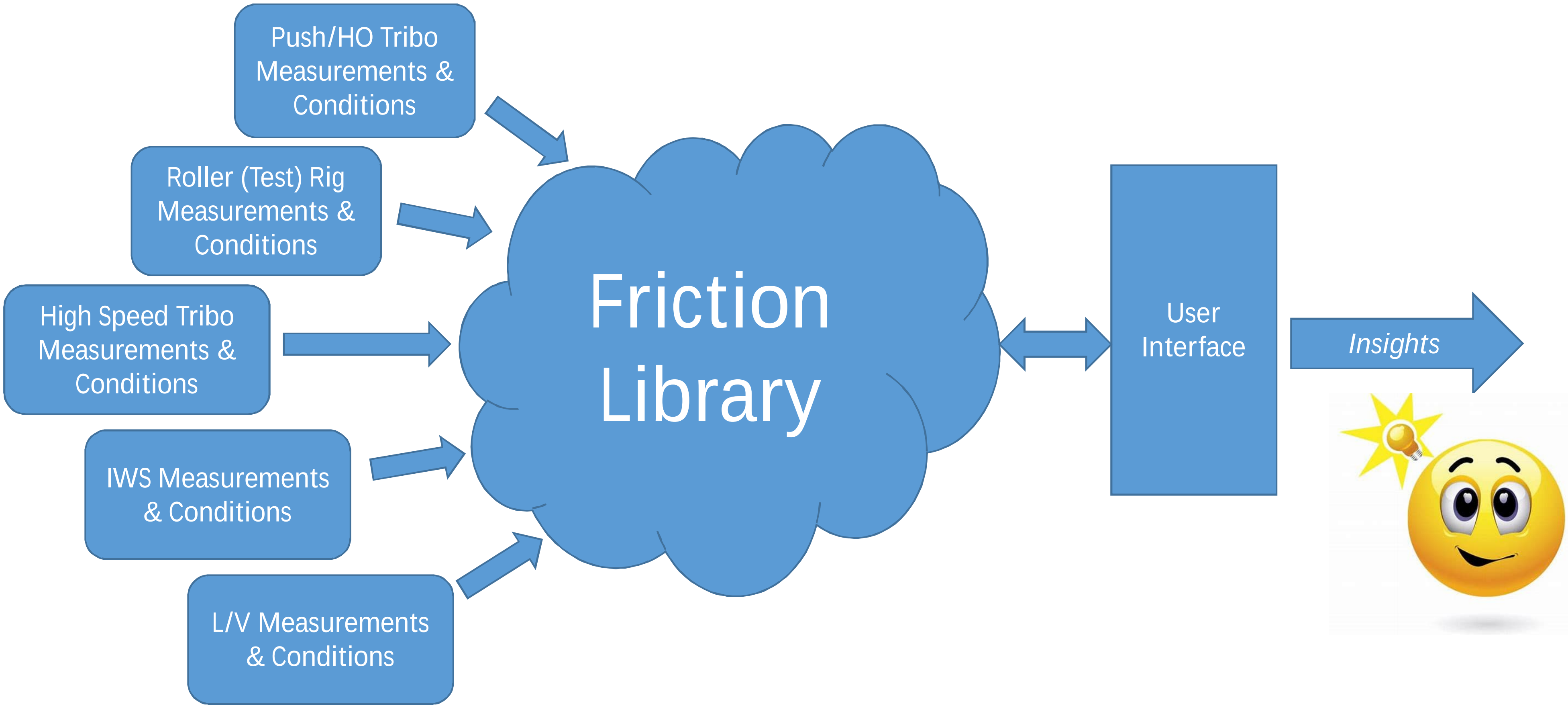






Kalousek's "Bathtub Model" of the third body layer

The Friction Library Concept



Objectives / Roadmap

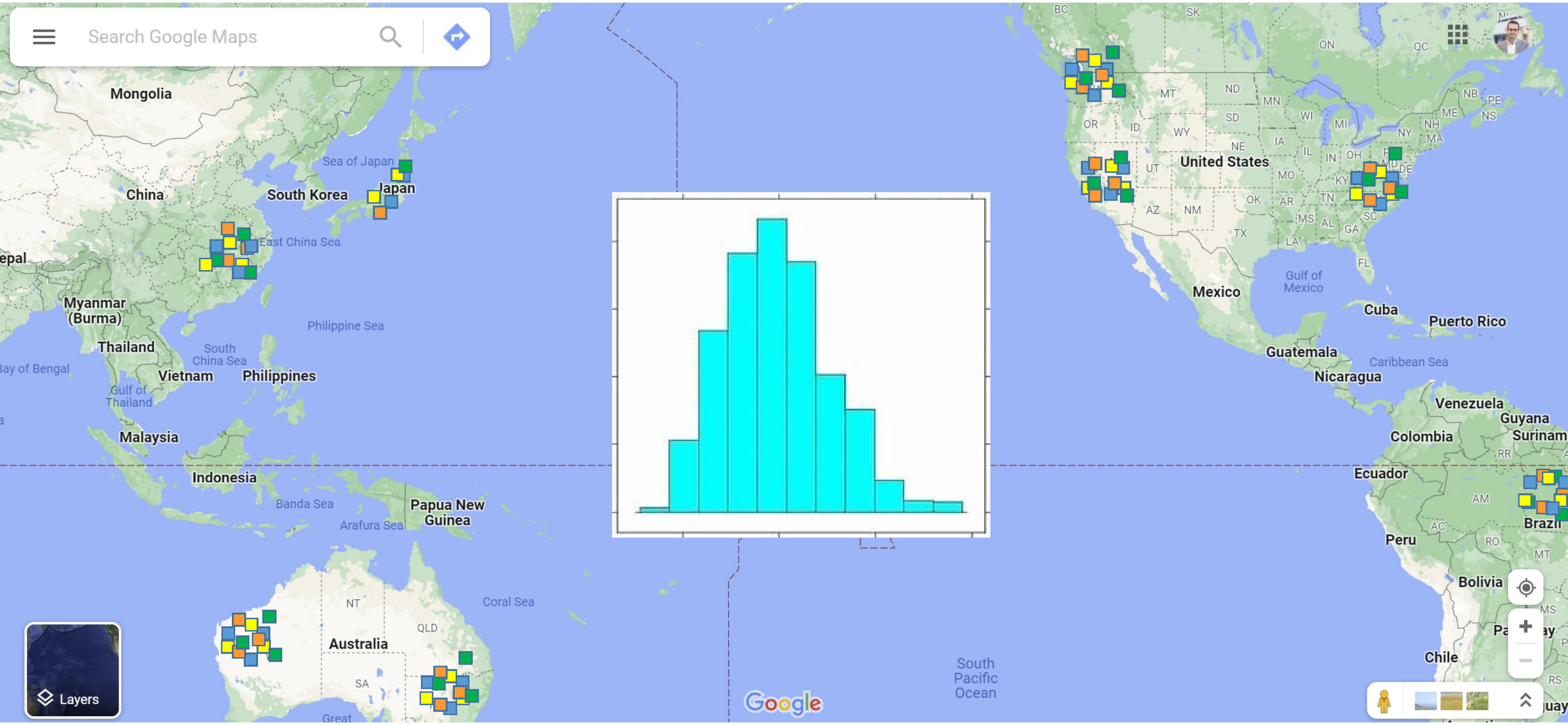
- Engage the wider community throughout the project.
  - e.g., railroads/agencies, engineering & design firms, product suppliers, educational institutions
- Develop a list of requirements for what would qualify as useful data.
- Develop a framework for the data repository, including:
  - Import data validation.
  - Compatibility with modeling software.
- Populate the data repository.
- Validate improved modeling capabilities.
- Continue to populate the data repository as new data becomes available.

Initial feedback from the modelling & simulation community: **would this be useful?** If so, how?

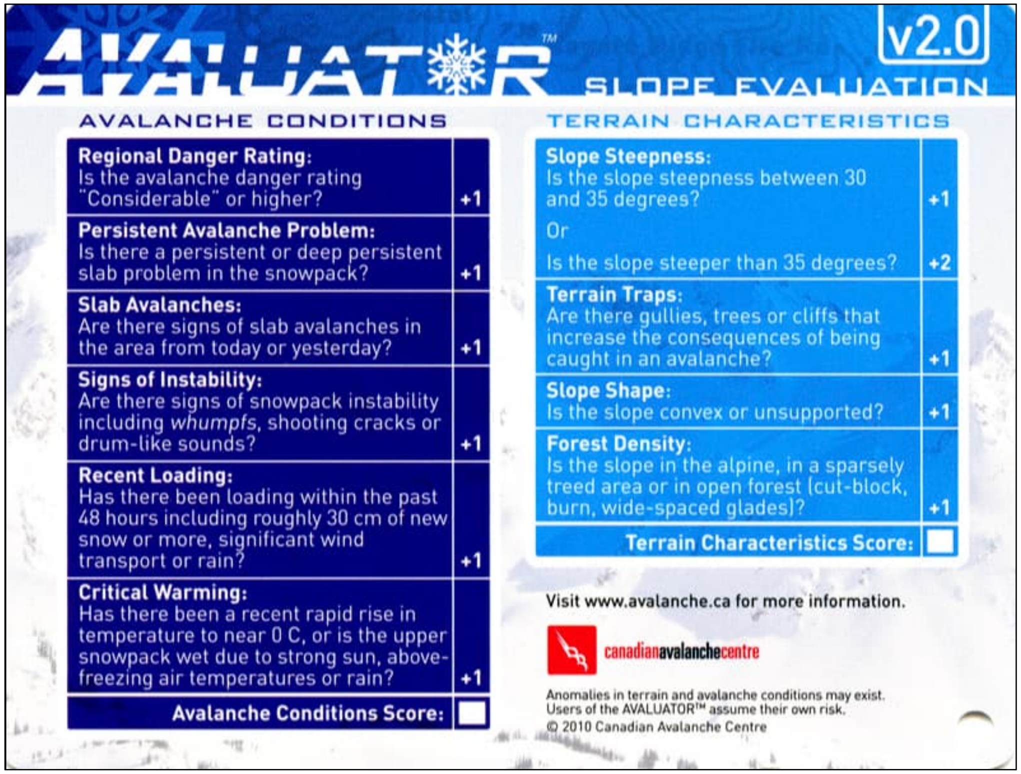
- Modelling & Simulation Use Cases:
  - Design Studies (e.g. vehicle qualification) ✗
  - Life Cycle Studies (e.g. track life cycle) ✓
  - Evaluation Studies (e.g. lubrication & friction management) ✓
  - Specialized Studies (e.g. detailed 3rd body layer modelling) ✗

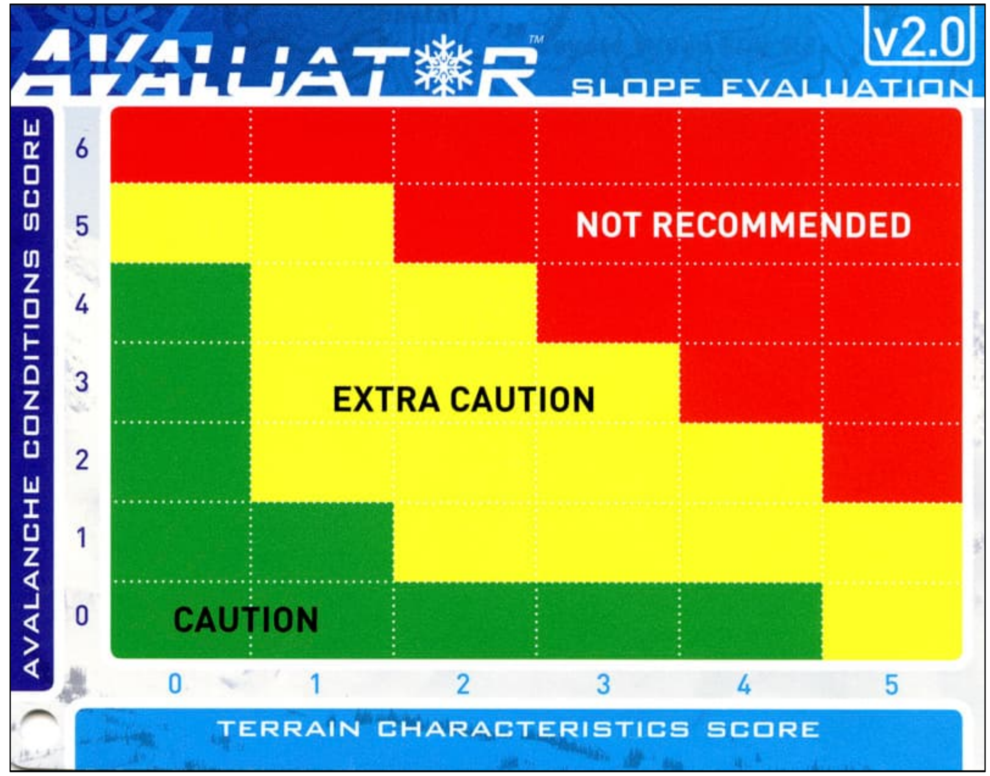
- Alternative / Additional Use Case: ✓
  - Comparing tribometer measurements to what is “normal” for a given set of operating conditions.

Conceptual Example 1: Geographic & Seasonal “Clustering”



Conceptual Example 2: Decision-Making Tool





Status & Next Steps

- Continue engaging the wider community.

- Assuming we remain convinced that the result will be useful:
  - Develop a list of data requirements.
  - Develop a framework for the data repository.
  - Populate the data repository.
  - Validate identified use cases.
  - Develop a usable interface.
  - Continue to populate the data repository as new data becomes available.

Discussion

- Interested in getting involved?

Contact Davey Mitchell – DMitchell@lbfoster.com

OnTrak Tribometer

Business continuity plan

Robert Caldwell

OnTrak hand operated tribometer

- Harold Harrison
  - Developed the Salient Systems push tribometer
    - The de-facto railway industry tribometer for several decades
  - Recognized its limitations, and wanted a better instrument
    - Developed the OnTrak HO tribometer
    - More features, lighter, easier to use
  - Harold passed away last summer
    - He was the driver for the instrument's development and refinement
    - Where do we go from here?

What do we do now?

