SAHAYA CONSULTING

RAIL TRANSIT SEMINAR

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August 26-28, 2025

WRI2025RT SEATTLE, WA

Rail Damage Mechanisms and Remediation

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Outline

- Rail Damage
    - Classifications/Types
    - Remediation
- Sound Transit Case Study
- Experience at Other Transits
- Takeaways

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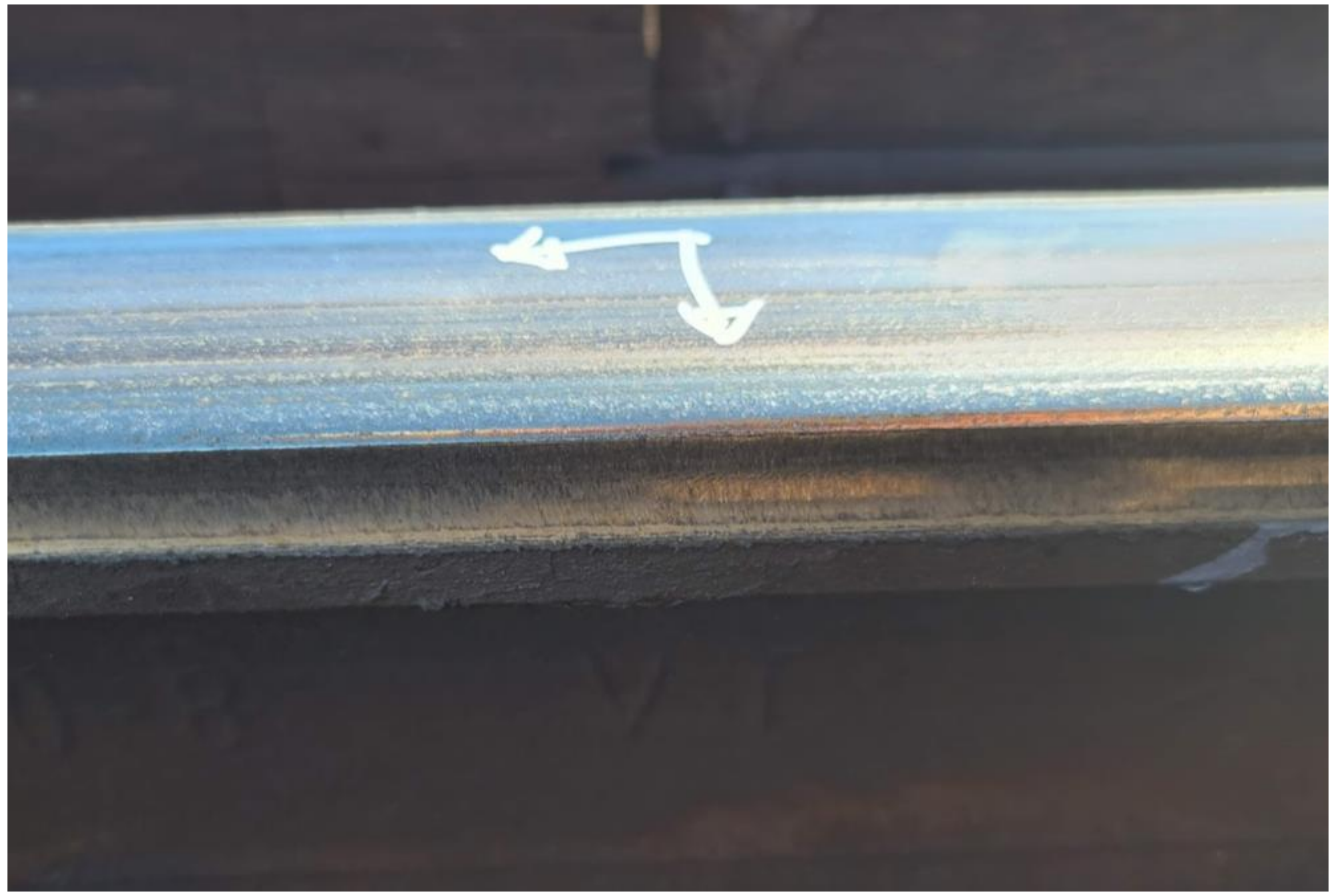
Rail Damage - Classifications

- Understanding and characterizing existing rail damage can help develop and execute rail remediation programs
- Develop and implement solutions such as wheel/rail profile design, maintenance regimes, and friction management



Rail Surface Defect	Monitor & Grind	Monitor, Schedule Milling, weld, repair or Replacement	Replace ASAP
Wheel burns	< 0.060", < 1"	0.060 - 0.125", 1-2"	> 2", > 1/8" deep, broken piece
Squats	<0.060" ,< 1 "	0.060 - 0.125"	> 2", > 1/8" deep, broken piece
Gauge corner shells	<0.1"	0.1 - 0.125"	> 2", > 1/8" deep, broken piece
Head Checks	<0.060"	0.060 - 0.125"	> 1", flaking, spalling severe, wet
Corrugations	<0.060"	0.060 - 0.125" deep	> 1/8" deep
Dipped or low welds	<0.030"	0.030 - 0.125"	> 1/8" deep
Rail end batter	<0.050"	0.050 - 0.125" deep	> 1/8 " deep

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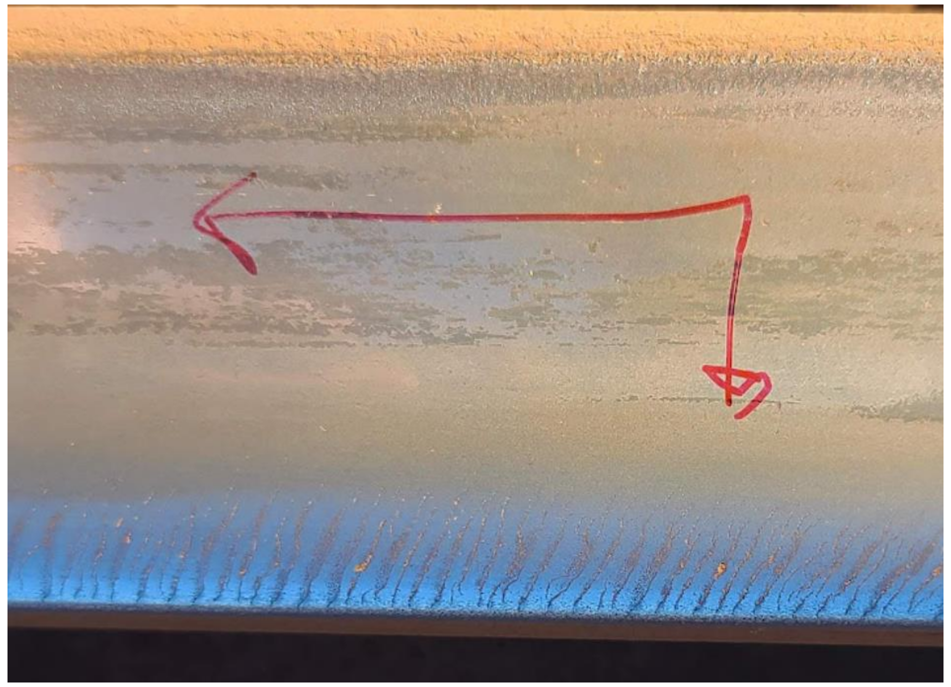
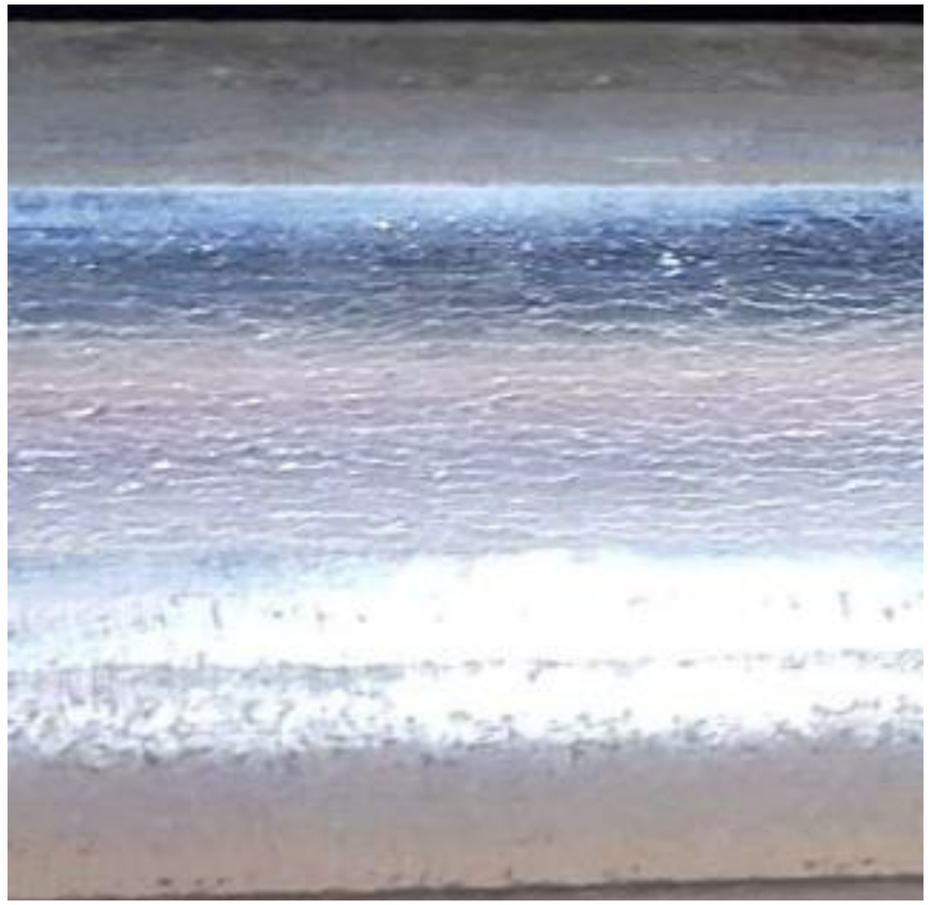
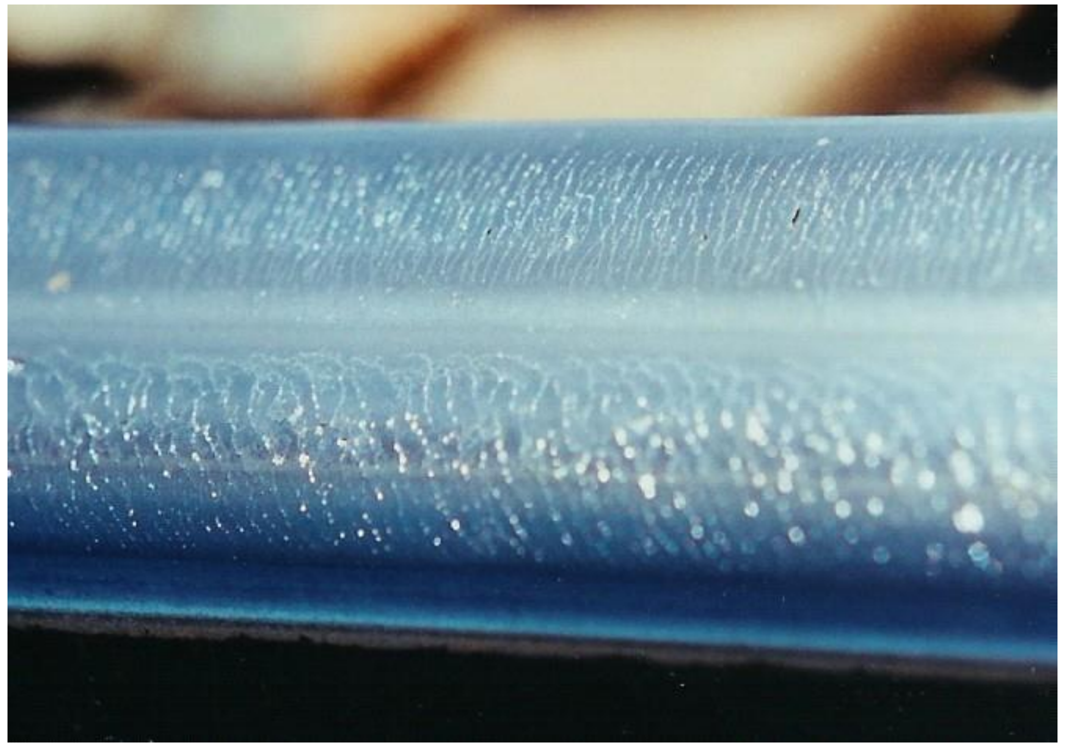
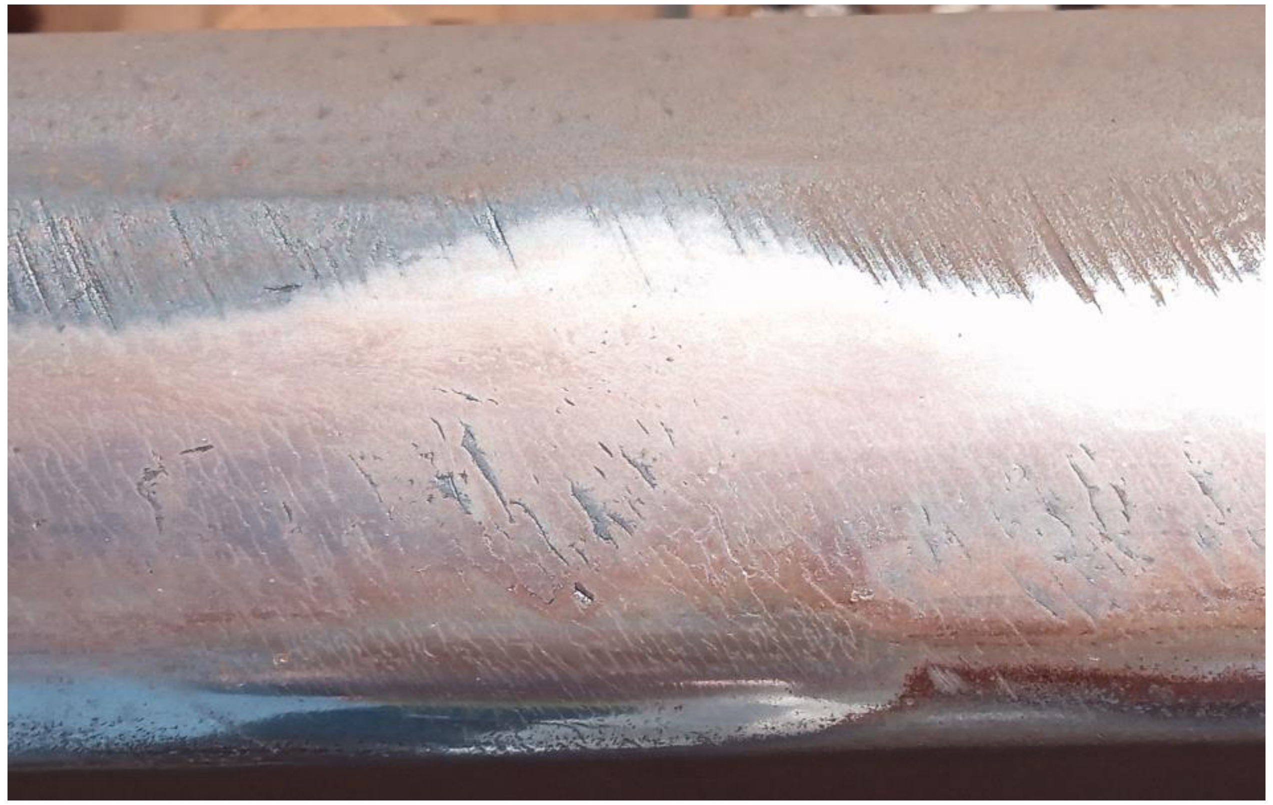
Rail Damage – Head Checks, Gauge corner cracking

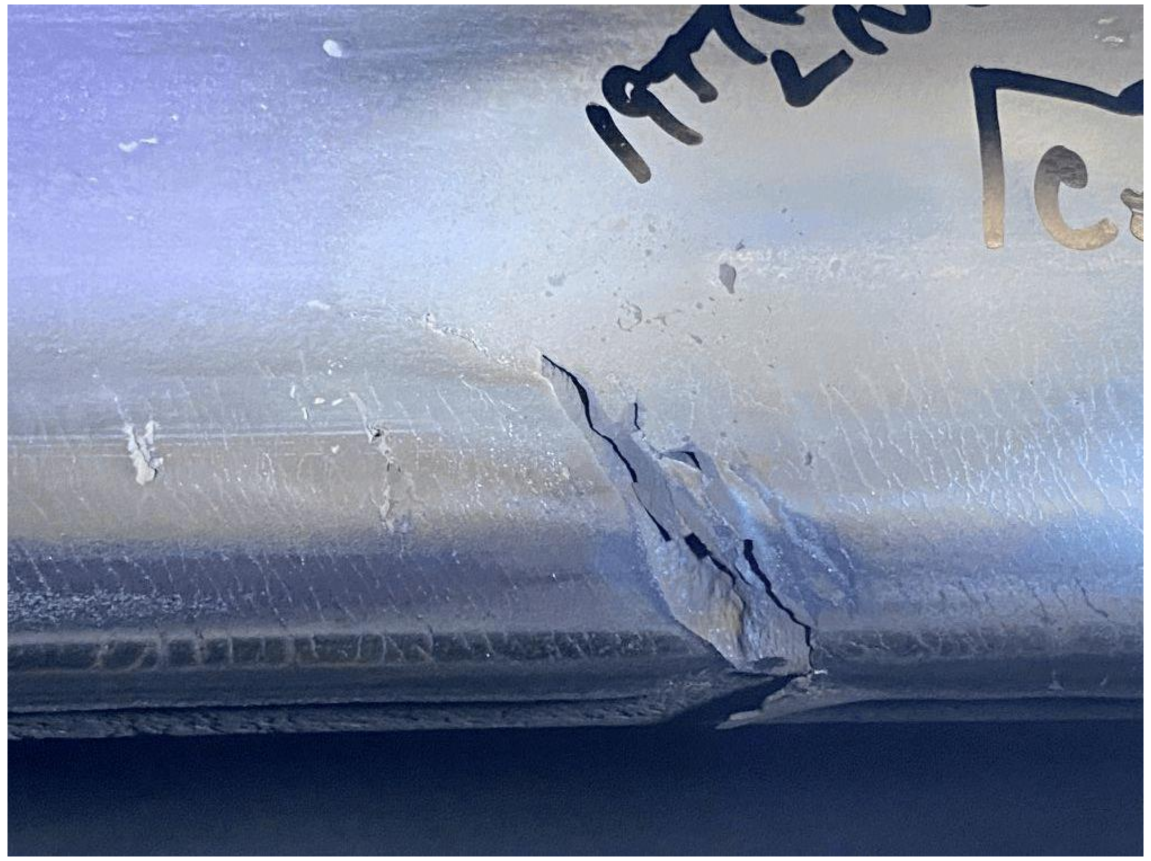






Rail Damage – Shelling and Spalling





Rail Damage - Deep Seated Shells

gauge-corner collapse in a dry environment

gauge-corner collapse in a well-lubricated rail

transverse defect from a shell

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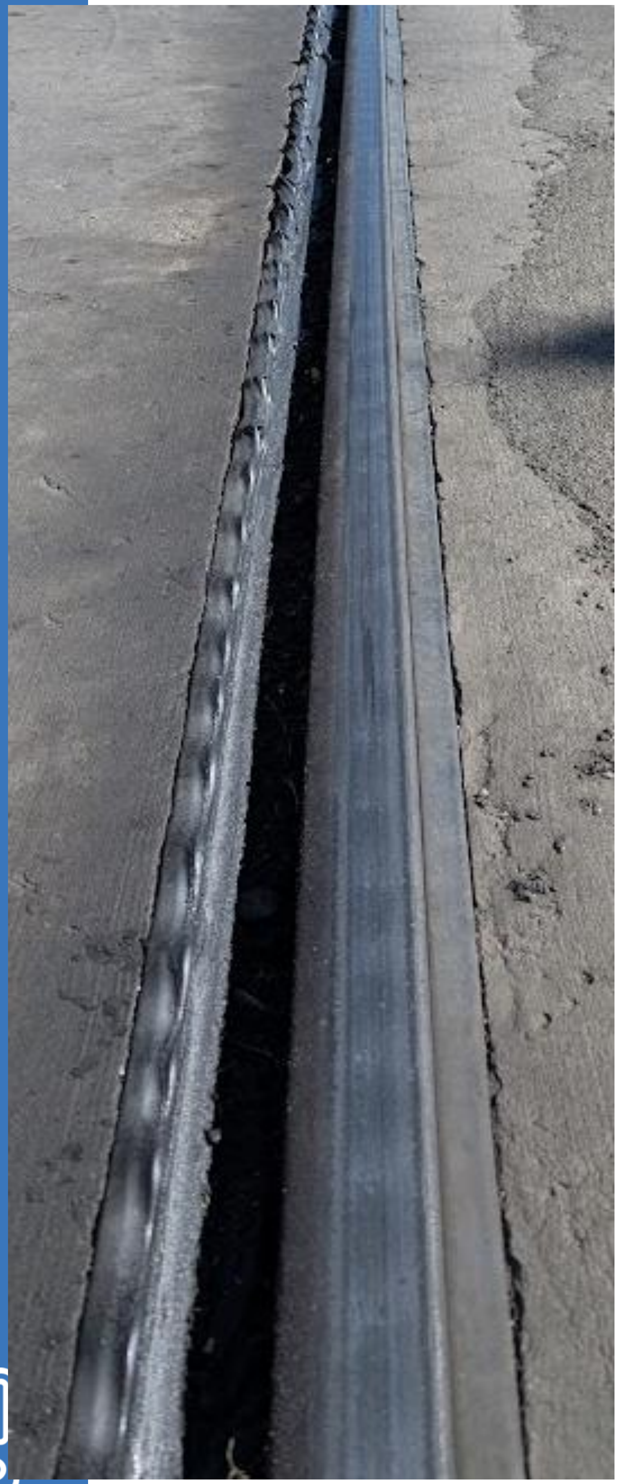
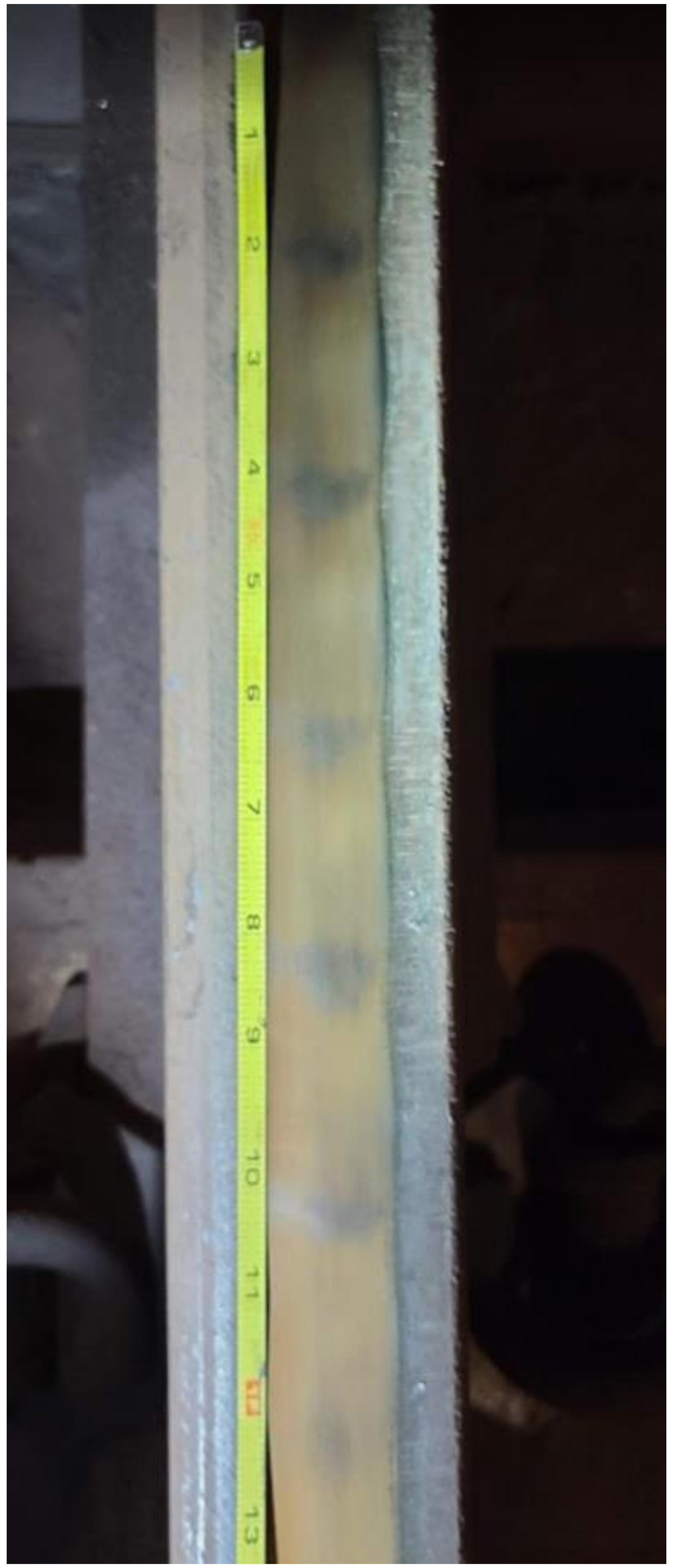
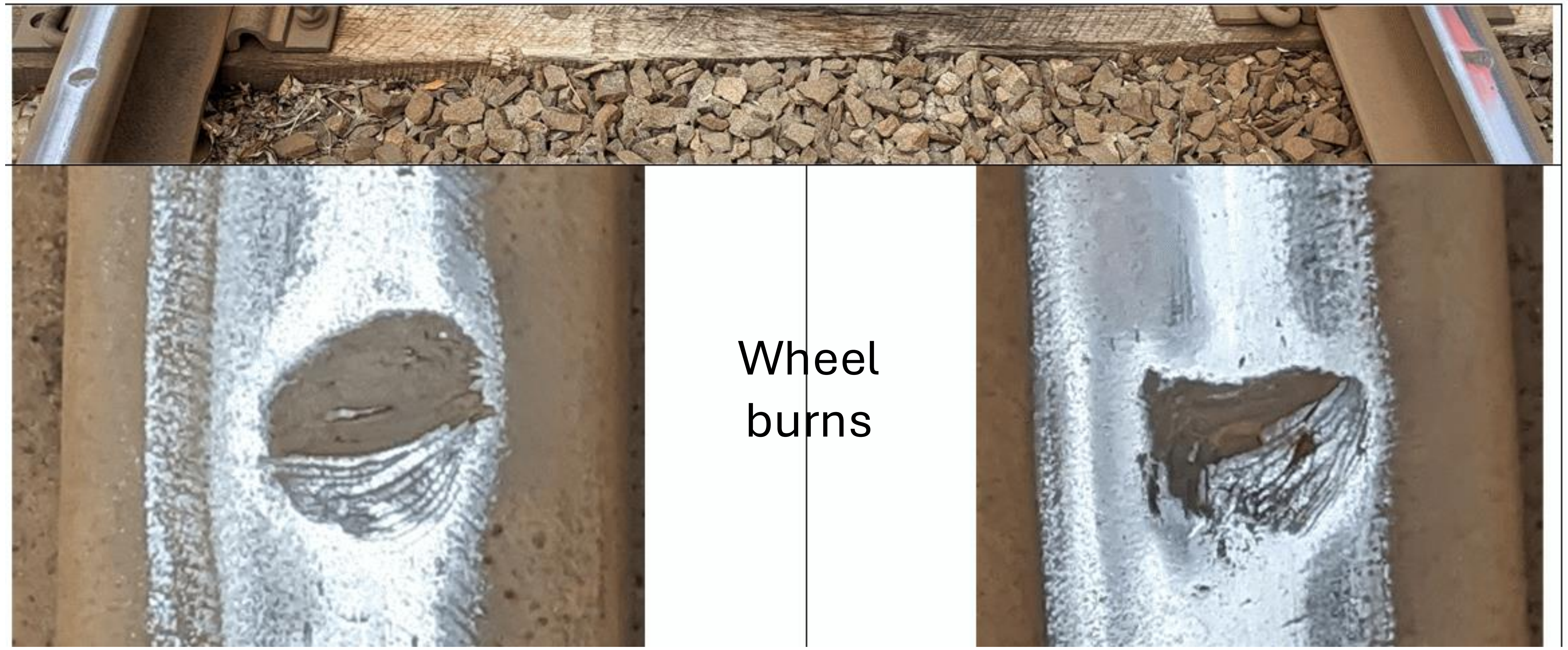
Rail Damage – Rail Wear