- Tribometer Business Continuity Plan
  - New ICRI project formed in late 2021
  - Led by Ben White, University of Sheffield
  - Description: Portable tribometers allow the measurement of railhead friction in the field, useful for comparing laboratory friction testing to field data, as well as supporting modelling work and assessing railhead condition. This user group continues the development and helps troubleshoot the OnTrak railhead tribometer, whilst also providing a platform to collaborate and share friction data.

Members

- Ben White, Sheffield
- Roger Lewis, Sheffield
- Ryan McWilliams, International Engineering
- Davey Mitchell, LB Foster
- Josh Rychtarczyk, ARM
- Ali Tajaddini, FRA
- Sylvie Chénier, NRC
- Rob Caldwell, NRC
- Paul Di Natale, Dipostel
- Kari Gonzales, MxV
- Nicholas Wilson, MxV
- Alexander Keylin, MxV

Push tribometer

- Pros
  - Quick to get on and off track
  - Measures from the TOR to the gauge face
  - CoF value displayed on screen every 20-30 feet
  - Can measure as much track as you are willing to walk
- Cons
  - Heavy to carry about
  - Does not record the measurements
  - Measurements linked to locations only through your notes
  - Finicky to adjust as curves get sharper
  - Takes effort to push when CoF > ~0.7
  - Watch out for joint bars!

OnTrak tribometer - Pros

- Very light and portable
- Frame attaches magnetically to the rail
- Carriage containing measurement wheel runs in frame
- 7 pre-set angular roll positions of head (TOR to GF)
- Can select angle of attack, vertical downforce for wheel
- Can set to run a series of measurements at one or many roll angles
- Tablet controlled, data recorded, hands-free operation
- Can produce a μ value, or a creep curve

OnTrak tribometer - cons

- Measures over a short (12 inch) length of rail
- Measurement cycle is long (~30-40 seconds)
- Several pages of info available to configure a measurement
- Many options per page, hard to view on tablet
- Wi-Fi connection from tablet to tribo sometimes gets lost
- Aborting a measurement to take tribo off track is slow
- Delicate – more of a research instrument than a field tool

Issues

- OnTrak tribo needs many, many runs to produce a steady state value
- The two instruments produce different values under the “same” conditions – why?
- OnTrak tribo tends to produce lower values of μ
- All device knowledge/understanding was with Harold
- How will improvements be made?

What is the new ICRI project doing?

- Create an OnTrak/new Tribometer testing program to validate instrumentation - Ryan McWilliams
- Software to develop/support OnTrak tribometer - Ryan McWilliams
- Sheffield is available to support testing program - Ben White/Roger Lewis
- Determine the specific outcomes that this group is trying to accomplish and map how to get there - Ben White
- Are there any funding or grant programs that could be used for this Tribometer work? (Ben White to look into UK Europe – other members to survey their networks)
- Alexander Keylin and Nicholas Wilson will write up their thoughts and discuss with TTCI president, Kari Gonzales.
- Collating the data – a separate ICRI effort “Friction Library” led by Davey Mitchell overlaps with this action. We will discuss how we can incorporate this at the next Friction Library meeting
- Creating a "good practice guide" including an FAQ to help solve mechanical/software issues where possible would be good – this could be added to the ICRI Website. – Ben White/Sylvie Chenier

Progress so far

- Ryan McWilliams – International Engineering
  - Responsible for:
    - Creating a testing/validation program
    - Look into software development for the OnTrak tribo
  - Result
    - iE is currently in discussions with 2 different European based companies
    - We are in discussions to structure a deal which turns over the tribometer program to an organization which will invest in the next step of development as well as support the customer service of all users.
    - Both of these companies have a strong industry platform to take the tribo to the next level.
    - We are expecting to have this sorted by the end of the summer.

Progress so far

- Davey Mitchell – LB Foster
  - Leading the ICRI Friction Library project
  - Ultimately, data measured with the OnTrak will be included in the Library
  - First need to have confidence in the measurement values given the environment in which they were collected

Summary

- Off to a slow start, but making headway
- Stay tuned for updates, will be posted on the ICRI project site
- Interested in joining this project?
    - bwhite2@sheffield.ac.uk, sylvie.chenier@nrc.ca

Quantifying Surface Damage

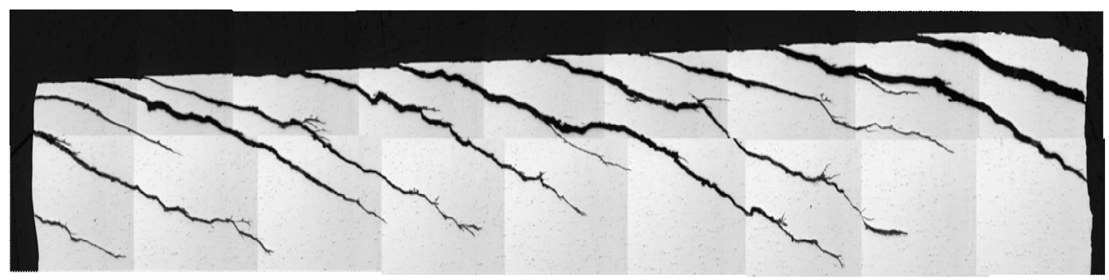
Daniel Szablewski

Quantifying Surface Damage

ICRI Meeting – June 22, 2022

Presentation made by:
Daniel Szablewski
Automotive and Surface Transportation
National Research Council (NRC) Canada

Research funded by:
U.S. Department of Transportation
Federal Railroad Administration (FRA)

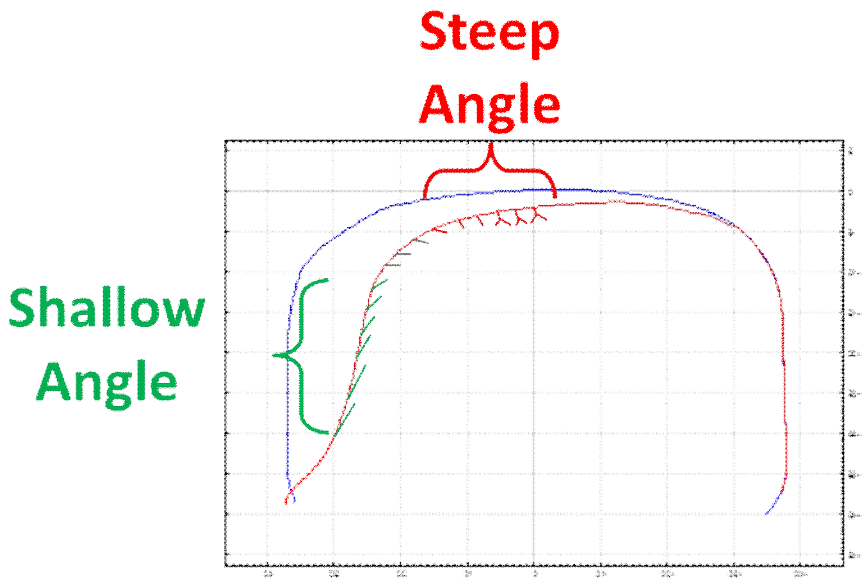


U.S. Department of Transportation
Federal Railroad Administration

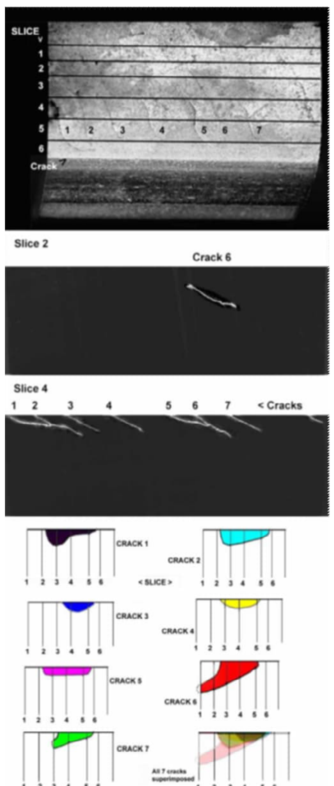
Quantifying RCF

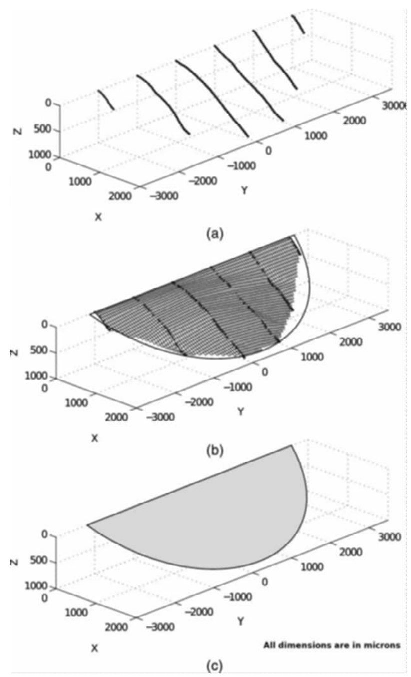
Crack plane cross-sectional morphology

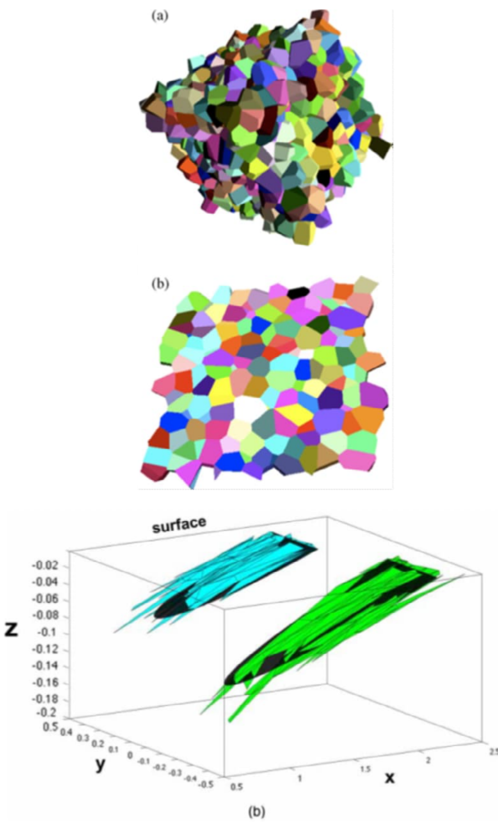
- Steep to shallow angle vs. position on railhead running surface



RCF Modeling – Crack Metallography / 3D Representation



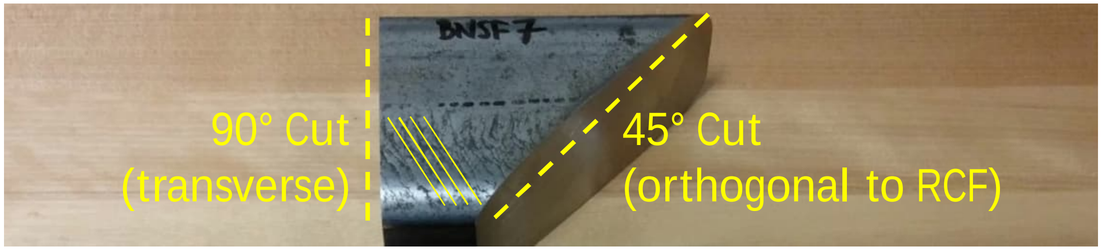




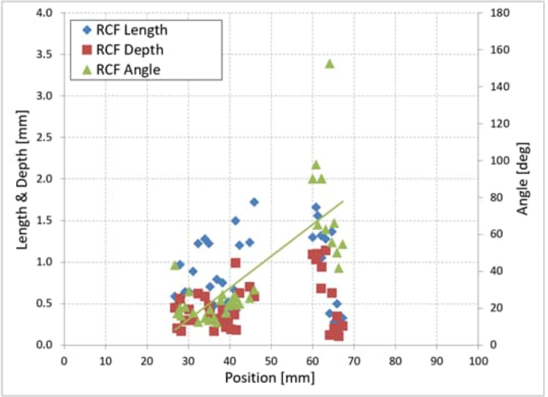
J.E. Garnham et al., 'Visualization and modelling to understand rail rolling contact fatigue cracks in three dimensions', Proc. IMechE Vol. 225 Part F: J. Rail and Rapid Transit

RCF Metallography Approach

- 2 cuts made in the rail
  - Transverse (90°)
  - Orthogonal (45°)
- Crack metrics acquired
  - Length
  - Depth
  - Angle



(90° Cut)



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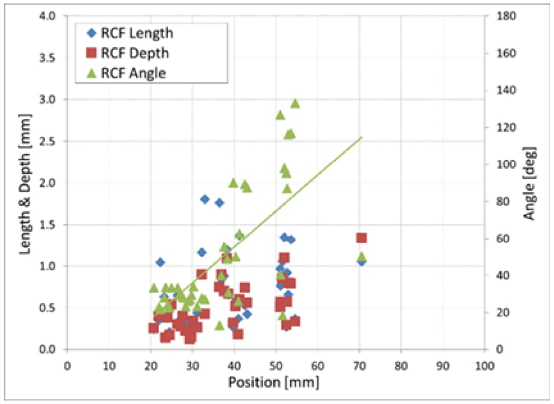
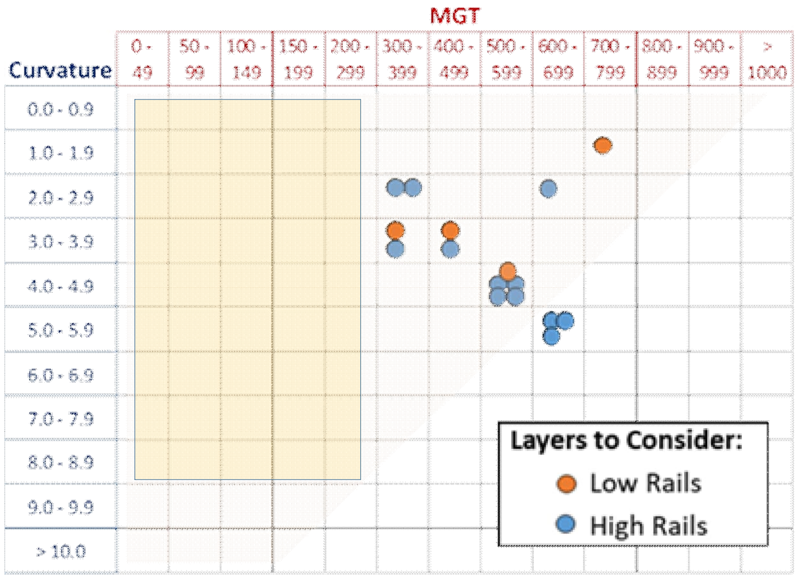