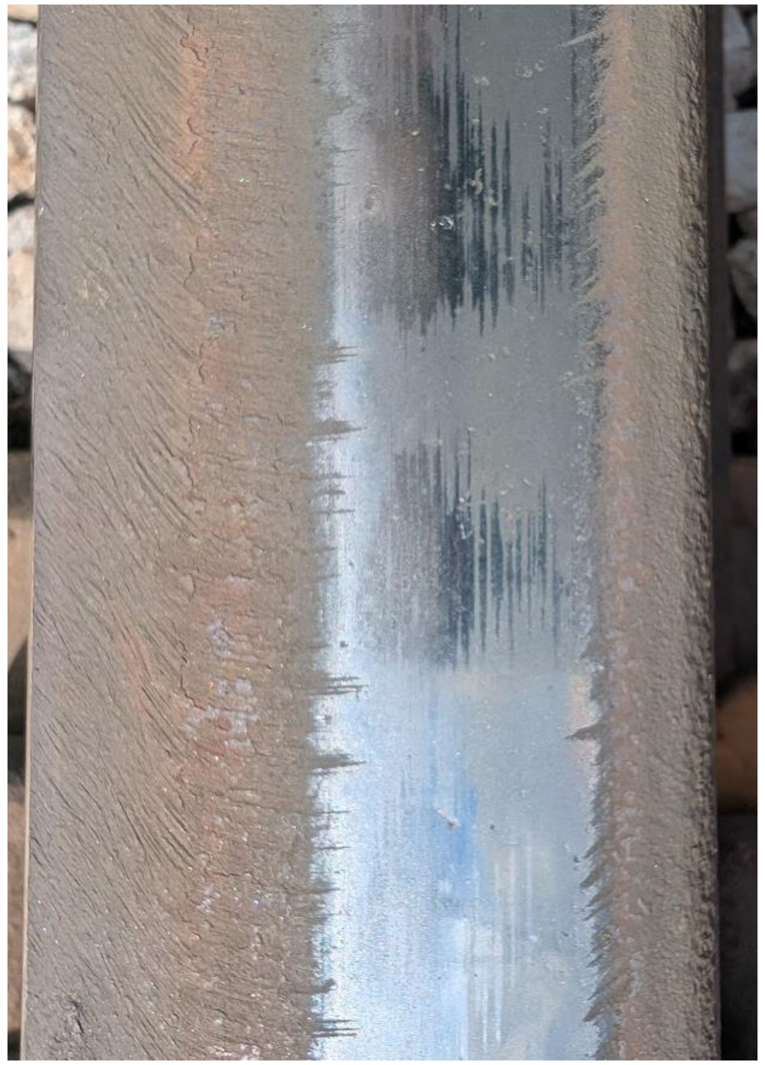
Rail Damage – Corrugation





Rail Damage – Thermal Damage





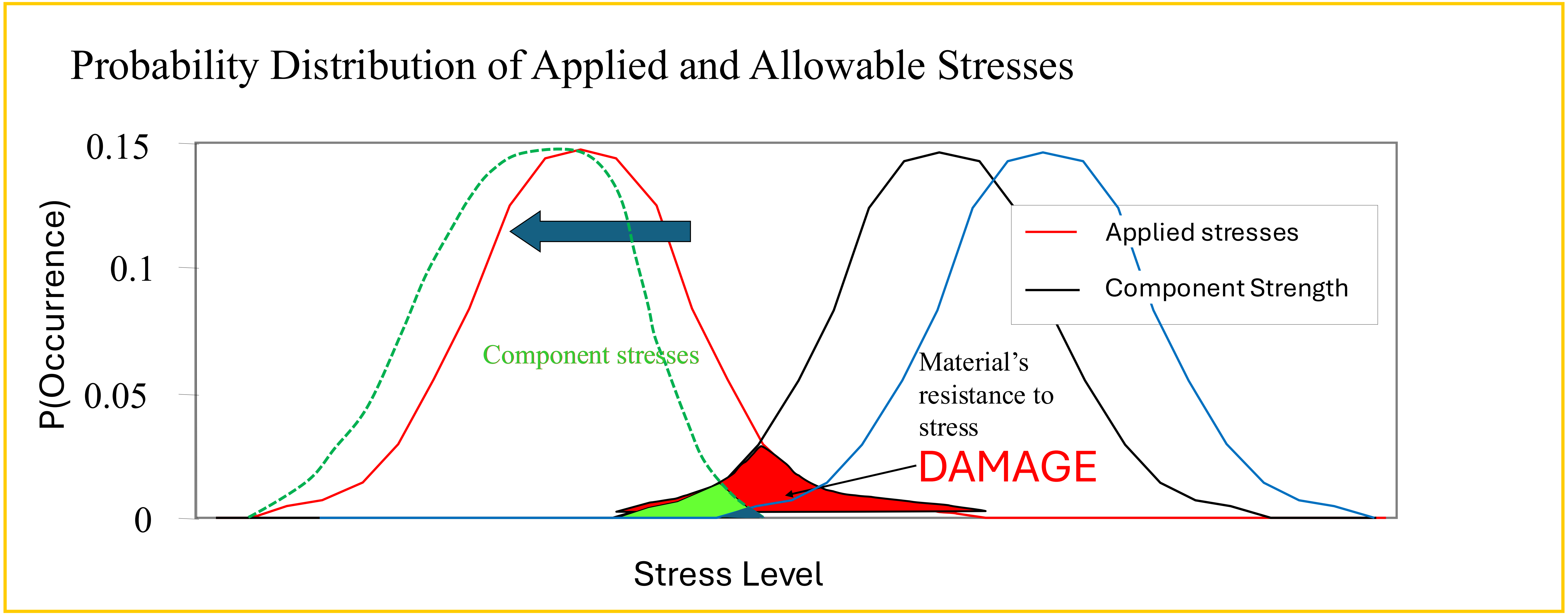
Rail Damage – Joints and Welds

Conditions that promote RCF

Condition	Effect
Mismatched wheel and rail contact geometry	Increase P_0, worsens steering and hence increases traction
High dynamic loads	Increases P_0
Track irregularities	Can increase tractions
Low material yield strength	Reduces k, so increases P_0/k
Misaligned wheelsets	Worsens steering and hence increases traction
Poor lubrication	Increases tractions in sharper curves
Excessive creepage	Brittle martensite that initiates cracks

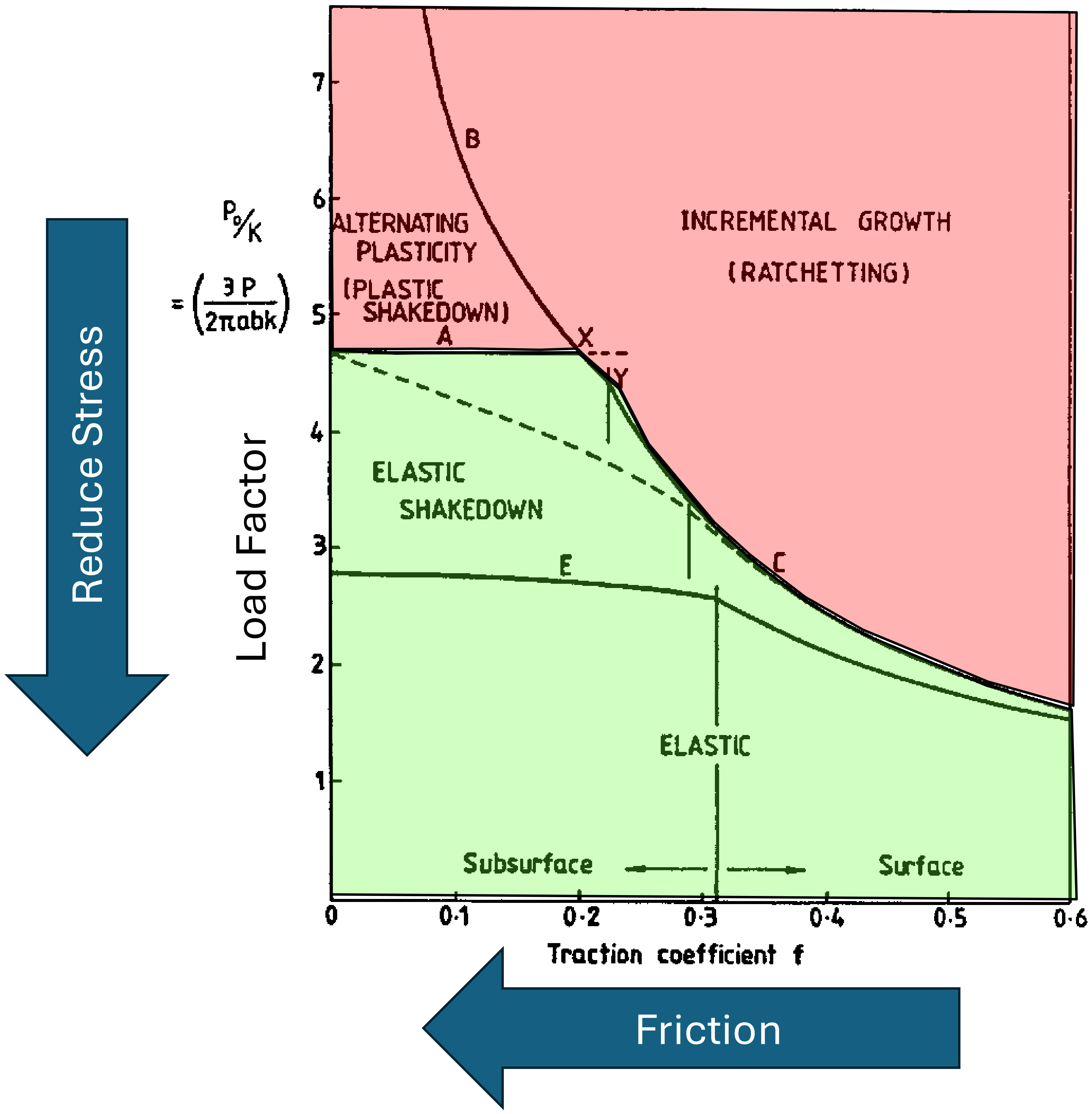
Shakedown diagram points way forward

Stress vs Strength



Shakedown

- Intense forces and creepage at the wheel-rail, especially under suboptimal conditions, lead to various forms of material deterioration
  - E.g., Wear, plastic deformation, cracking



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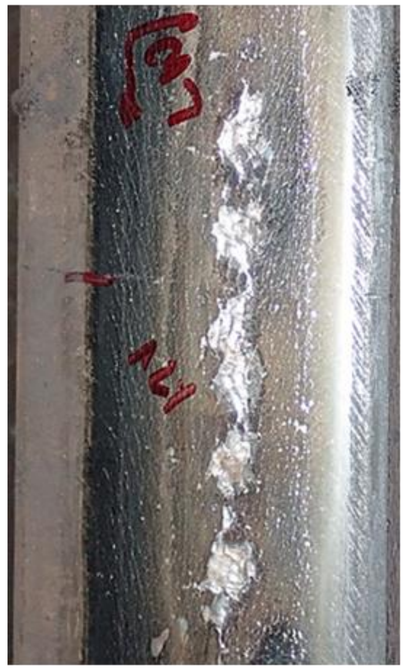
Rail Damage - Remediation

Pre-Grind



Post-Grind 1

13 passes, 8 stone

(28 amps, 4.25mph)

1.9mm crack depth RCF remaining

Pre-Grind

Post-Grind 1

25 passes, 8 stone

clean

Pre-Grind

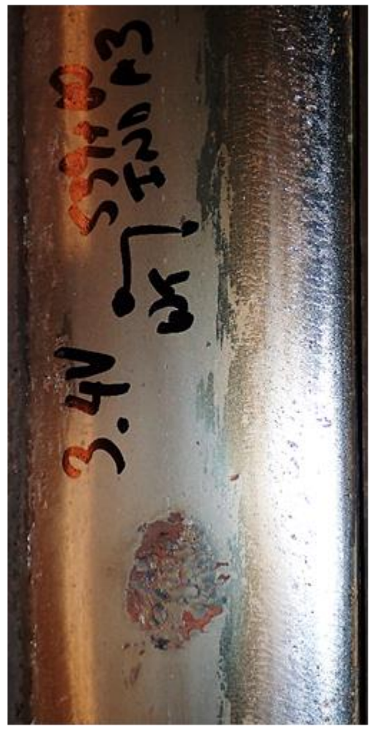
Post-Grind 1

12 passes, 16 stone

(27 amps, 5.0mph)

clean

Pre-Grind



Post-Grind 1

6 passes, 16 stone

(26 amps)

2.5mm crack depth WB, no GCC

Post-Grind 2

7 passes, 8 stone

(26 amps, 4.25mph)

1.1mm crack depth WB, no GCC

Pre-Grind

Post-Grind 1

6 passes, 16 stone

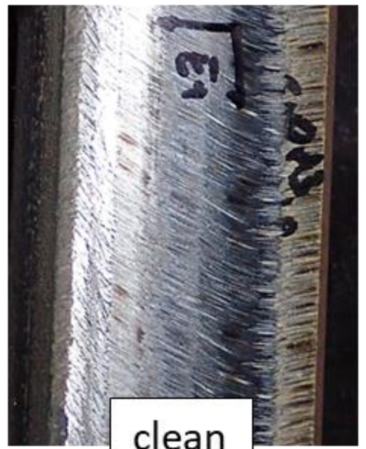
(26 amps)

0.8mm crack depth WB, no GCC

Post-Grind 2

6 passes, 16 stone

(26 amps)



clean

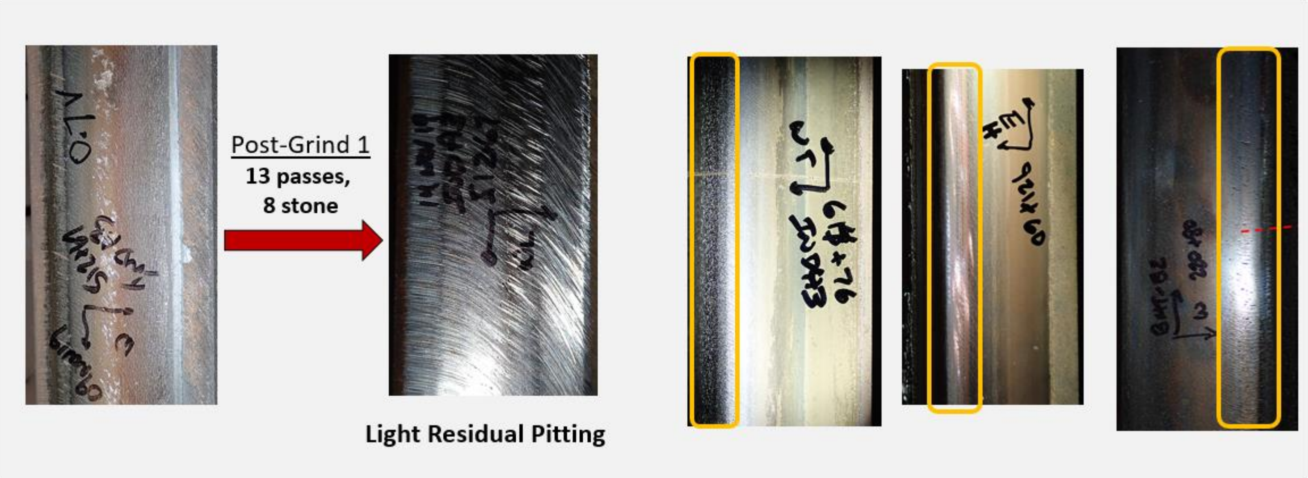
Rail Damage - Remediation

Rolling Contact Fatigue — Mild Case

RCF is a narrow band of cracks that initiate on the rail running surface and propagate into the rail subsurface, and can occur anywhere that there is wheel/rail contact.

Advisory

Grind: 1 cycle

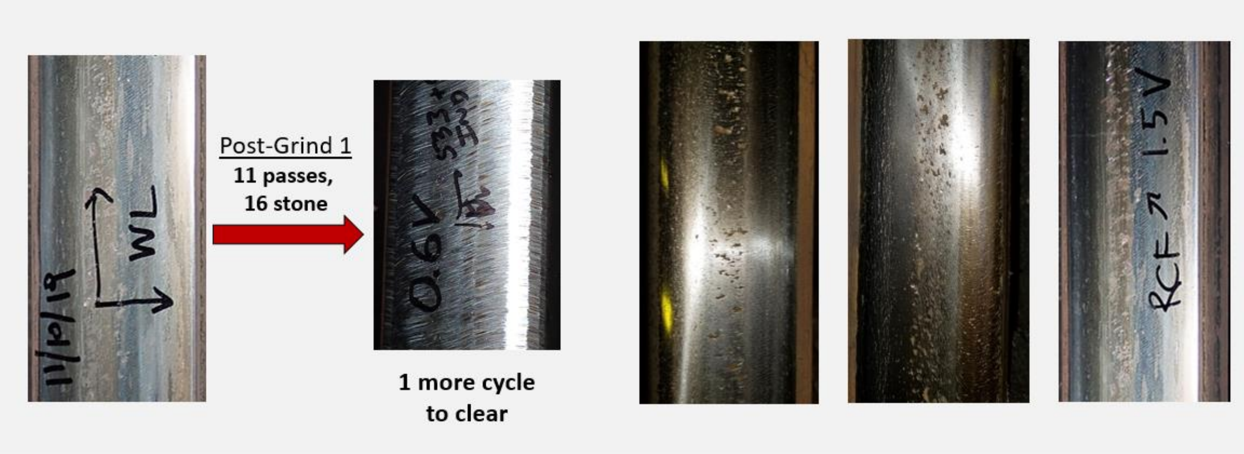


Rolling Contact Fatigue — Moderate Case

RCF is a narrow band of cracks that initiate on the rail running surface and propagate into the rail subsurface, and can occur anywhere that there is wheel/rail contact.

P3

Grind: 1-2 cycles

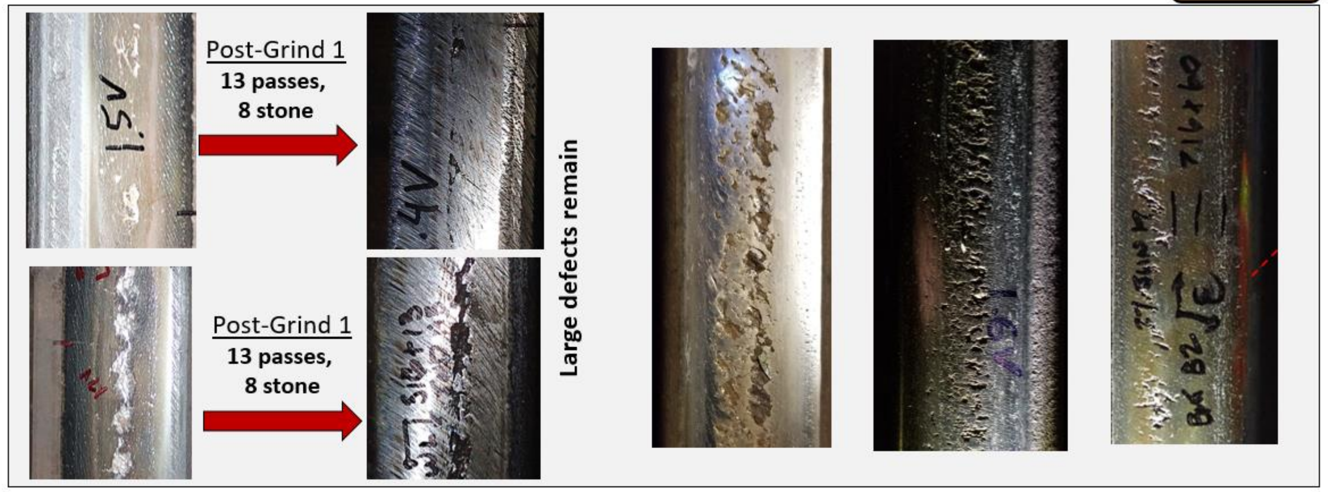


Rolling Contact Fatigue — Heavy Case

RCF is a narrow band of cracks that initiate on the rail running surface and propagate into the rail subsurface, and can occur anywhere that there is wheel/rail contact.