RCF Metallography Database

Latest iteration of rails added to the data matrix

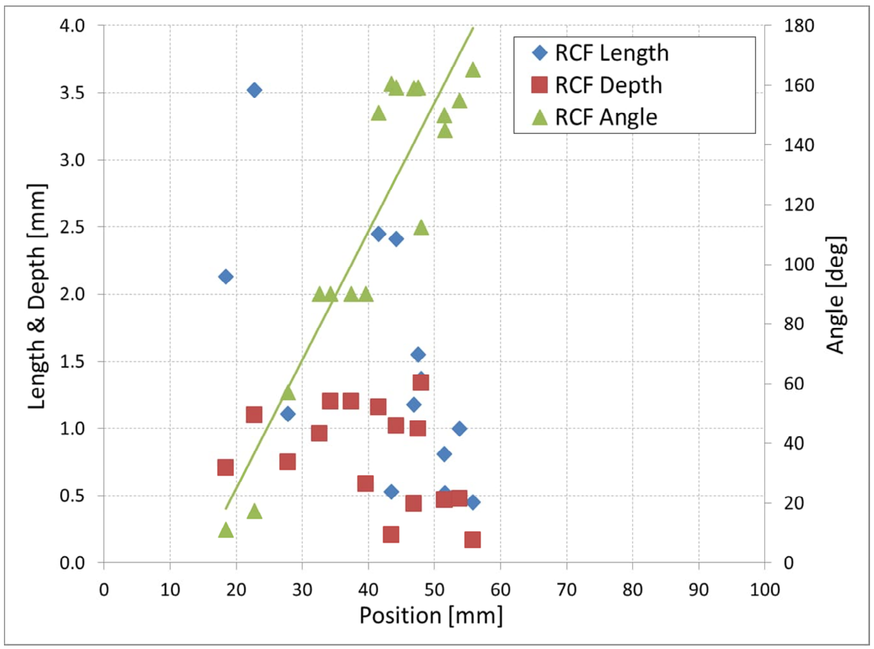
Sample ID	Rail Origin	Angle of Cut [deg]	HR	LR	Lub	Rail Type (Manf.)	Service Removed	Approx. Accum. MGT	Curvature [deg]
NPH-H2	TTCI FAST loop	90	X		No	Nippon HEX 2015	end 2018	650	5.0
NPH-H4	TTCI FAST loop	90 & 45	X		No	Nippon HEX 2015	end 2018	650	5.0
NPH-H5	TTCI FAST loop	90 & 45	X		No	Nippon HEX 2015	end 2018	650	5.0
DH1H	CSX Jessup ANA 620.9	90 & 45	X		Yes	Mittal 141 VT 2006	mid 2018	360	3.0
DH4H	CSX Jessup ANA 587.7	90 & 45	X		Yes	Mittal 141 VT 2003	mid 2018	450	3.3
DH1L	CSX Jessup ANA 620.9	90		X	No	Mittal 141 VT 2006	mid 2018	360	3.0
DH4L	CSX Jessup ANA 587.7	90		X	No	Mittal 141 VT 2003	mid 2018	450	3.3
BNSF 7	BNSF Staples (MP 200.69)	90 & 45	X		Yes	136 RMSM 2002	2015	390	2.0
BNSF 10	BNSF Staples (MP 200.69)	90 & 45	X		Yes	136 RE 1994	2015	630	2.0
BNSF 12	BNSF Staples (MP 200.69)	90 & 45	X		Yes	141 RMSM 2004	2015	330	2.0
BNSF 14	NS Hardy Sub.	90 & 45		X	No	136 RE 1990	Nov 2014	750	1.0
Y1	CN Superior (MP 417.3)	90 & 45	X		Yes	Beth Steelton 1997	July 2016	570	4.45
Y2	CN Superior (MP 467.23)	90 & 45	X		Yes	Beth Steelton 1997	July 2016	570	4.75
UK-1	CN Superior (MP 417.3)	90		X	No	Beth Steelton 1997	July 2016	570	4.45
UK-2	CN Superior (MP 417.3)	90	X		Yes	Beth Steelton 1997	July 2016	570	4.45
UK-3	CN Superior (MP 417.3)	90	X		Yes	Beth Steelton 1997	July 2016	570	4.45



RCF Crack Morphology – Results

- High Rail 1.0 degree curvature, 750 MGT accumulated tonnage

(90° Cut)



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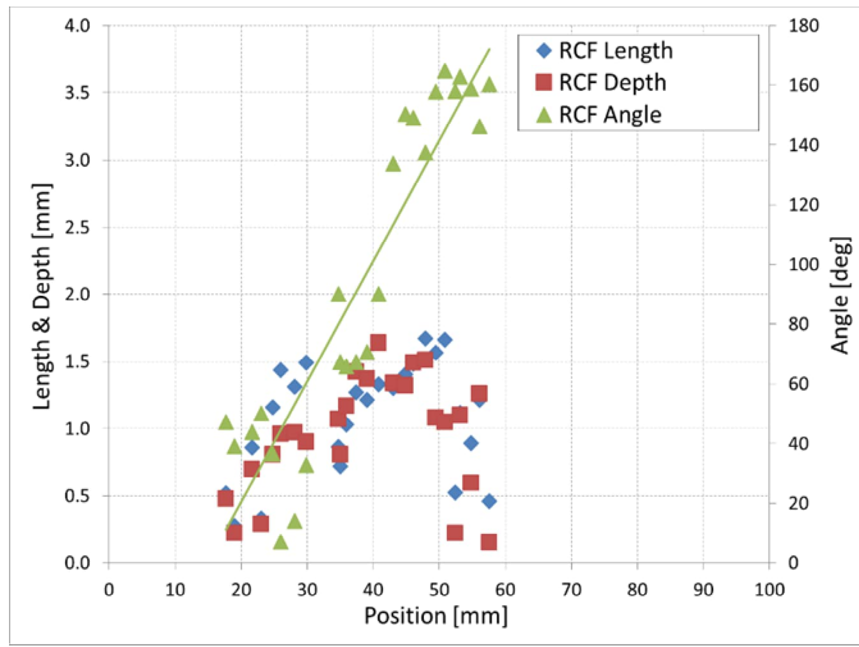
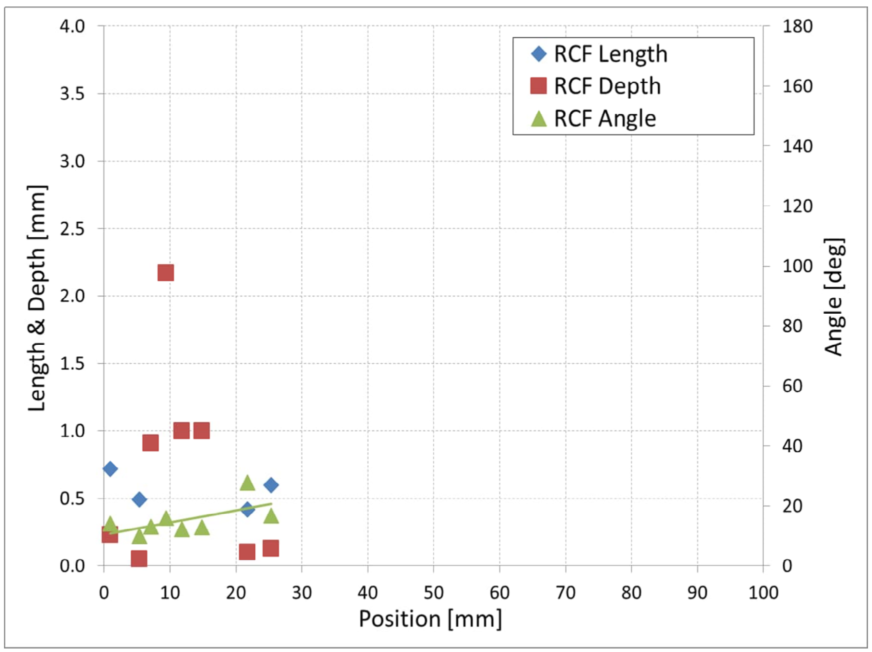


RCF Crack Morphology – Results

- High Rail 2.0 degree curvature, 390 MGT accumulated tonnage

(90° Cut)



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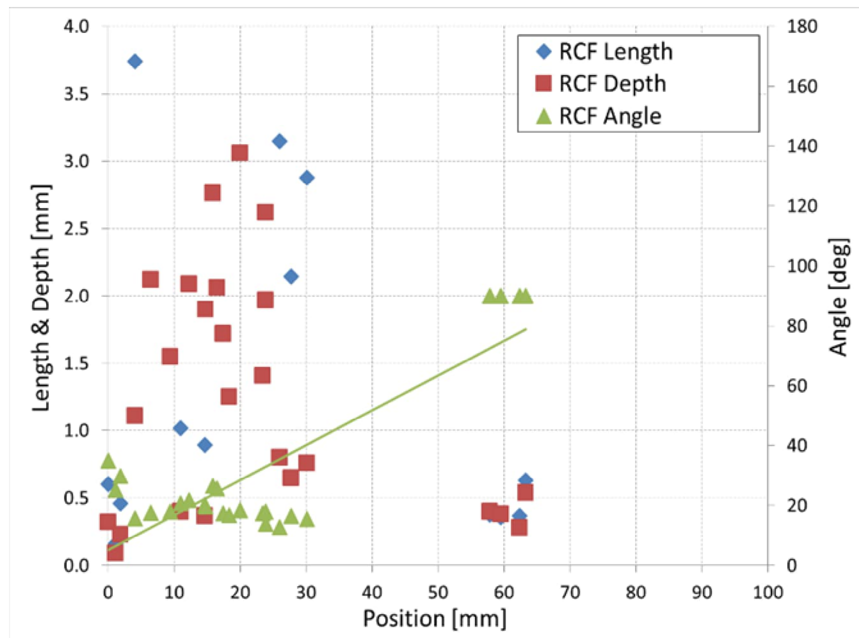
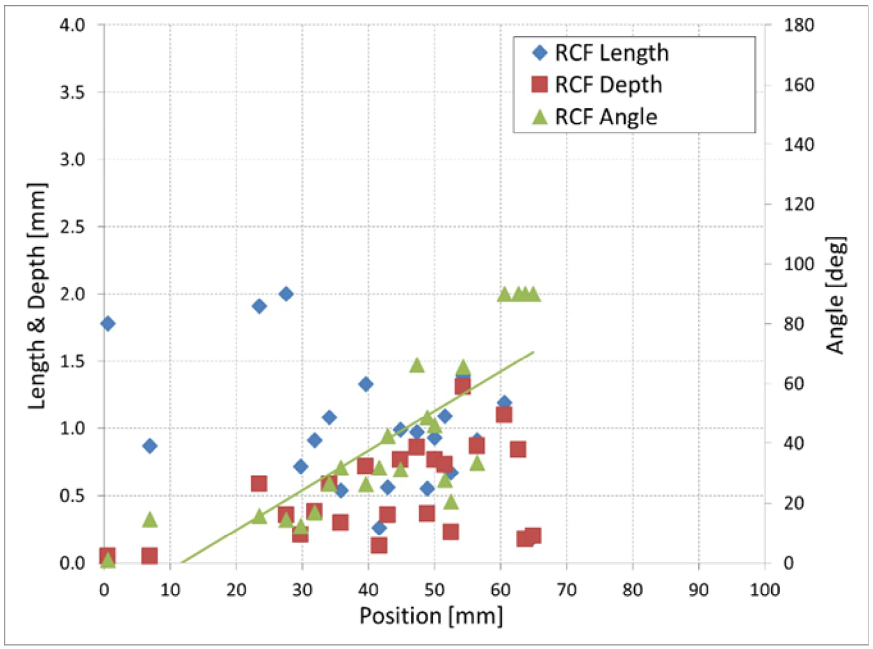


RCF Crack Morphology – Results

- High Rail 4.45 degree curvature, 570 MGT accumulated tonnage

(90° Cut)



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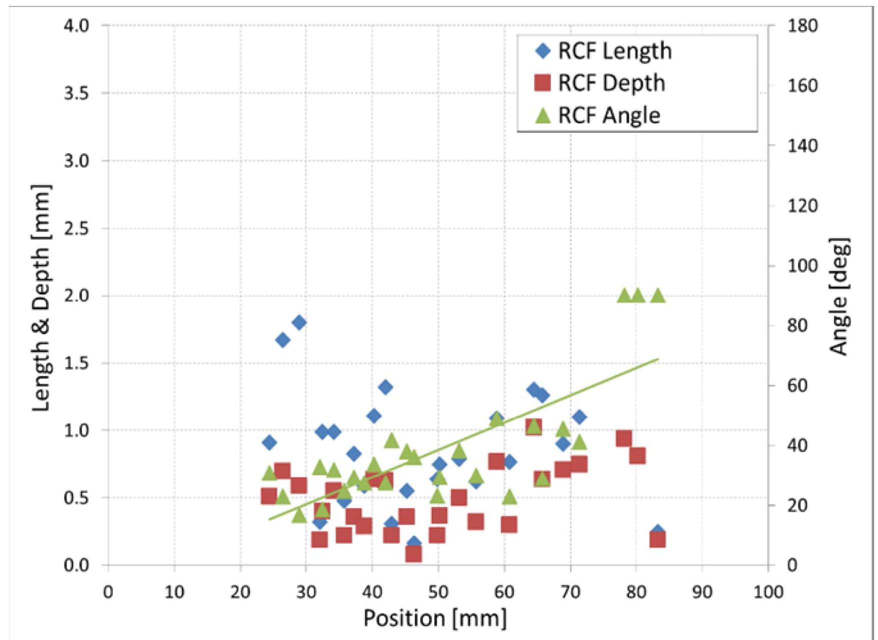

RCF Crack Morphology – Results

- High Rail 4.75 degree curvature, 570 MGT accumulated tonnage

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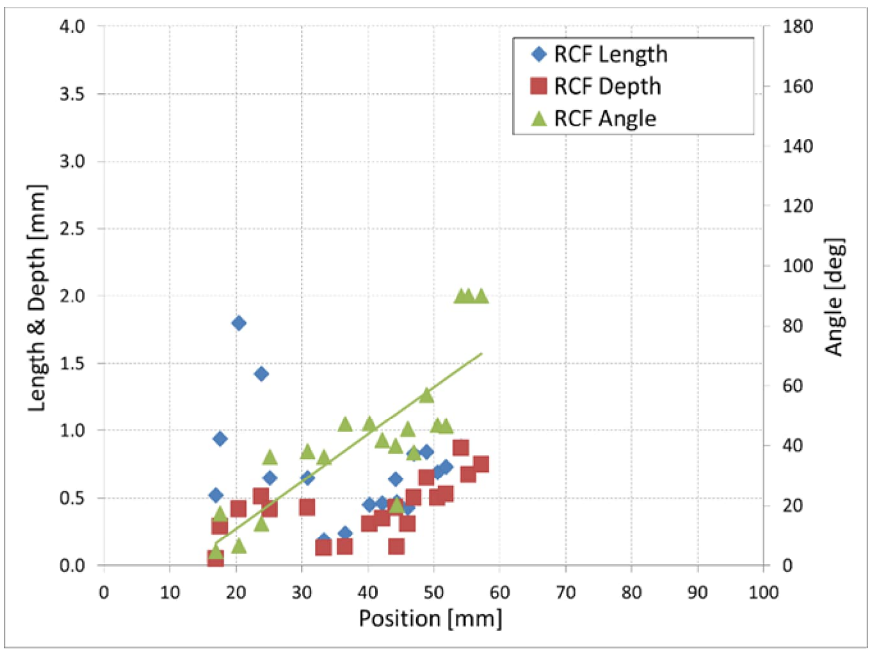

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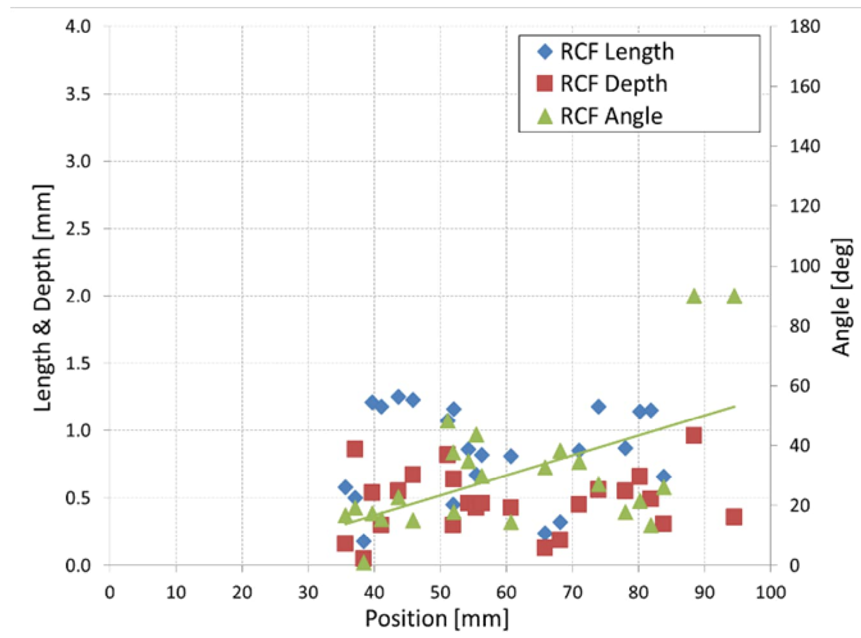
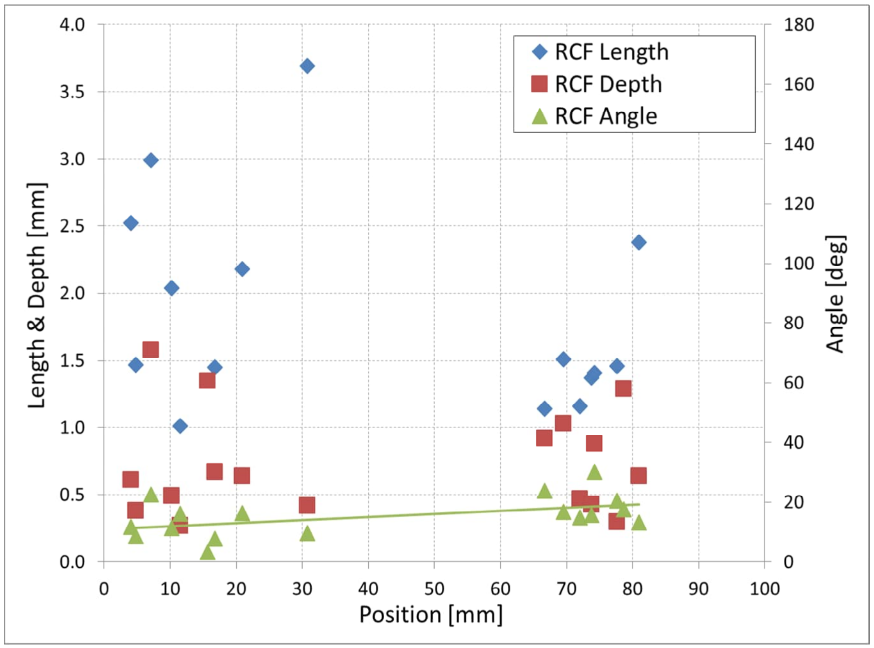


RCF Crack Morphology – Results

- High Rail 7.62 degree curvature, 430 MGT accumulated tonnage

(90° Cut)



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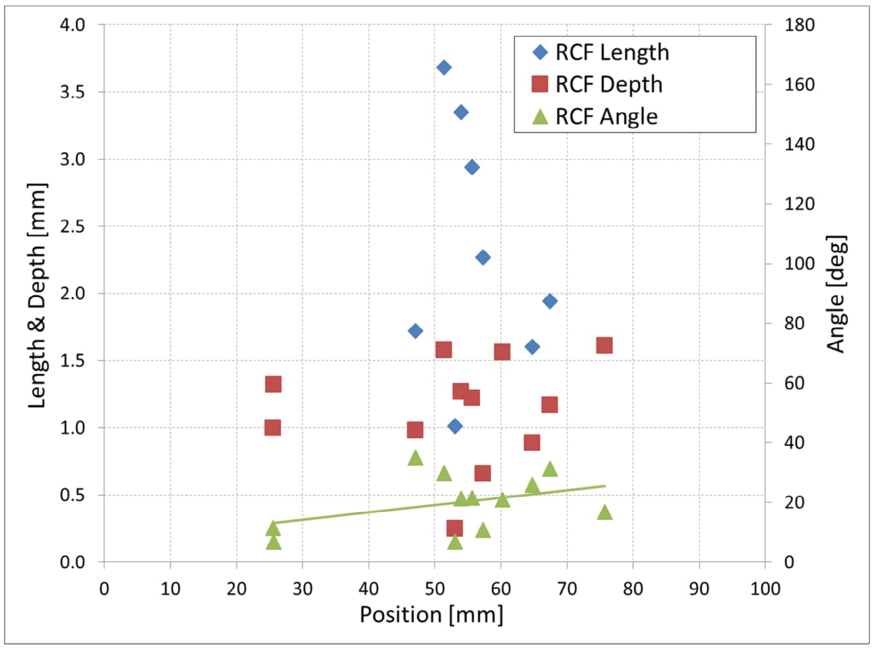
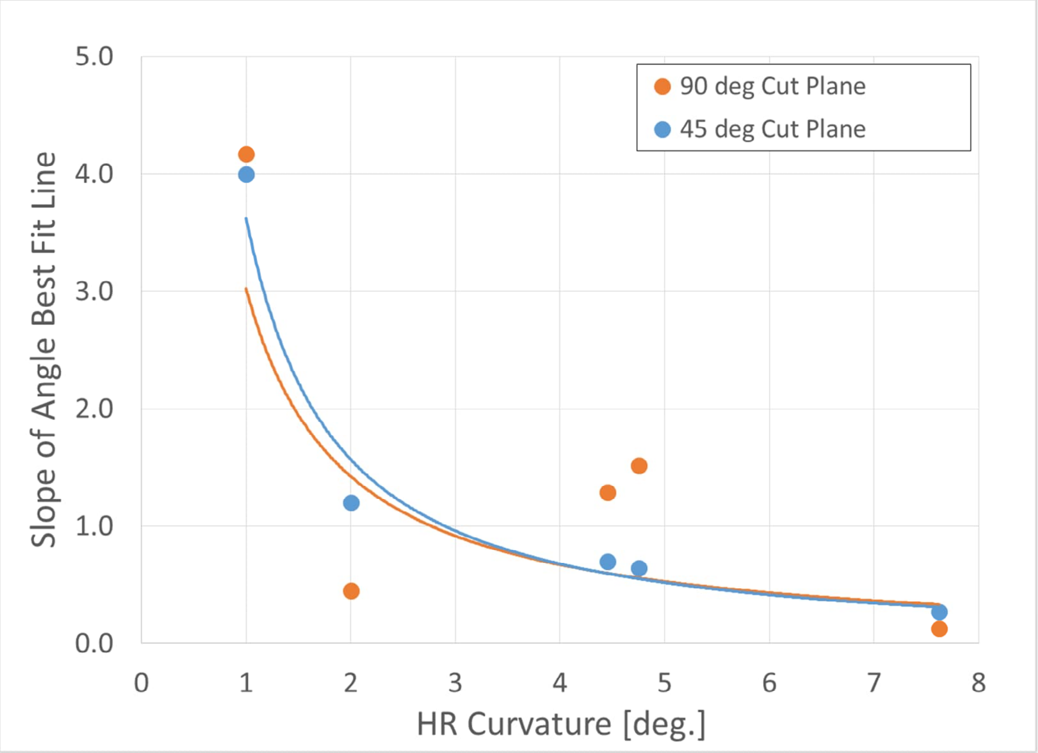
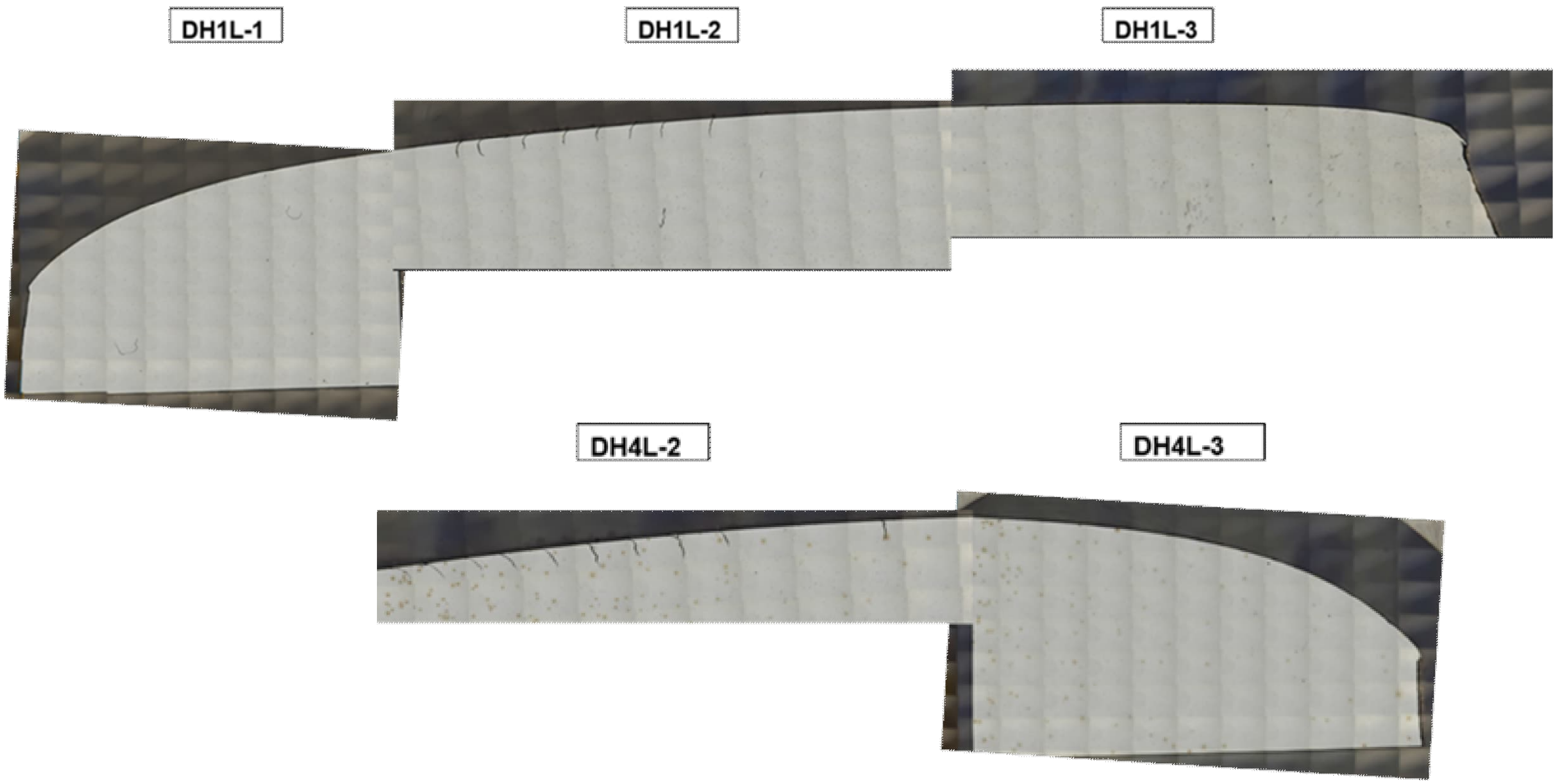


Trend in HR RCF: Angle vs. Track Curvature

- Rapid decrease in the slope of the line
- More data needed to strengthen this relationship