P2

Control:	Remove:
Grind to reduce severity	Grind: 3+ cycles
	Mill



Rolling Contact Fatigue — Severe Case

RCF is a narrow band of cracks that initiate on the rail running surface and propagate into the rail subsurface, and can occur anywhere that there is wheel/rail contact.

P2+

Control:	Remove:
Grind to reduce severity	Plan for Replacement
Mill to reduce severity	

Rail Damage - Remediation

	Mild Case – Advisory	Moderate Case – S3	Heavy Case – S2	Severe Case – S2+ *
Rolling Contact Fatigue (RCF)	Advisory – Schedule 1 grinding cycle to remove	S3 – Schedule 1-2 grinding cycles to remove	S2 – Schedule milling or 3+ grinding cycle to remove, or grind to reduce severity	S2+ – Control with maintenance (milling or grinding) to reduce severity, but plan for replacement to remove defect.
Gage Corner Cracking	Advisory – Schedule 1 grinding cycle to remove	S3 – Schedule 1-2 grinding cycles to remove	S2 – Schedule milling or 3+ grinding cycle to remove, or grind to reduce severity	S2+ – Control with maintenance (milling or grinding) to reduce severity, but plan for replacement to remove defect.
Rail Wheel Burns	Advisory – Schedule 1 grinding cycle to remove	S3 – Schedule 1-2 grinding cycles to remove	S2 – Schedule milling or 3+ grinding cycle to remove, or grind to reduce severity	S2+ – Control with maintenance (milling or grinding) to reduce severity, but plan for replacement to remove defect.
Corrugation	Advisory – Schedule 1 grinding cycle to remove	S3 – Schedule 1-2 grinding cycles to remove	S2 – Schedule milling or 3+ grinding cycle to remove, or grind to reduce severity	S2+ – Control with maintenance (milling or grinding) to reduce severity, but plan for replacement to remove defect.

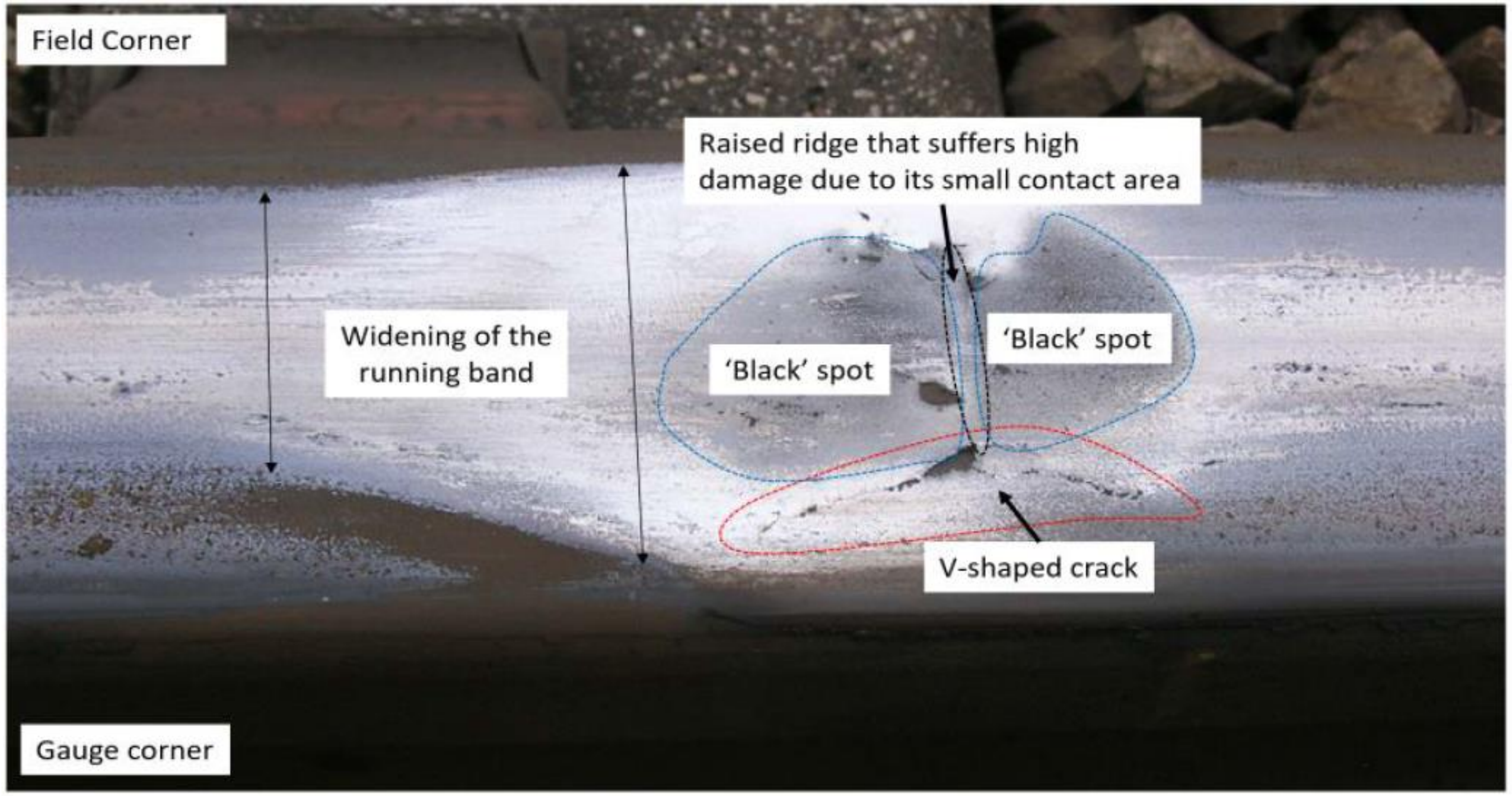
Studs

Studs – Spalls believed to be associated with wheel spin

Treatment: (possibly) traction control, preventive rail grinding, rail milling (for removal), friction management

Rail Damage – Squats and studs

- Appear the same, but the causes and consequences are different



Rail Damage – Squats and Studs

Squats	Studs
• RCF initiated usually at gauge corner	• Wheel slip initiated in middle of running band
• Martensite may be present	• Martensite always present
• 40-100 MGT to develop	• **Can develop within 10 MGT**
• Clear unidirectional plastic deformation (ratcheting) of the surface layer	• Minimal subsurface plastic deformation exists
• Cracks follow sheared inter-granular ferrite	• Cracks wander around and through pearlite grains
	• No consistent crack angle inclination
Cracks initiate at about 20º to rail surface	• Hydraulic entrapment not involved
• Hydraulic entrapment common	• **Not seen to progress to TDs and broken rails**
• Can progress to TD's	• Found in locations with high driving and braking traction
• Found in locations with high driving traction	• Can be found in high, low and tangent rails
• Are most common on the high rail of curves	

The Squat-Type Defect (stud)

- Characteristics:
  - Almost no plastic deformation
  - Formation within 10MGT or less
  - Old and new rails, tangent and curves
  - Presence of WELs
  - Not found in tunnels
- Preventive rail maintenance strategies of limited mitigation success

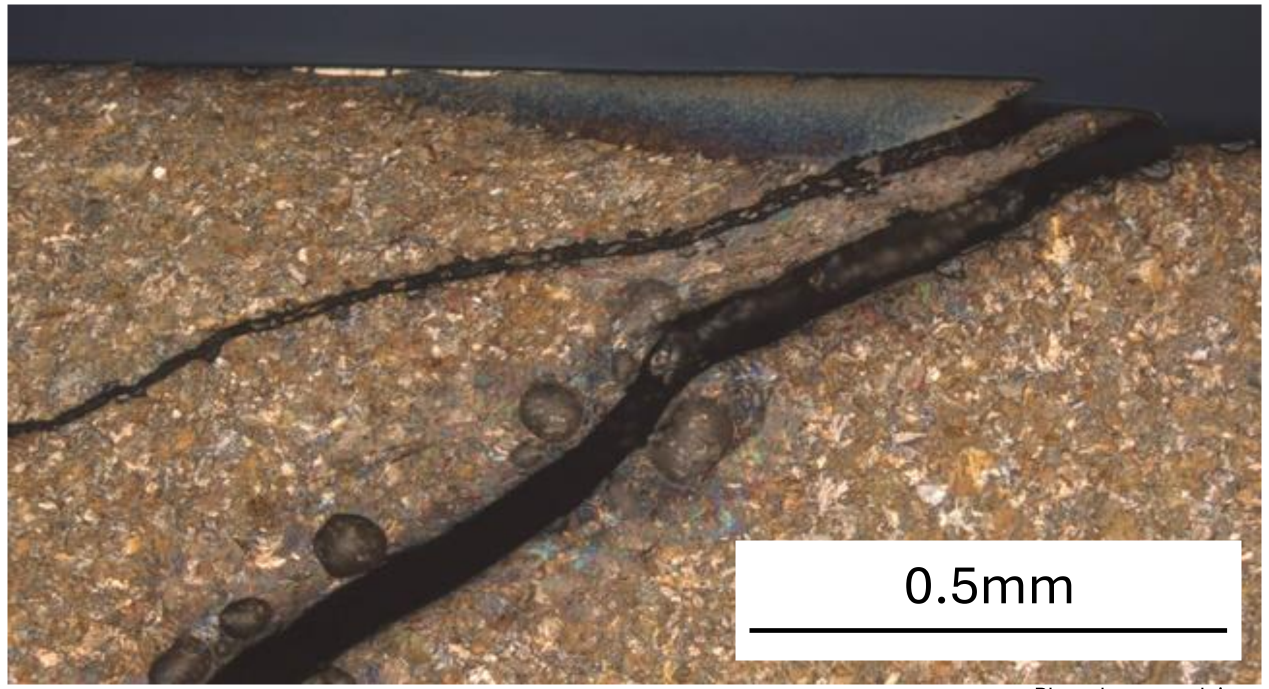


Photo by voestalpine

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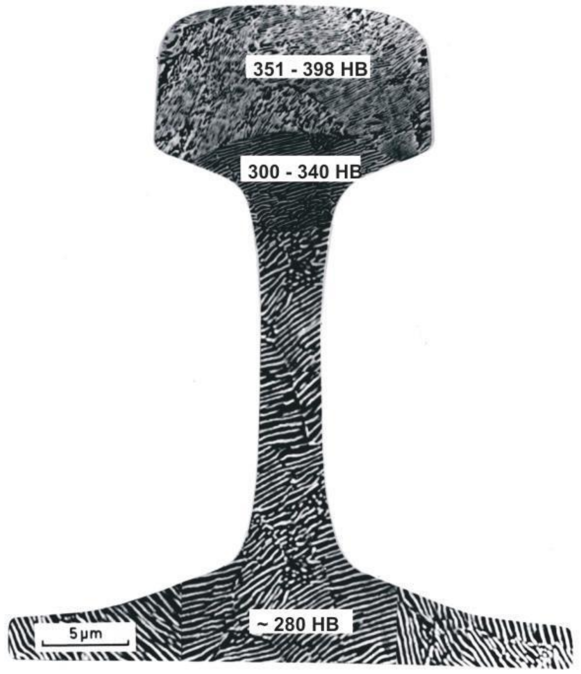
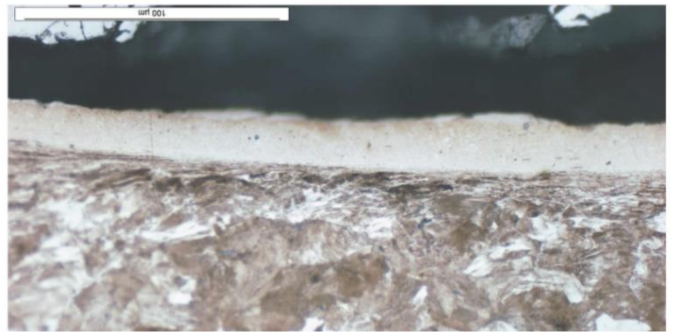
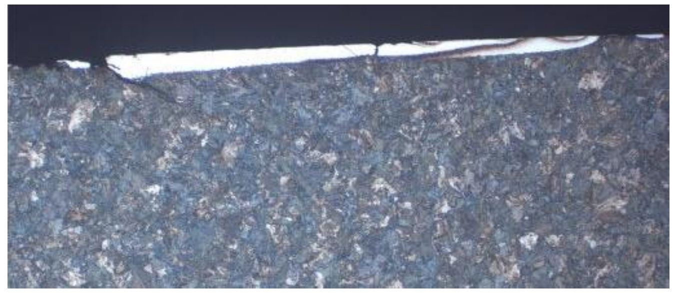
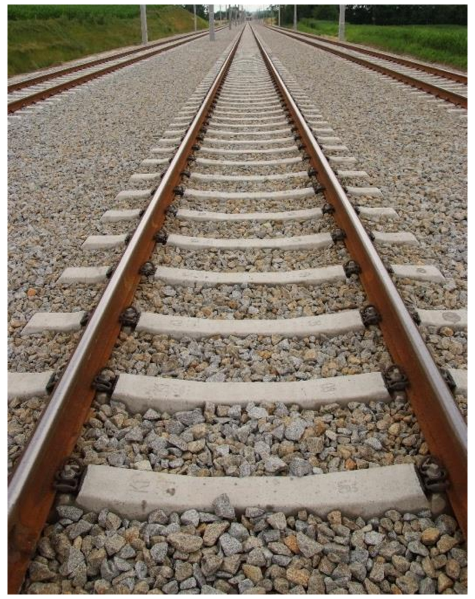
STUDs – contributing factors