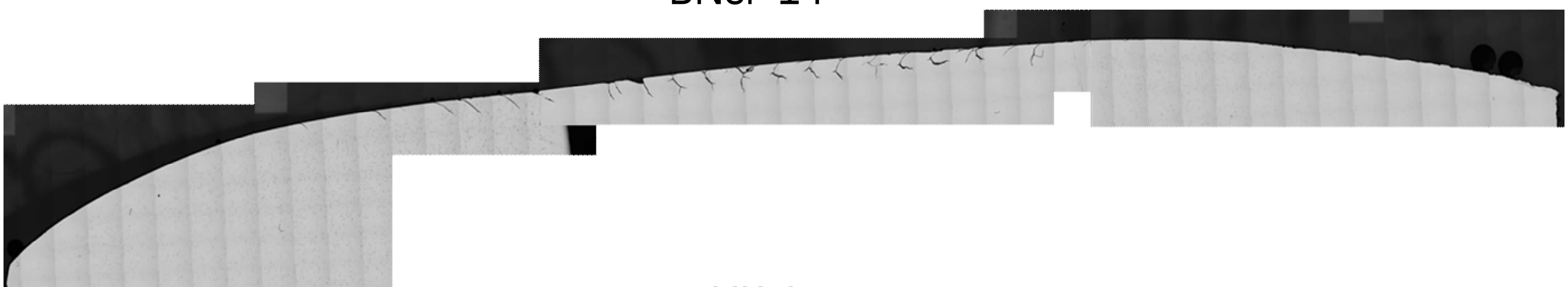


Low Rail RCF in TOR

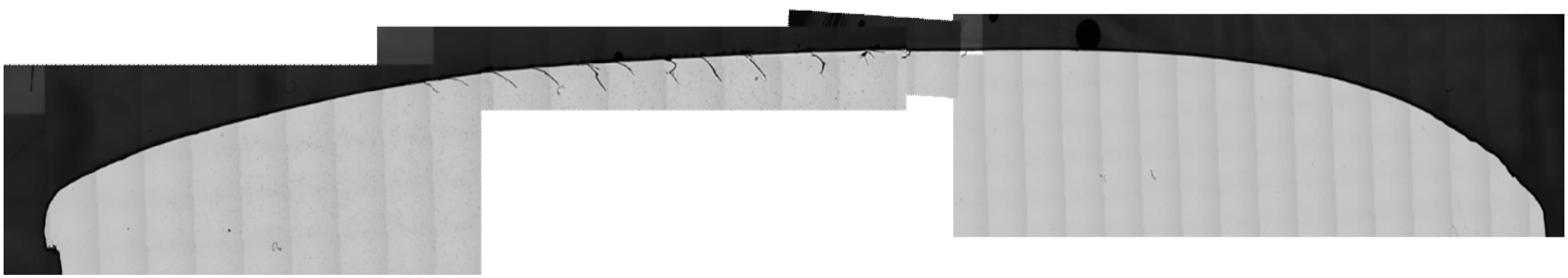


Low Rail RCF in TOR

BNSF 14



UK-1



Principles and operations of Electromagnetic Field Imaging and its application to the wheel rail interface

Paul Gies

Athena Industrial Services

Calgary, Canada

This presentation may be made available separately

2:55 - 3:15 pm: coffee break

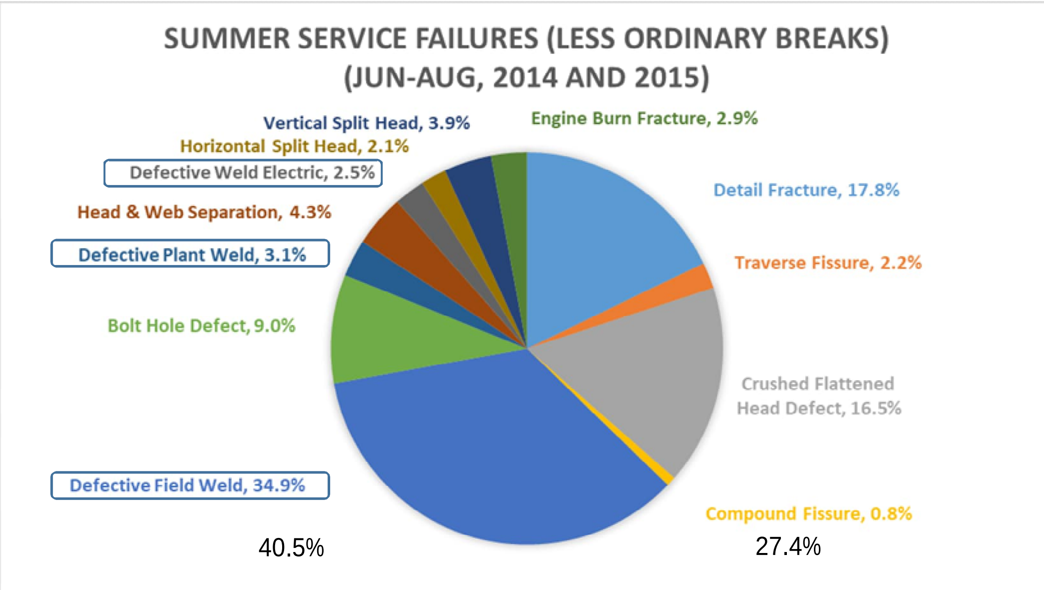
Analyzing Broken Rail Caused Derailments using a Risk Mapping Tool

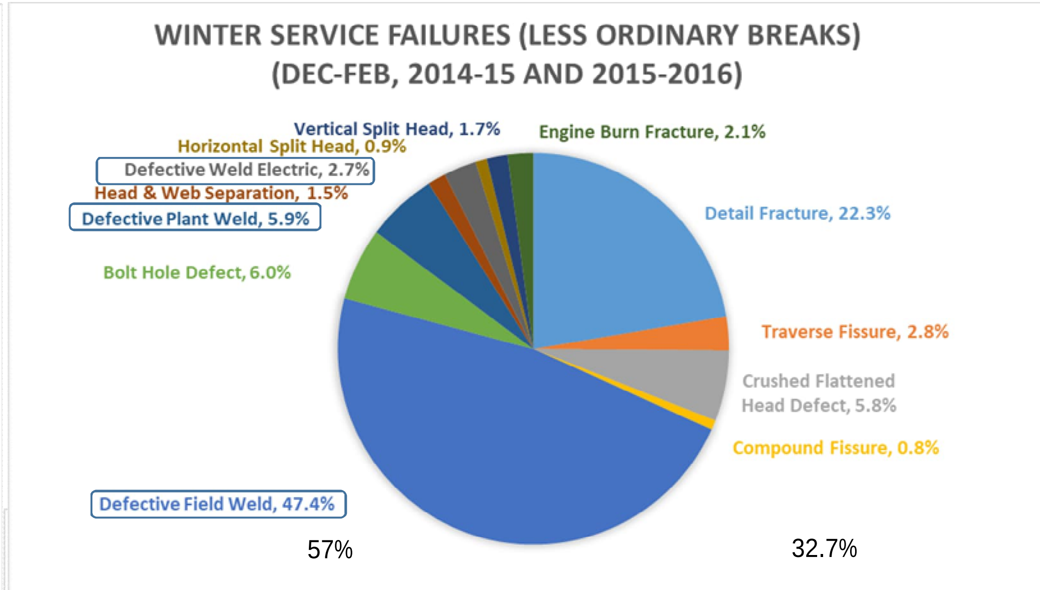
Yan Liu

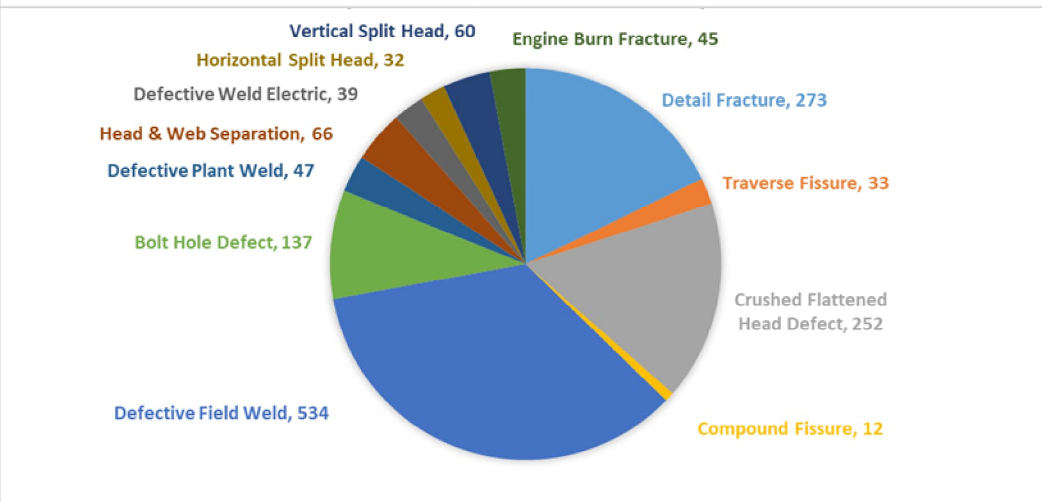
National Research Council, Canada

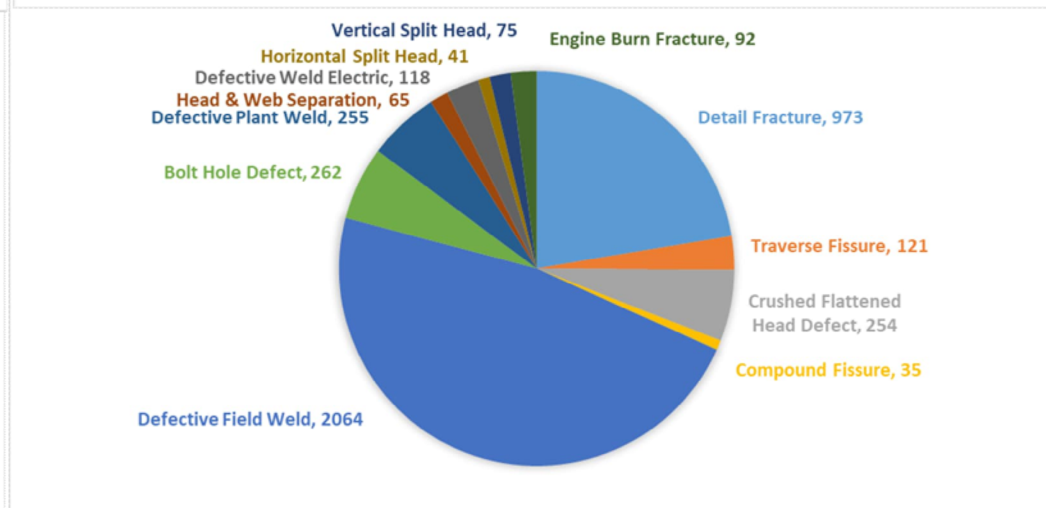
Ottawa, Canada

This presentation is not available for general distribution. Please contact Yan.Liu@nrc-cnrc.gc.ca directly to request access.

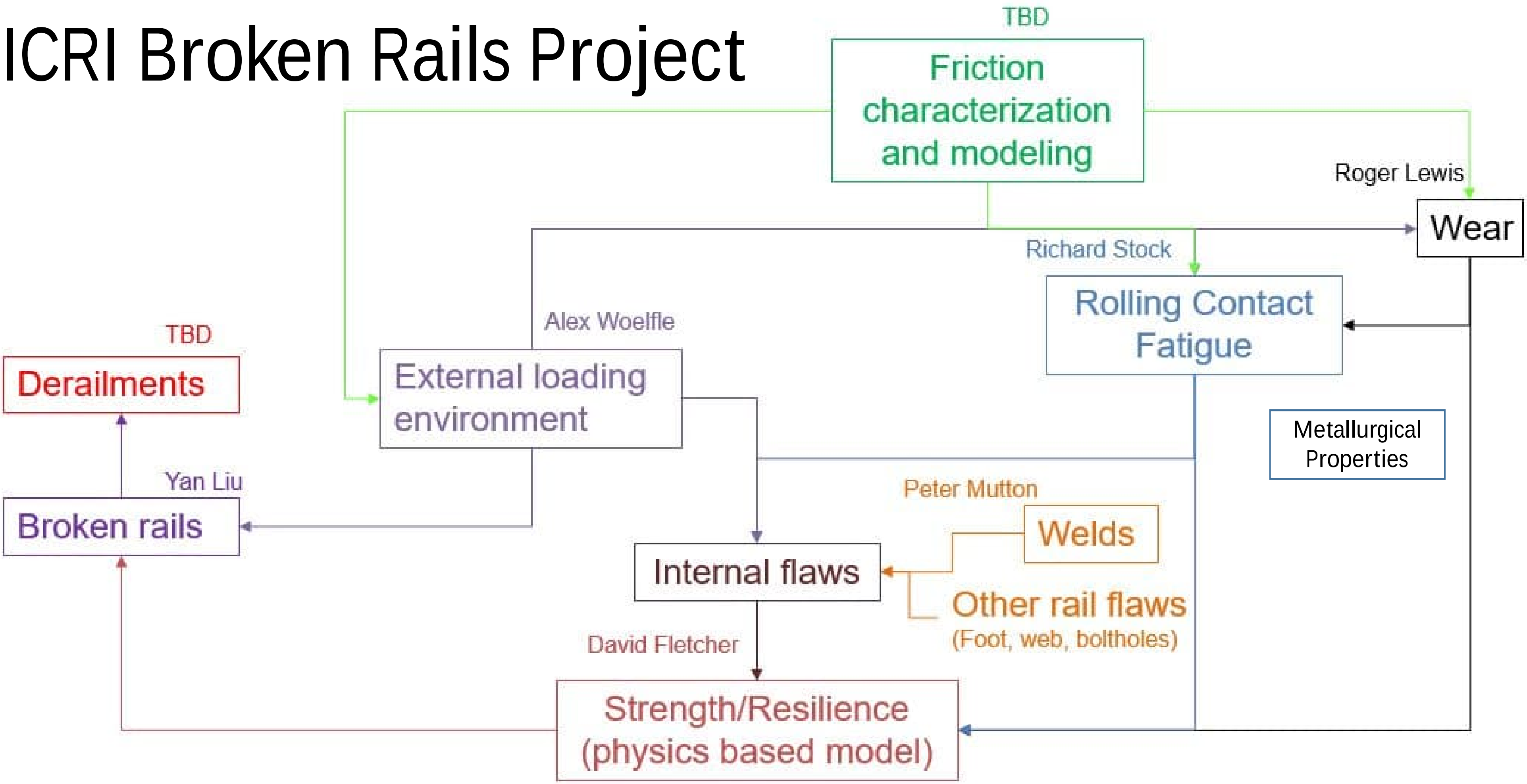

SUMMER SERVICE FAILURES (LESS ORDINARY BREAKS)
(JUN-AUG, 2014 AND 2015)
Vertical Split Head, 3.9%
Engine Burn Fracture, 2.9%
Horizontal Split Head, 2.1%
Defective Weld Electric, 2.5%
Head & Web Separation, 4.3%
Defective Plant Weld, 3.1%
Bolt Hole Defect, 9.0%
Detail Fracture, 17.8%
Traverse Fissure, 2.2%
Crushed Flattened Head Defect, 16.5%
Compound Fissure, 0.8%
Defective Field Weld, 34.9%
40.5%
27.4%


WINTER SERVICE FAILURES (LESS ORDINARY BREAKS)
(DEC-FEB, 2014-15 AND 2015-2016)
Vertical Split Head, 1.7%
Engine Burn Fracture, 2.1%
Horizontal Split Head, 0.9%
Defective Weld Electric, 2.7%
Head & Web Separation, 1.5%
Defective Plant Weld, 5.9%
Bolt Hole Defect, 6.0%
Detail Fracture, 22.3%
Traverse Fissure, 2.8%
Crushed Flattened Head Defect, 5.8%
Compound Fissure, 0.8%
Defective Field Weld, 47.4%
57%
32.7%


Vertical Split Head, 60
Engine Burn Fracture, 45
Horizontal Split Head, 32
Defective Weld Electric, 39
Head & Web Separation, 66
Defective Plant Weld, 47
Bolt Hole Defect, 137
Detail Fracture, 273
Traverse Fissure, 33
Crushed Flattened Head Defect, 252
Compound Fissure, 12
Defective Field Weld, 534


Vertical Split Head, 75
Engine Burn Fracture, 92
Horizontal Split Head, 41
Defective Weld Electric, 118
Head & Web Separation, 65
Defective Plant Weld, 255
Bolt Hole Defect, 262
Detail Fracture, 973
Traverse Fissure, 121
Crushed Flattened Head Defect, 254
Compound Fissure, 35
Defective Field Weld, 2064

ICRI Broken Rails Project



ICRI Broken Rails project

- Load Characterization – Alex Woelfle
- Wear modeling – Eric Magel (for Roger Lewis)
- RCF modeling – Richard Stock
- Rail Resilience/Broken Rails – Chris Ladubec
- Derailment modeling – Eric Magel

ICRI Broken Rails Modeling External Loading Environment Characterization

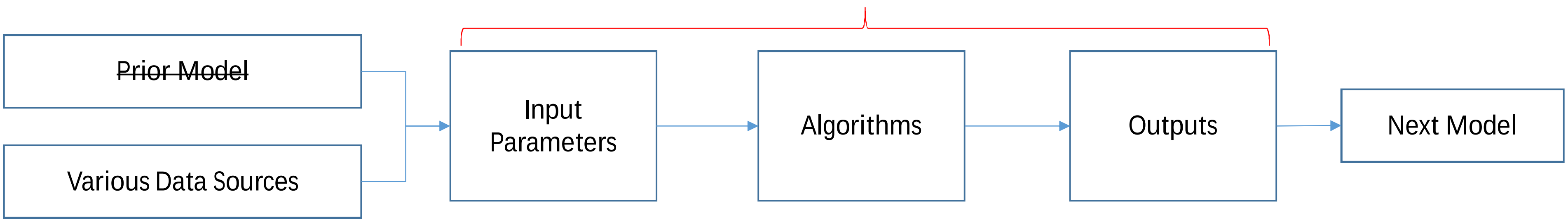
Alexandre Woelfle

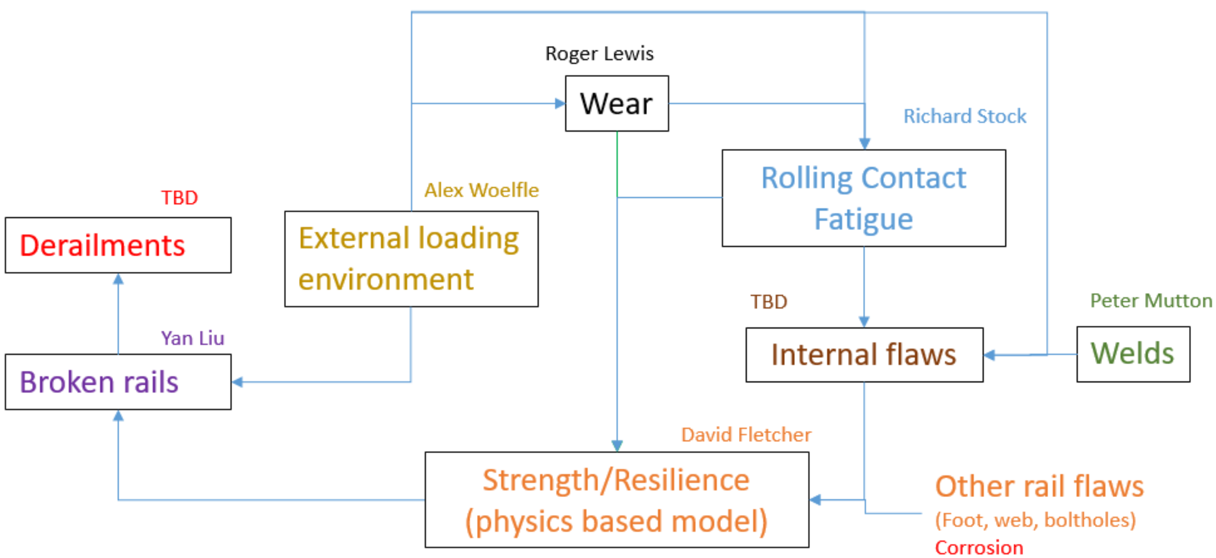
Outline

- Goal
- Current State
- Next Steps

Goal – External Loading Environment (ELE)

Workshop Goals: Identify main features of each block and the gaps/research needs





- Inputs: list all possible inputs, then parse to only those required
- Algorithms: the simplest block of the ELE with only a few steps and options
- Outputs: ELE feeds into 4 models, each with different needs

Current State – Input Parameters & Algorithms

Input Parameters → Algorithms → Outputs

Input Parameters

Train
- Speed
- Composition
- Frequency
- Direction
- Traction & braking

Vehicle
- Weight
- Dimensions
- Centre of gravity
- Number of axles

Truck
- Wheelbase
- Flexibility
- Suspension

Axle
- Back-to-back distance

Wheel
- Transversal profile
- Diameter
- Frequency and magnitude of impacts
- Surface condition

Friction Conditions
- Top of rail
- Gauge face
- Back of flange
- Contaminants & precipitations

Rail
- Transversal profile
- Cant
- Surface condition

Track
- Curvature
- Superelevation
- Grade
- Gauge
- Track geometry irregularities
- Guard rail
- Welds
- Joints
- Vertical stiffness
- Lateral stiffness

Algorithms

Input Parameter Selection
- Matrix – case comparison
- Stochastic – realistic loading environment

Vehicle-Track Interaction Software
- VAMPIRE
- NUCARS
- Simpack

! Convert vehicle-referenced outputs to rail-referenced outputs

Current State – Outputs

Input Parameters → Algorithms → Outputs

Outputs →
- Wear
- Rolling Contact Fatigue
- Internal Flaws
- Broken Rails

Vehicle
- Roll angle
- Yaw angle

Truck
- Roll angle
- Yaw angle

Axle
- Roll angle
- Angle of attack
- Lateral position
- Forces

Rail
- Contact positions and angles

Wheel
- Contact positions and angles
- Rolling radius

Contact Patch
- Contact patch dimensions
- Creepages
- Creep forces
- Contact force and stress

Next Steps – External Loading Environment (ELE)

- Identify Outputs Needed from the External Loading Environment. Review the progress of the relevant Broken Rail Modeling workgroups to establish their input needs, then identify gaps in ELE outputs.
- Define Algorithm box in flowchart. Identify common uses and approaches during the next workshop, then investigate gaps in our ability to create needed outputs.
- Adjust List of Inputs. Review list of inputs and identify the essentials to make future broken rail data acquisition more efficient.

Wear Modeling

Roger Lewis (Sheffield University)

Wear Modeling

- Most wear analysis and test data reflect dry surfaces, whereas the wheel/rail contact always has a third body (interfacial layers).
- Only limited combinations of materials have so far been tested in the laboratory.
- In modeling of wear we need more data on deformed layer properties and damage thresholds.
- Real world traction-creepage curves are needed
- More work is required to understand the tradeoff between wear and RCF.

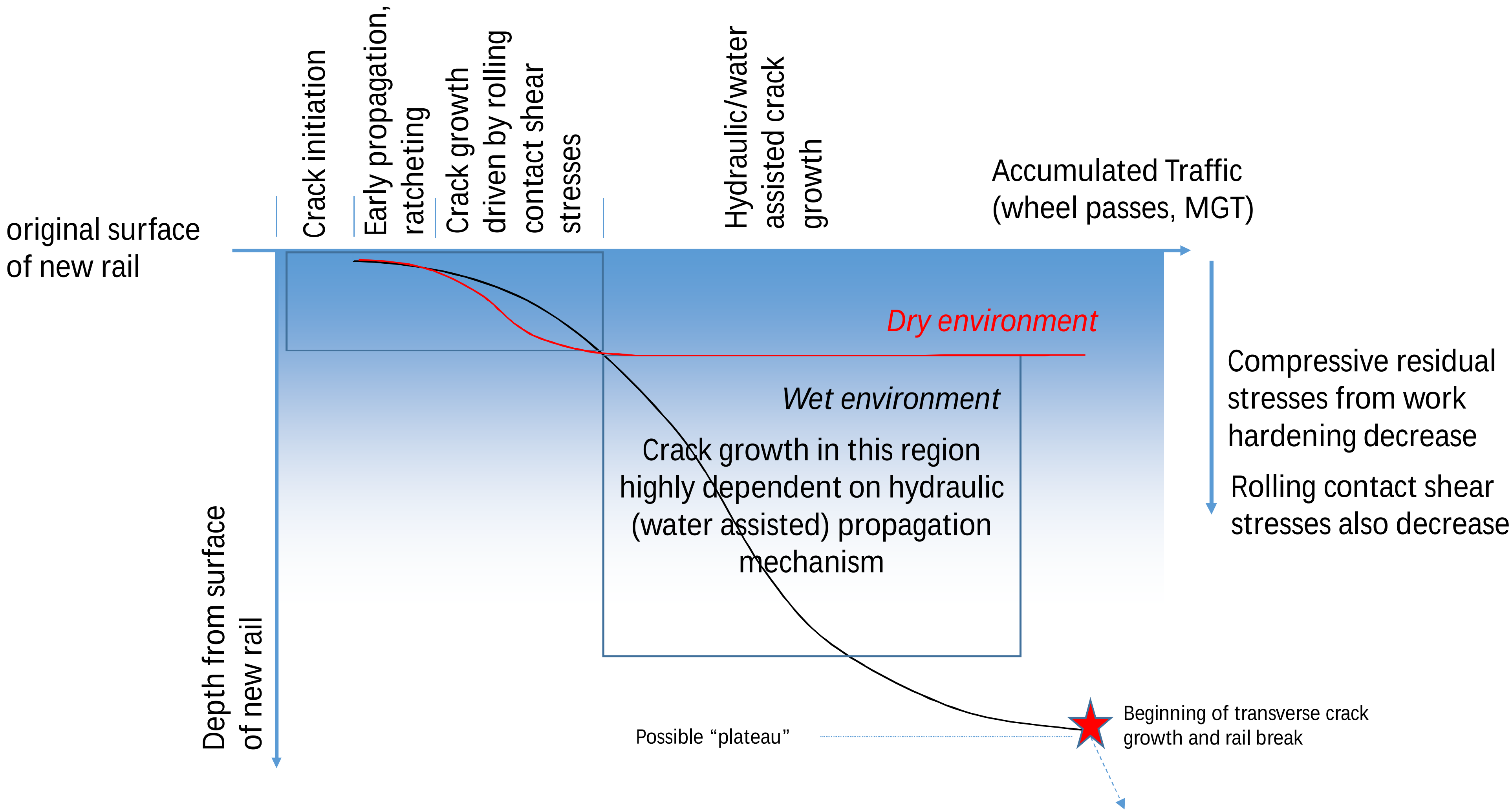
Wear Modeling – Cont'd

- How do bi-directional running, traction and braking affect wear and RCF?
- Most wear modeling has been of wheels, more is needed for rails.
- Proposed Activities:
  - Generate needed wear data by setting up mini-projects for Masters students (set-up test protocol, list needs and distribute)
  - Challenge for the research community: to develop techniques for real time monitoring of deformed layer and damage evolution using NDT techniques (e.g. Barkhausen noise?)