- Premium Heat Treat rails
  - Increased hardness, strength, similar toughness
  - Increased wear and RCF resistance
  - Studs form in areas with low rail wear
- Anti-head check profiles
  - Gauge corner undercutting
  - Concentrating contact on TOR
- White Etching Layers
  - Contributing factor but usually wear away
- Traction Effort
  - DC to AC, multiple driven axles
  - Significant increase of traction forces in last 30 years
- System Stiffness
  - High system stiffness will increase dynamic reaction

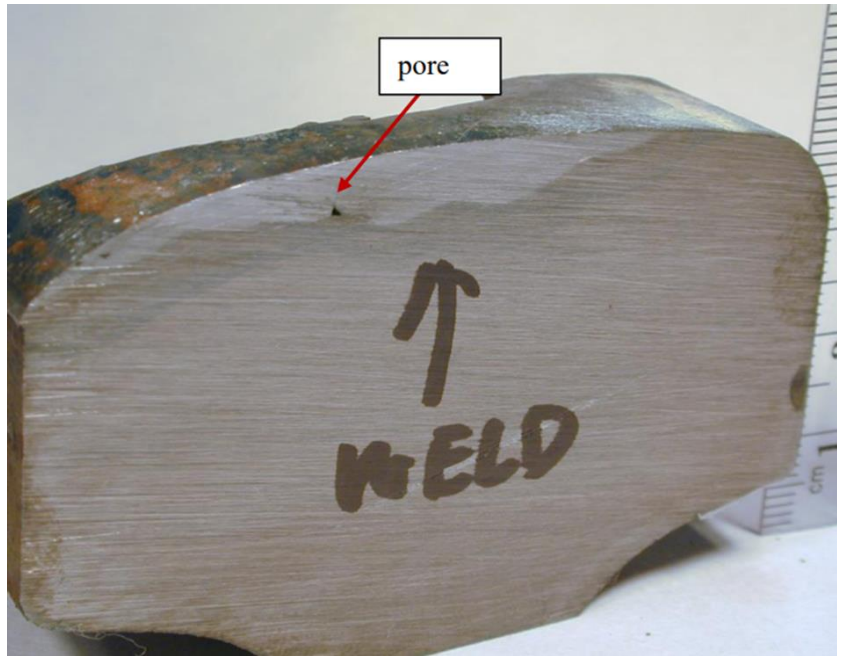








Squats and studs - consequences



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Seattle Sound Transit

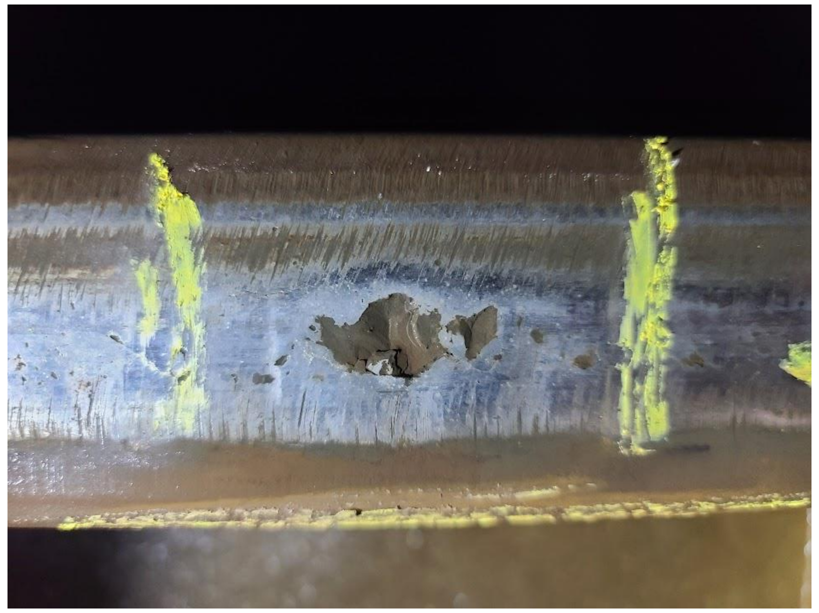
- 5-mile segment of elevated track
  - Includes high speed segment (55 mph)
  - Also seen in other ballasted segments
- Occurs in tangent, curves, and grades
  - First high occurrence area was level, tangent track with corrugation
- Started in small batches and were weld head repaired, eventually ground, milled and/or replaced

Seattle Sound Transit

- Suspected originally that defects could be associated with “bad” rail
- Defects found in almost all ages of rail but since 2018 limited recurrence

Seattle Sound Transit

- Major concern was potential for a rail break and safety concerns
  - Secondary: ride quality and noise
- No evidence that rail breaks had or will occur from these defects
  - Operational impact still exists due to slow orders



Seattle Sound Transit

- Significant effort put into monitoring
  - Routine visual inspections
  - Eddy Current
  - Noise and Vibration
  - Ultrasonic
  - Grinding, Milling, and Rail Replacement
- Still need to understand root cause and potential for safety impacts

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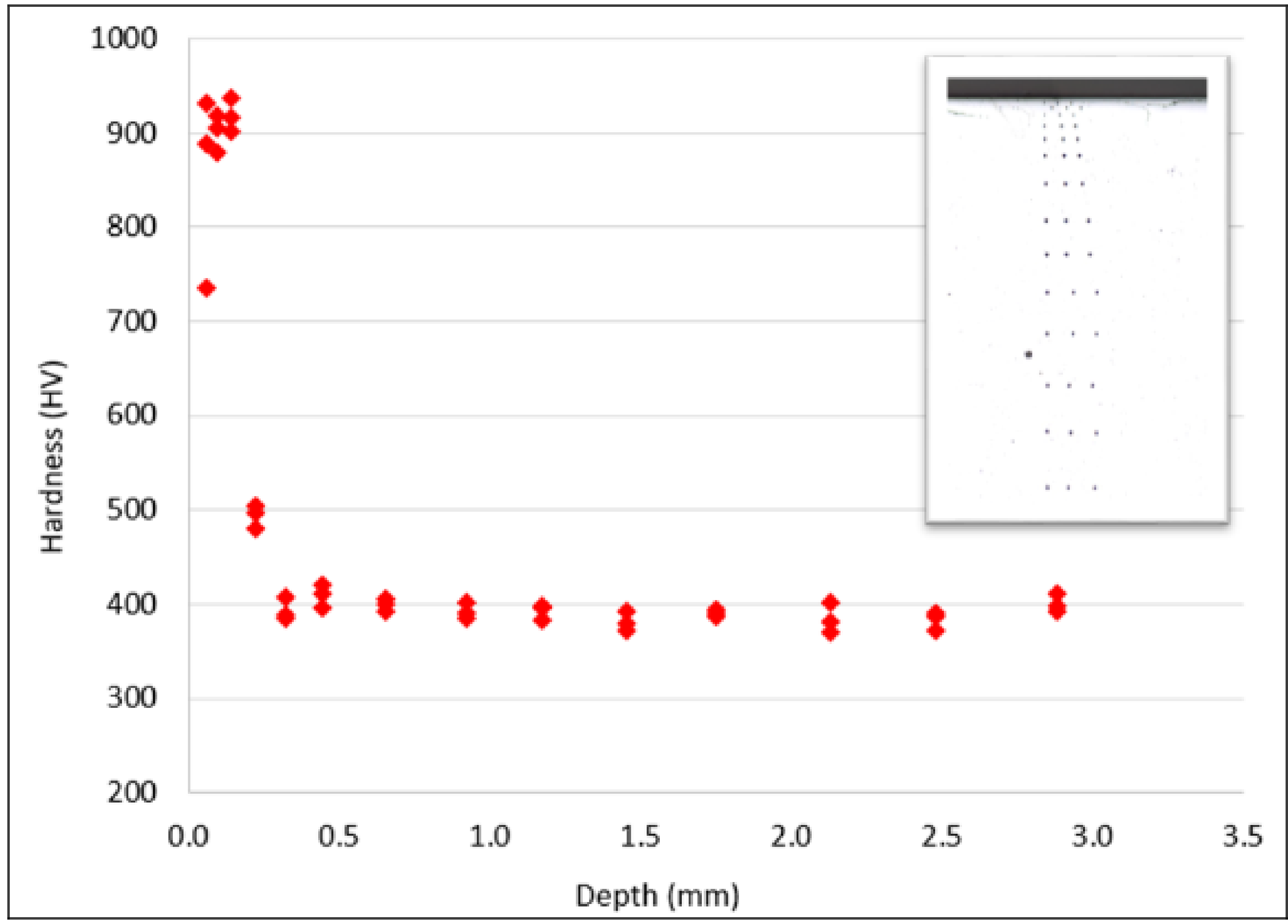
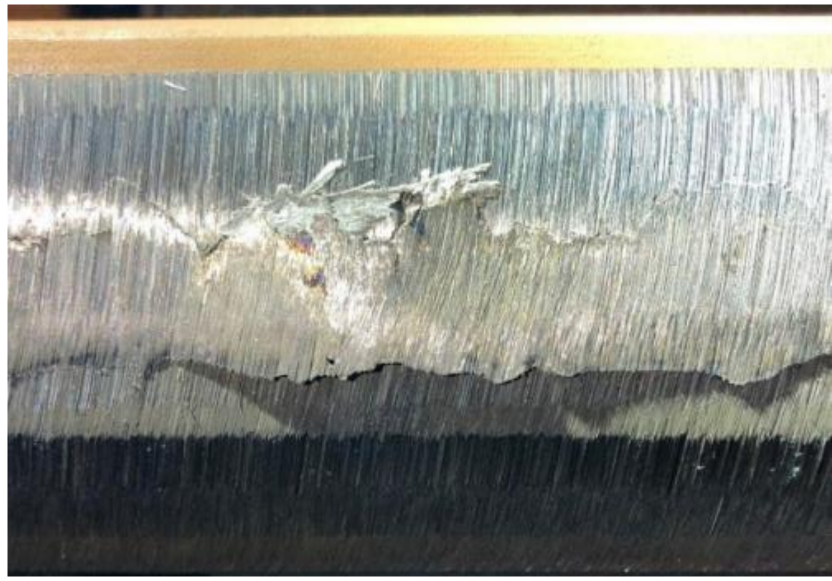
Seattle Sound Transit