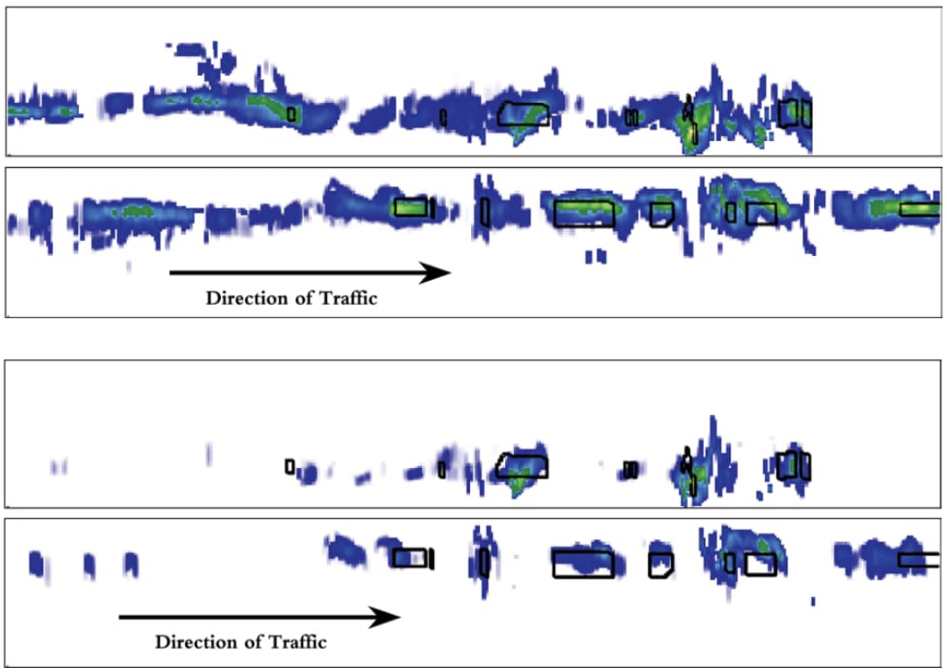
RCF Modeling

Richard Stock

For surface initiating rolling contact fatigue cracks

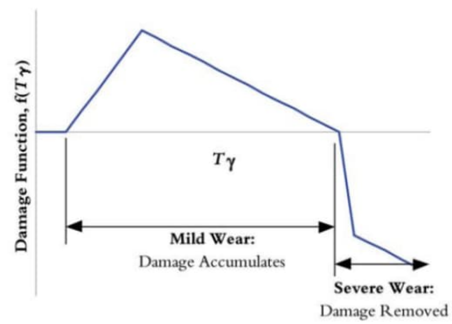


Crack initiation model – damage criterion



RCF modeling of cracks at Roscombe

Shakedown



TGamma

Crack initiation modeling generally ignores any actual crack.
What is the relationship between the damage index and size of crack? Does it matter since it is quite shallow in comparison with cracks of concern?

From: Burstow, M.C., Watson, A.S., Beagles, A.E., & Kapoor, A. (2003). Current developments in the Whole Life Rail Model to predict rolling contact fatigue in rails.

Damage... how to simulate?

Questions - and hopefully some answers

1. What constitutes a "deep" crack and how best to model it?
2. How well understood is the impact of different metallurgies on performance with respect to RCF? While shakedown modelling using hardness is common, hardness alone is not a sufficient indicator of real-world performance. What other properties should we be measuring?
3. Can we measure the relevant metallurgical properties with confidence?
4. How well understood is the impact of those metallurgical/mechanical properties on RCF initiation and propagation?
5. How does metallurgy interact with other factors (e.g. contact mechanics, friction management etc.)

Output of Discussion (April 14th)

- Extended discussion on the topics in question but no conclusion / agreement was achieved
  - Complex Situation
  - Long vs. short cracks
  - Contact stresses, residual stresses
- Suggestion of simulation methodology by M Spiryagin (CQ University Australia)
  - Definition stage
  - Simulation feasibility stage (parameters, simulation models=
  - Simulation platform development
- Further Discussion required

ICRI Broken Rail Safety Initiative Rail Resilience Workshop - Update

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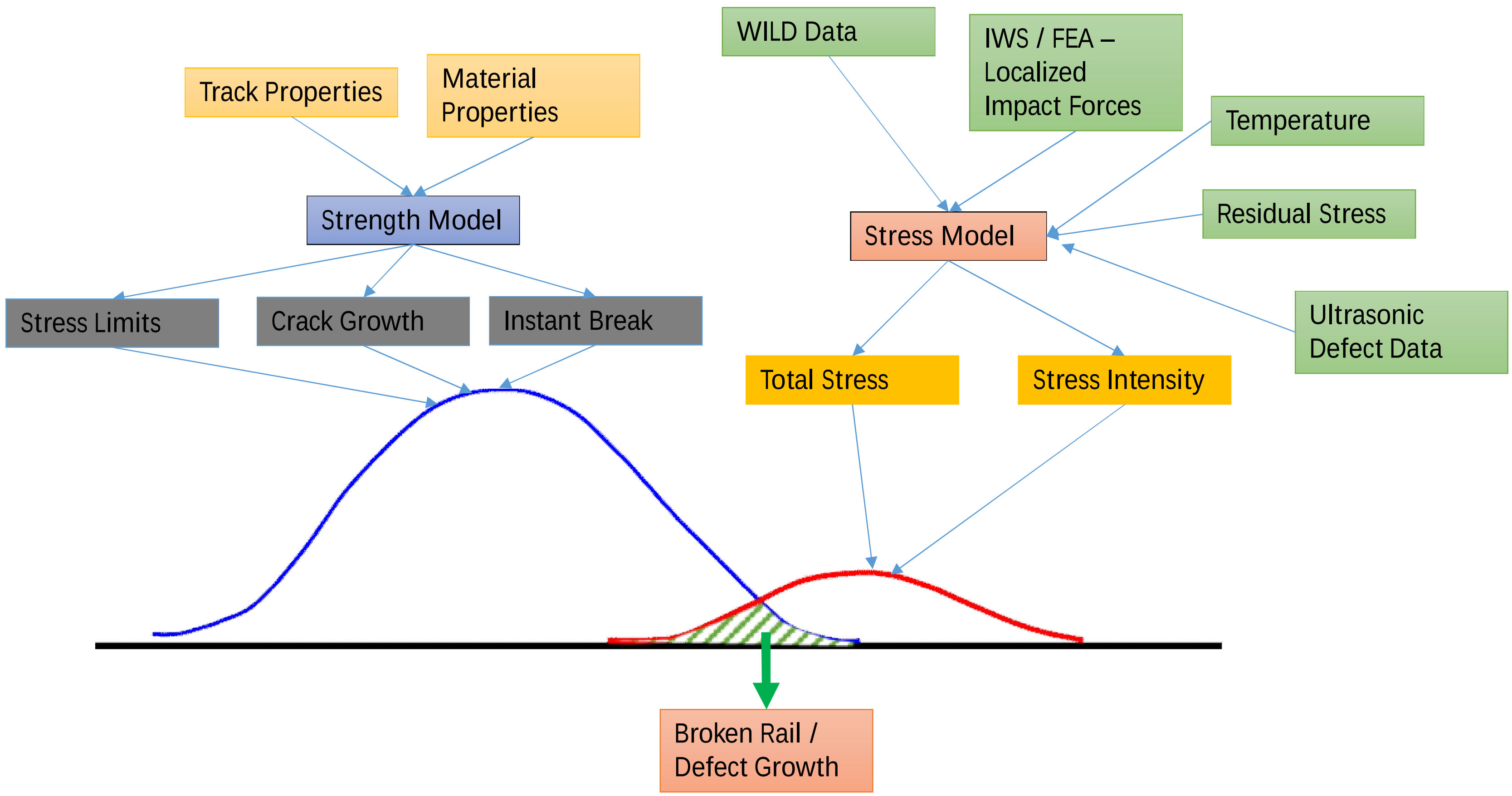
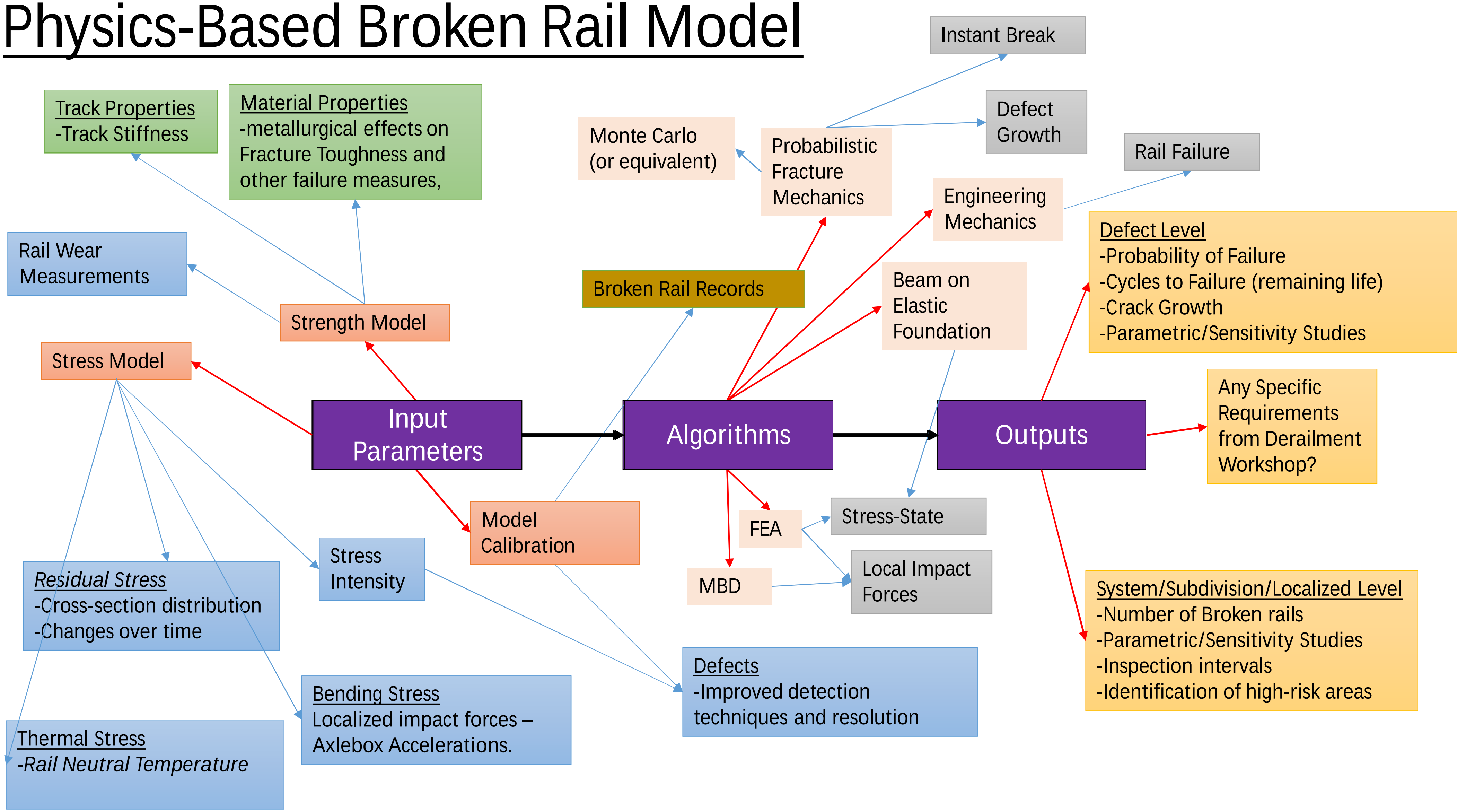
Merge Stress and Strength Workshops

- Feb 16, 2022: Strength-Resilience Model workshop
  - Moderator: David Fletcher, University of Sheffield
- Feb 17, 2022: Stress Modeling workshop
  - Moderator: Yan Liu, National Research Council Canada
- June 14, 2022: Rail Resilience Workshop
  - Moderator: Chris Ladubec, National Research Council Canada

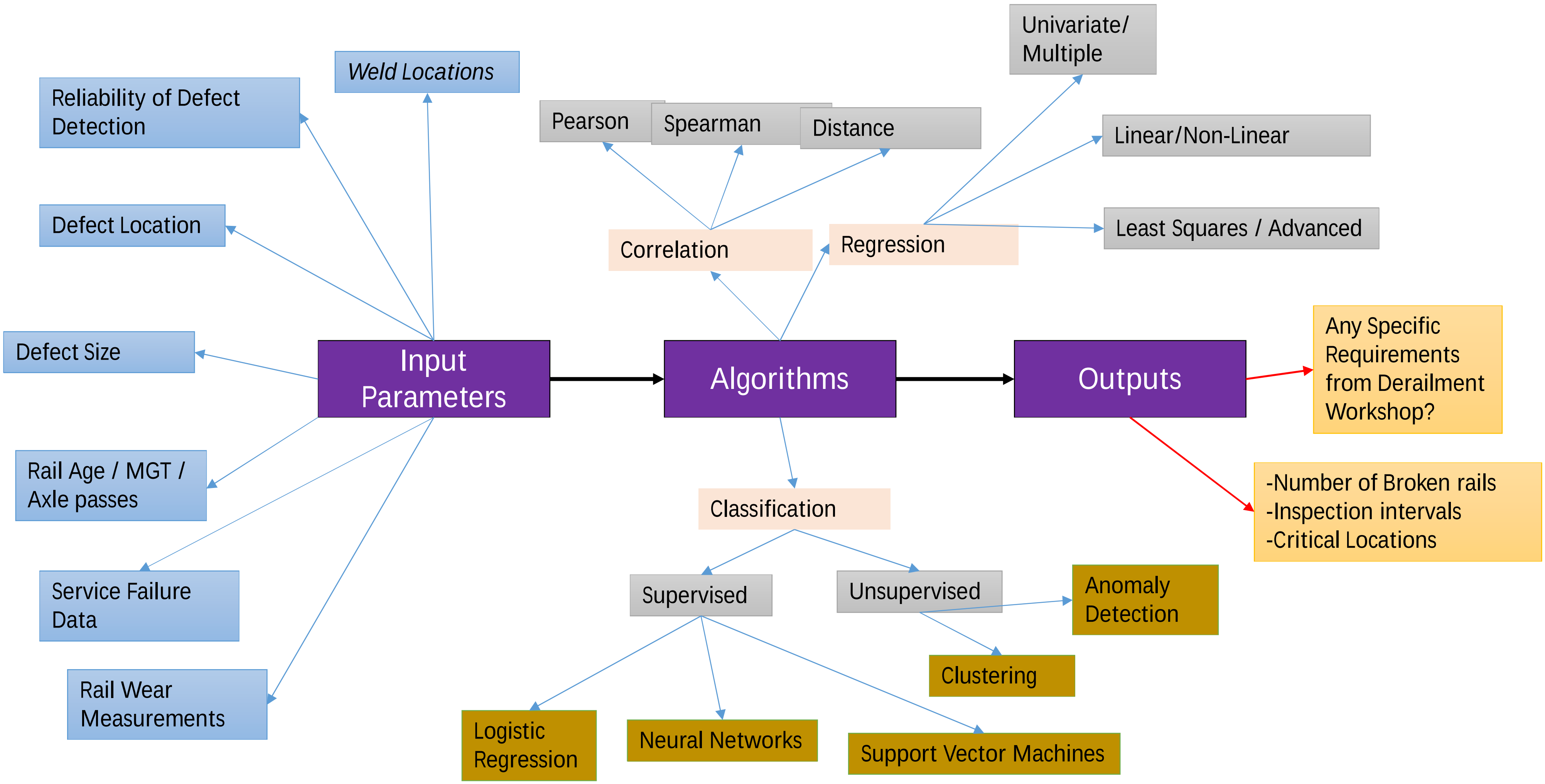
Physics-Based Broken Rail Model Concept



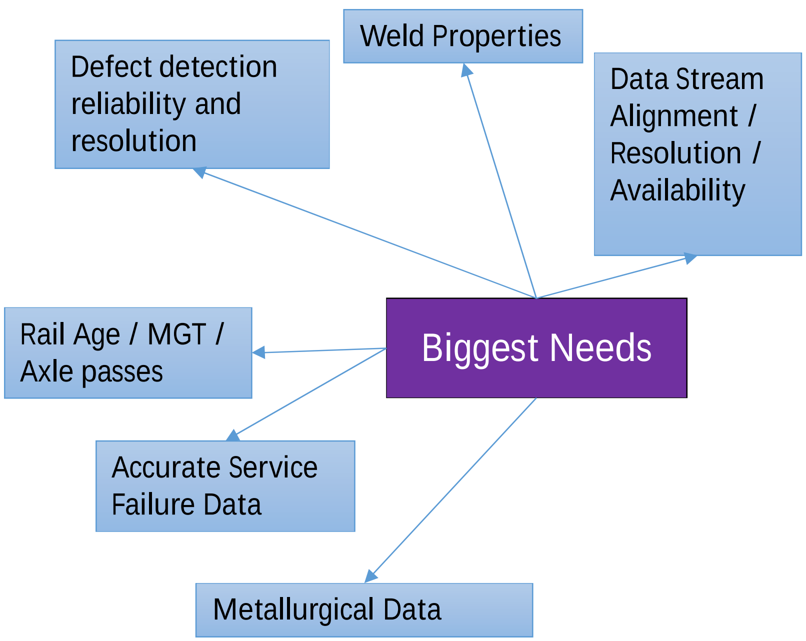
Physics-Based Broken Rail Model



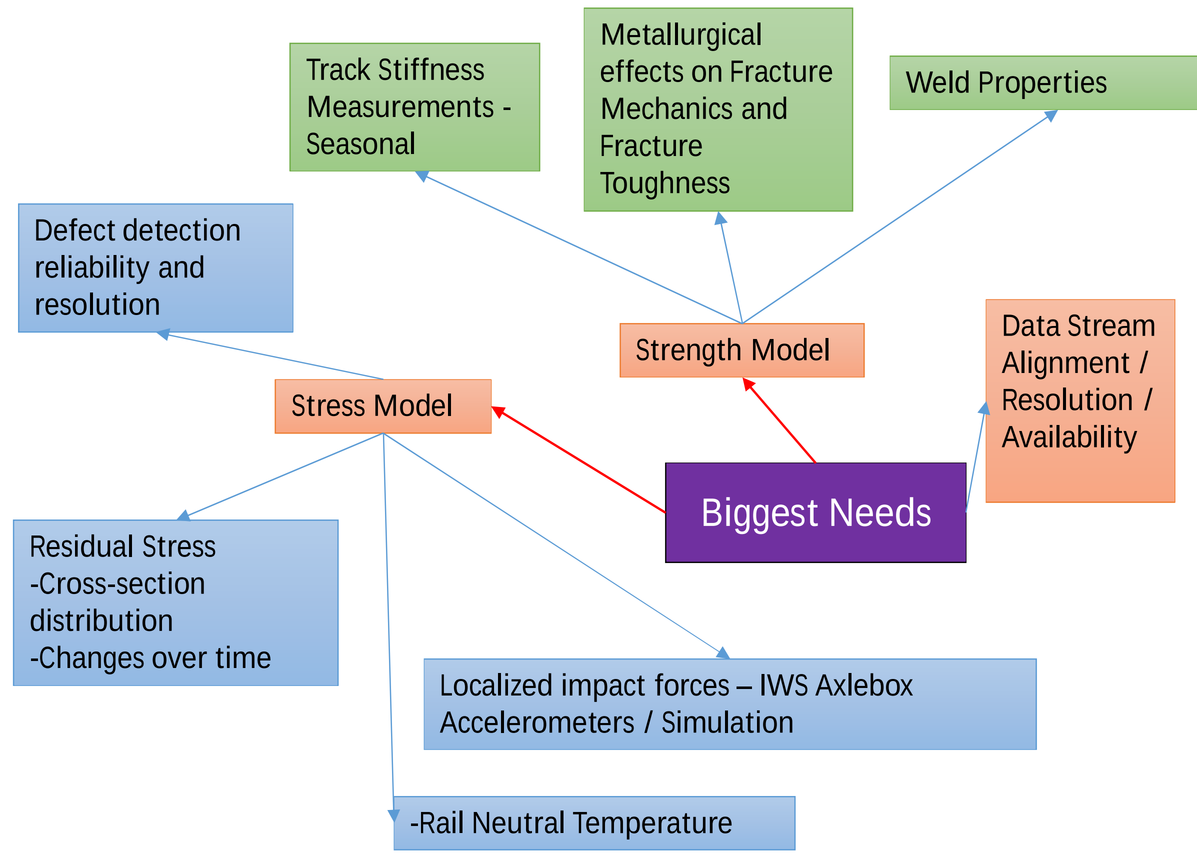
Data-Driven Broken Rail Model



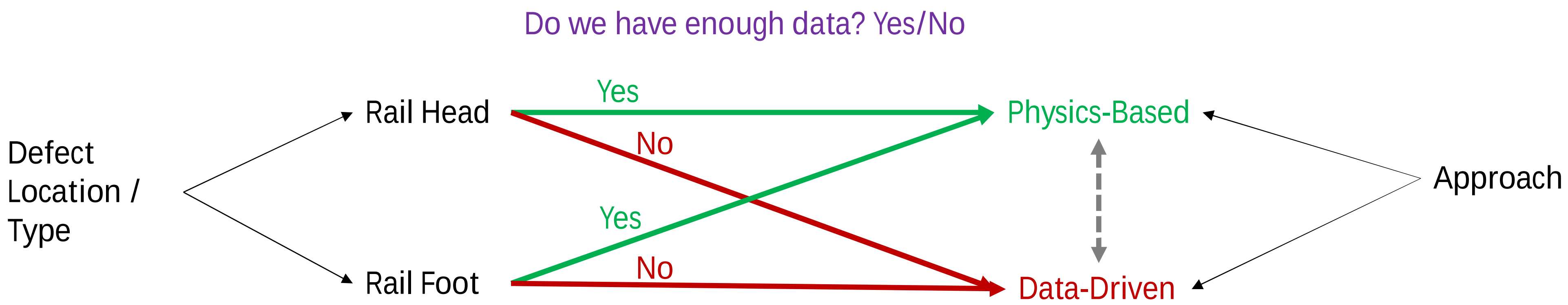
Data-Driven



Physics-Based



Defect Location and Model Approach



Key Areas for Future Research

- Residual Stress
- Rail Neutral Temperature
- Defect detection – improved reliability and resolution – head vs. foot defects
- Better alignment, availability and resolution of data streams
- Track stiffness measurements
- Better understanding of localized eimpact forces – IWS/Axlebox Accelerometer/FEA/MBD

Broken Rail and Derailment Modeling

Eric Magel – National Research Council, Canada

Broken Rails Modeling - Approaches

- Statistics Based
- Physics Based
- Agent Based

Physics-Based Broken Rail Prediction

- According to linear elastic fracture mechanics, fracture may occur when the stress intensity factor (K_I) exceeds the fracture toughness (K_{IC}):
- $K_I \geq K_{IC}$
- The stress intensity factor is calculated as:.
  - $K_I = \frac{2}{\pi} M_1(a) M_S\left(\frac{b}{a}\right)(\sigma_R + \sigma_T + M_G(a)\sigma_B)\sqrt{\pi a}$ * or
  - $K_I = (\sigma_\mathbf{t} + \sigma_\mathbf{r} + \sigma_\boldsymbol{w})\sqrt{\pi a}$ g **
- The fracture toughness is calculated as:
  - $K_{IC} = 1000(0.0013\,T^2 + 0.1541\,T + 36.33)$ ***
- Where a and b represent the semi-major and semi-minor axes of the elliptical defect; M_1, M_S and M_G are constants to account for the finite dimensions of the rail, the defect not having a circular shape and stress gradients in the head of the rail, respectively; σ_B, σ_R and σ_T are bending, residual and thermal stresses in the rail, respectively; σ_t is thermal stress, σ_r is residual stress, σ_w is stress from wheel loads and g is factor describing the geometries; T is the temperature of the rail.

* Jeong, D.Y., Tang, Y.H. and Orringer, O., "Estimation of Rail Wear Limits Based on Rail Strength Investigations", Federal Railway Administration Report
** Tornay, H., Shu, X. and Rakoczy, P., "The effect of high impact wheel loads on rail fracture from transverse defects", 11th International Heavy Haul Association Conference, Cape Town, South Africa, 2017
*** D. Stone, "The Fracture Toughness of Carbon-Steel, Alloy-Steel and Heat-Treated Railway Rails," AAR Report No. R-163, 1974.

Data-Based Broken Rail Prediction

$$E_{SF} = \frac{100e^{u}}{4(1+e^{u})}$$

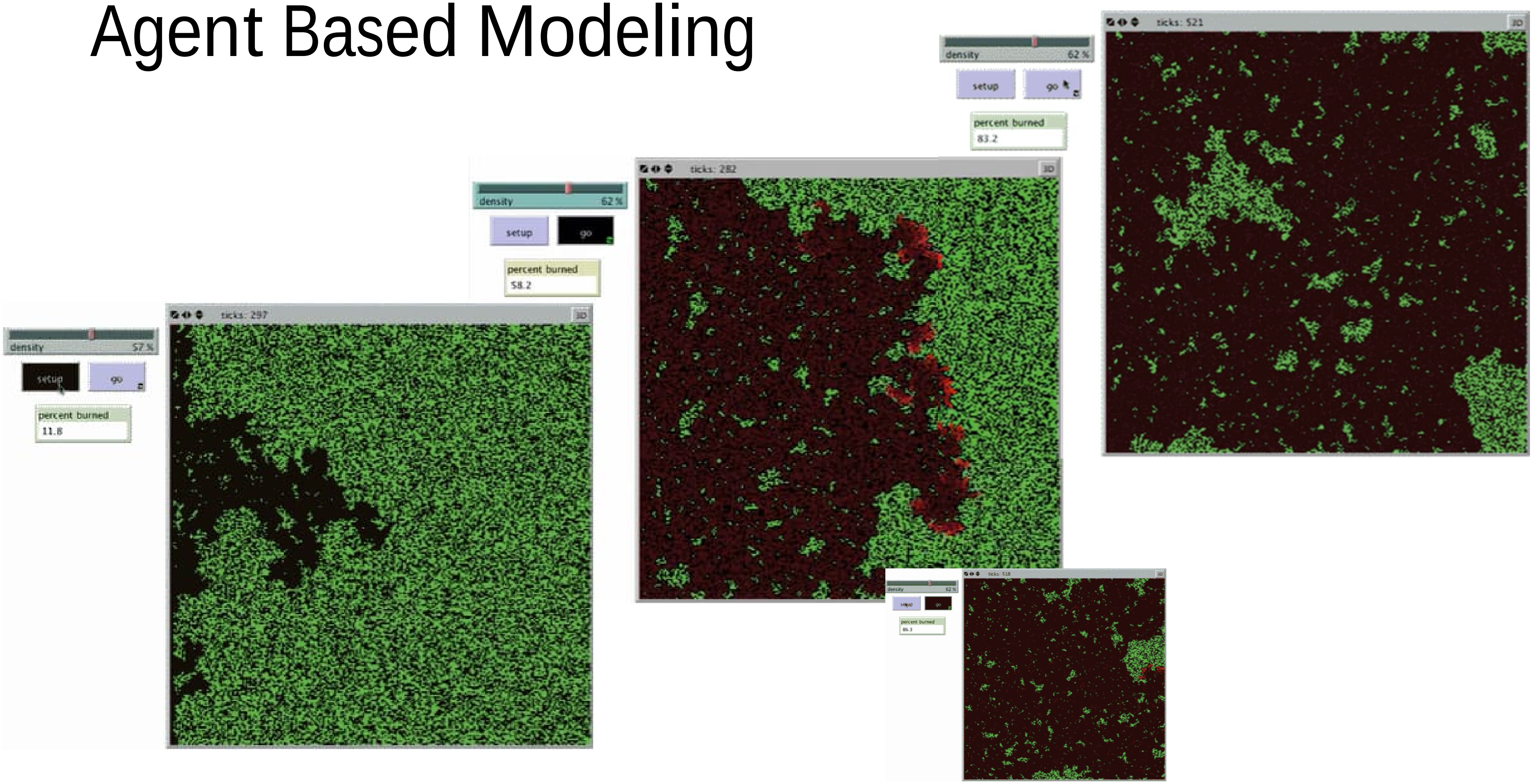
$$U = Z^{*} + C_1 S + C_2 R + C_3 A + C_4 T + C_5 L + C_6 I + C_7 G + C_8 B$$

where

E_{SF} = expected number of broken rails per mile per year on a specific segment
Z^{*} = adjusted model constant
S = rail weight (in pounds per yard)
R = rail type (1 if welded, 0 if bolted)
A = rail age (in years)
T = annual traffic (in million gross tons)
L = weight of car (in tons)
I = presence of an ultrasonic defect (1 if present, 0 otherwise)
G = presence of a bridge within 200 feet of segment (1 if present, 0 otherwise)
B = presence of a geometric defect (1 if present, 0 otherwise)
$C_1, C_2, C_3, \ldots, C_8$ = coefficients

Schafer, D.H. & Barkan, C.P.L., A Prediction Model for Broken Rails and an Analysis of their Economic Impact. Proceedings of the American Railway Engineering and Maintenance-of-Way Association Annual Conference, Salt Lake City, UT, 2008.

Agent Based Modeling



ABM of Broken Rails