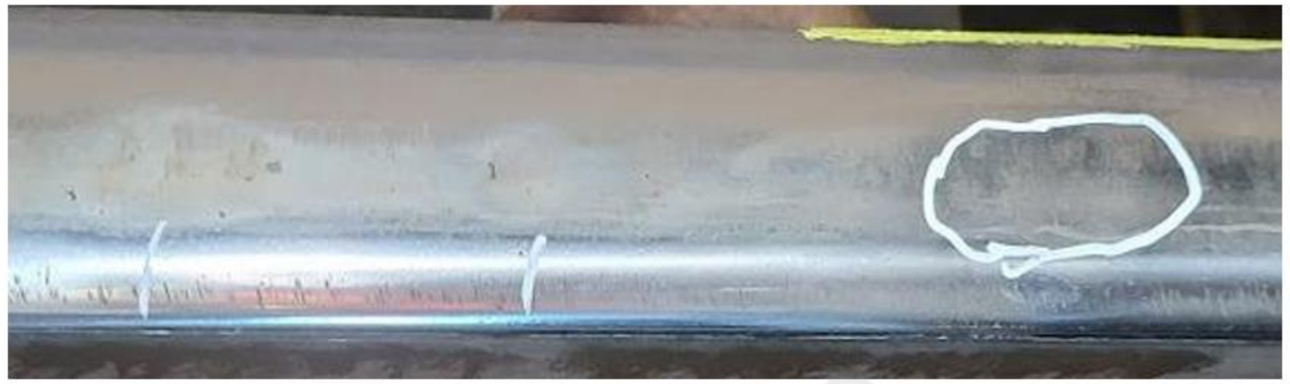
- Metallurgical analysis identified
  - No quality issues with original rail
  - WEL present at all defects
    - Hardness levels as high as 900 Vickers (850 HB)
  - No vertical cracks into rail

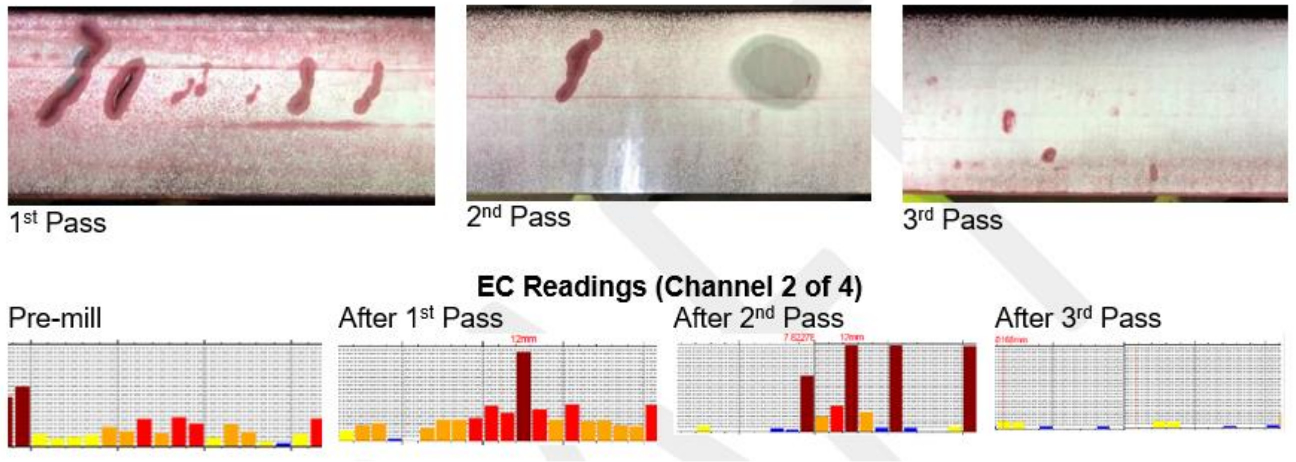


Seattle Sound Transit

- Rail grinding not efficient even at incipient level
    - ‘exposed’ subsurface cracks
- Rail milling required 3+ passes (4mm and more)
    - Severity would get worse before they got better







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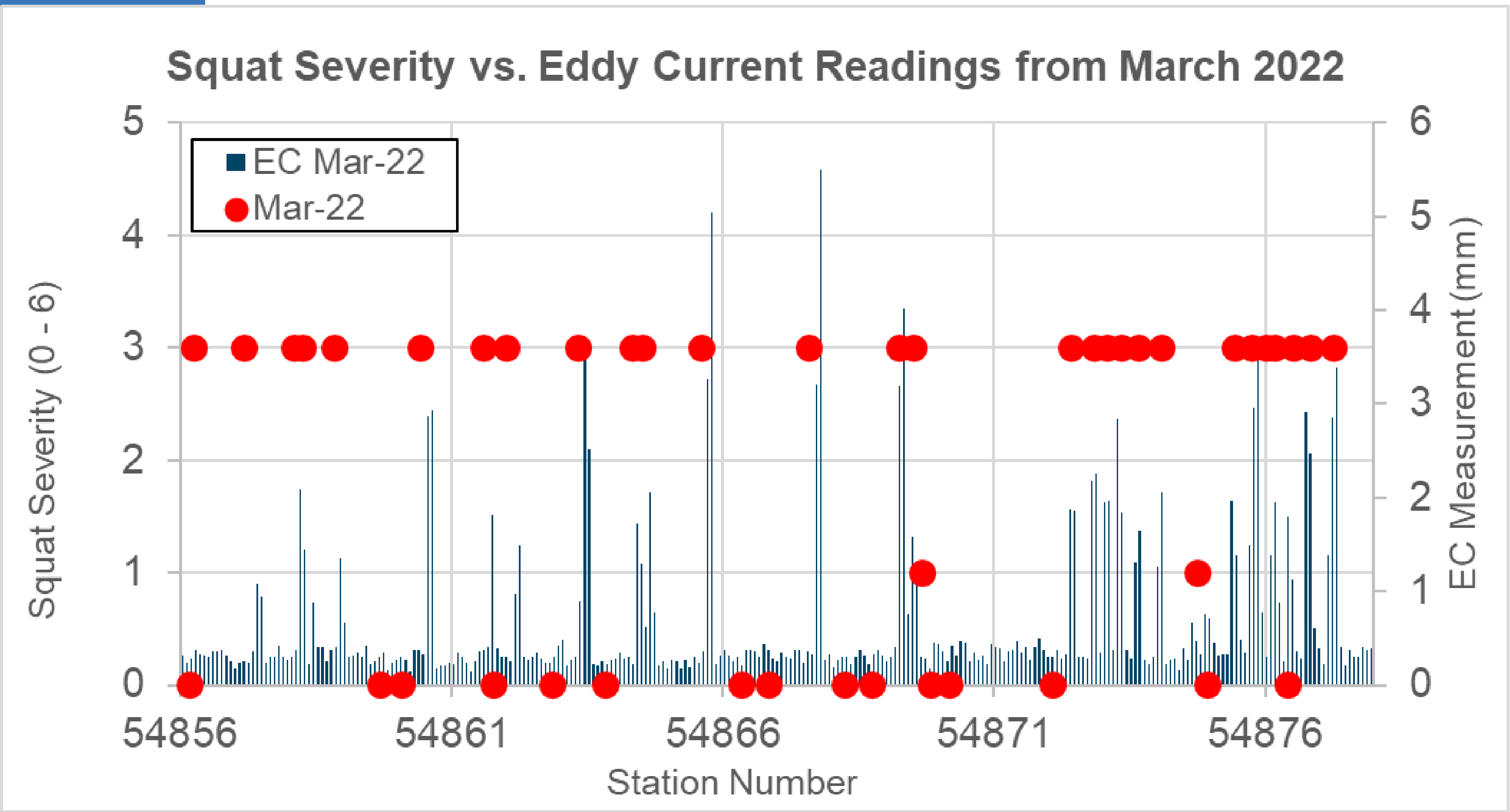
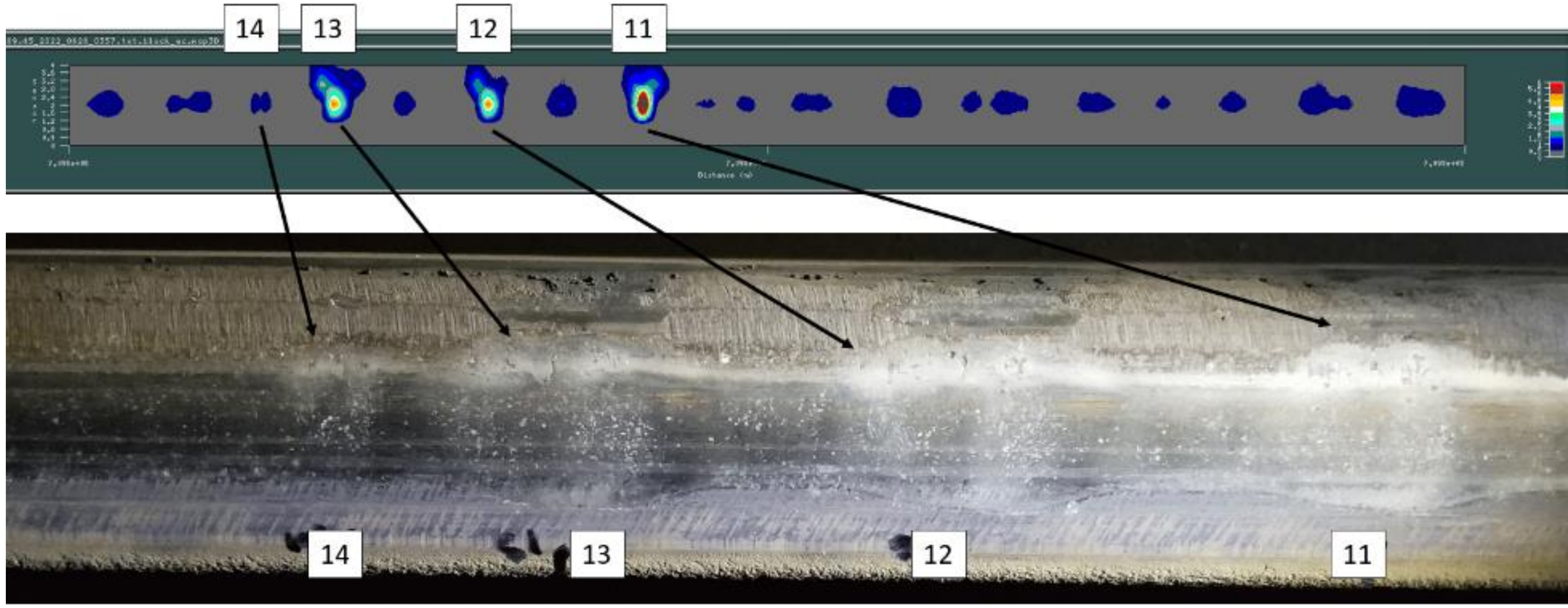
Seattle Sound Transit

- Milled rail after more than 2 years (~15 MGT) had no signs of defects returning
- Replaced rail (c. 2018 and newer) does not have the same level of studs of older rail
- Milled and replaced rail segments have been ground regularly starting in 2018
    - Area with studs had been scheduled for annual grinding

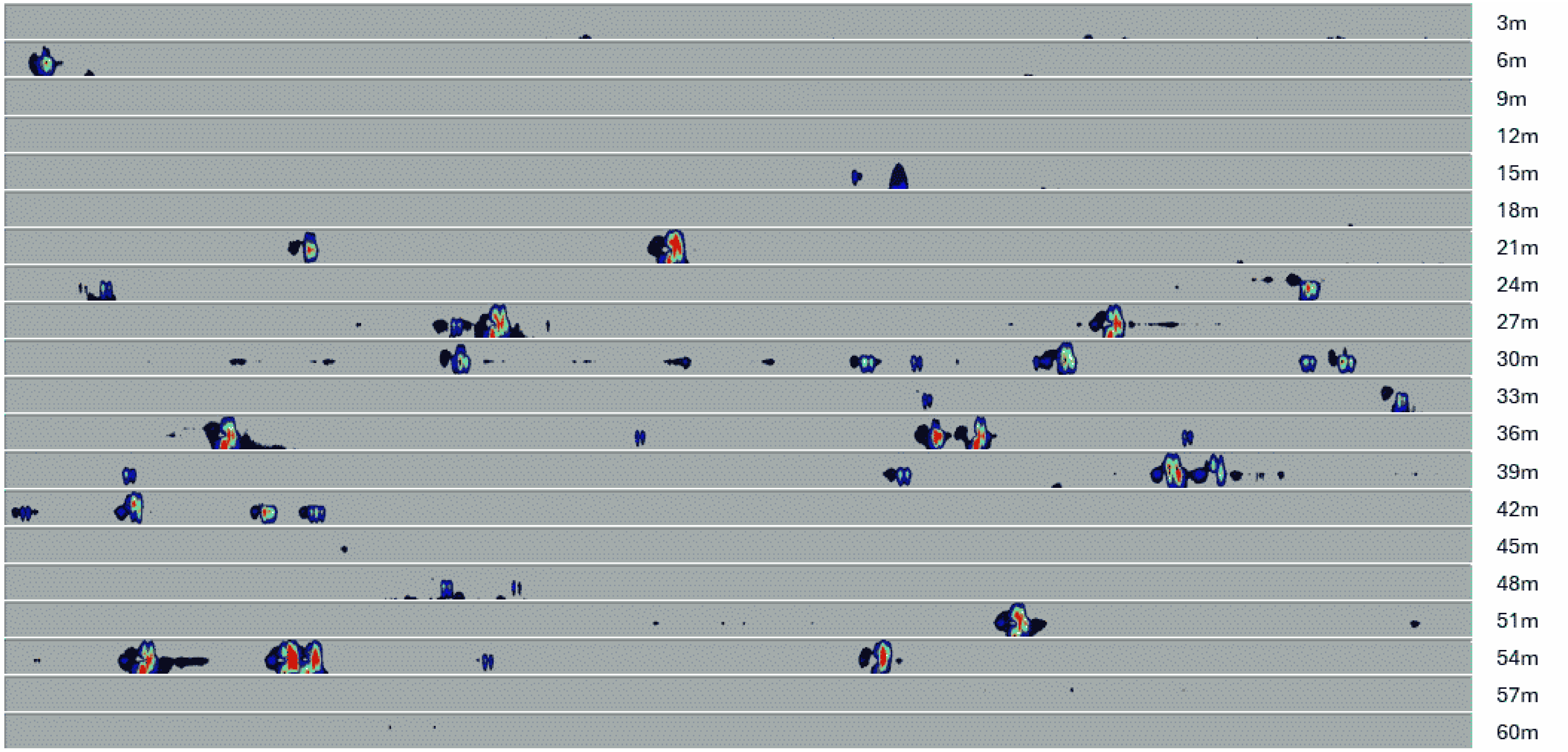
Seattle Sound Transit

- Use of eddy current and ultrasonic inspections show promise for mapping and monitoring existing studs



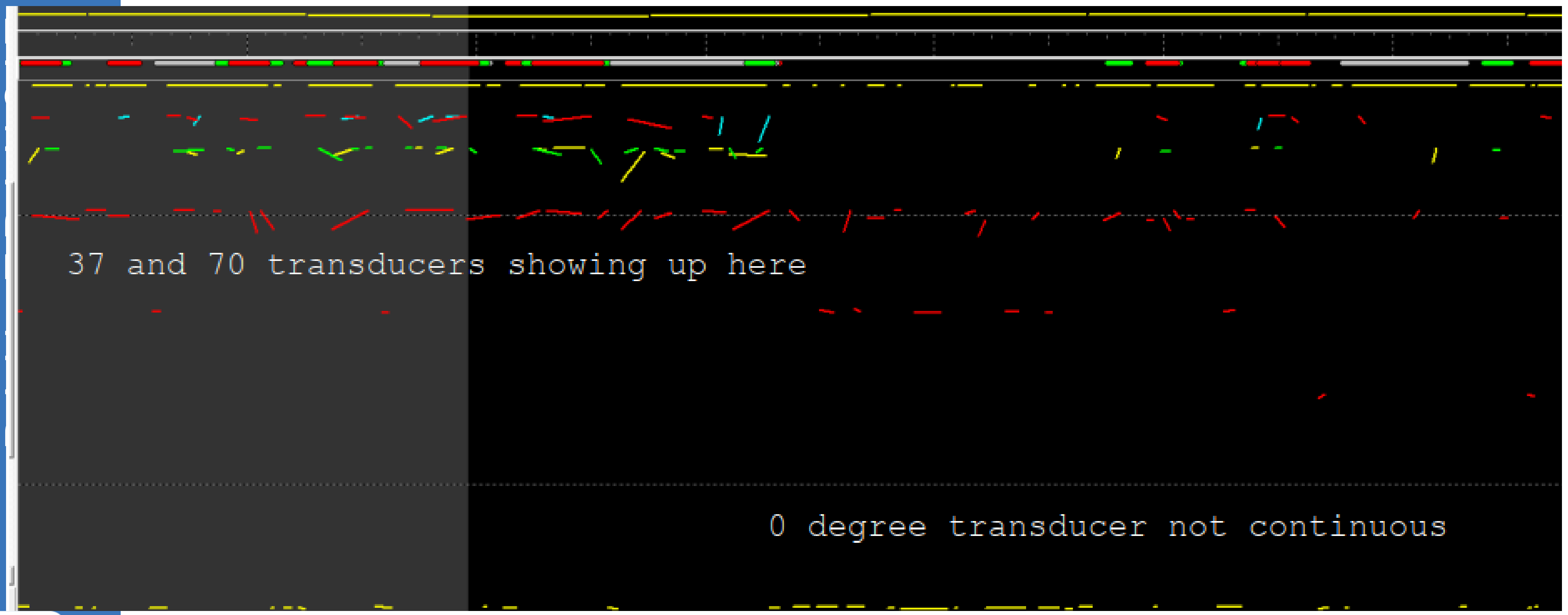


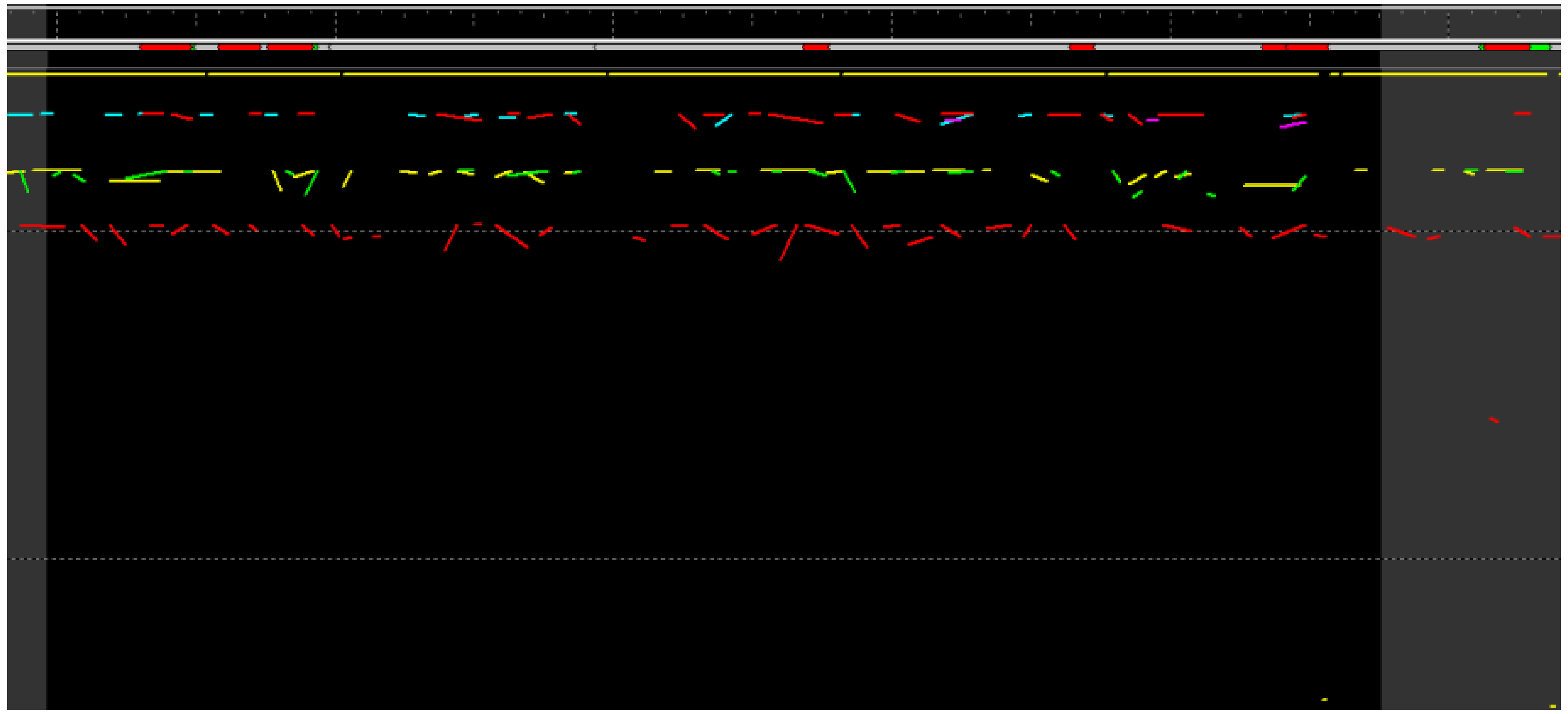
Mapping and Managing Studs



Seattle Sound Transit

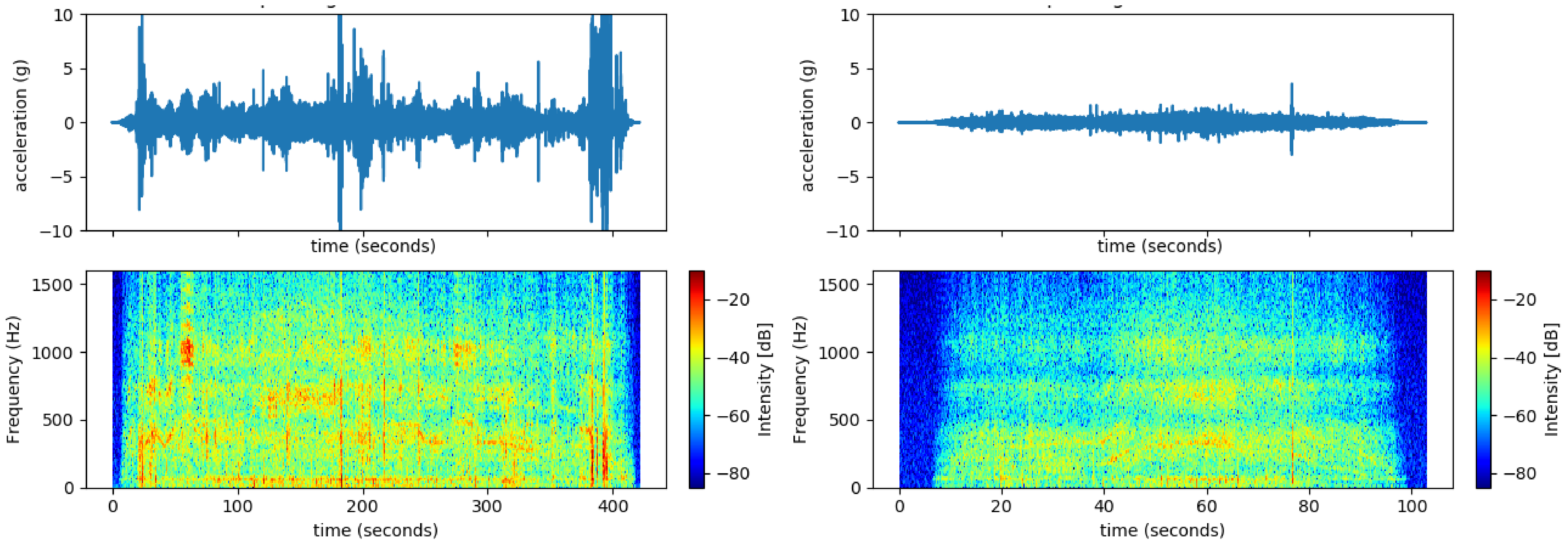
- Use of eddy current and ultrasonic inspections show promise for identifying existing studs





Seattle Sound Transit

- Use of axle box accelerometers can identify bad acting sections of track



Seattle Sound Transit

- Key challenges with studs remains
  - Identifying the primary root cause
    - If martensite: what can we do about it
    - Is corrugation a contributing factor?
  - Measuring early indicators
  - Determining a remediation plan, ideally preventive

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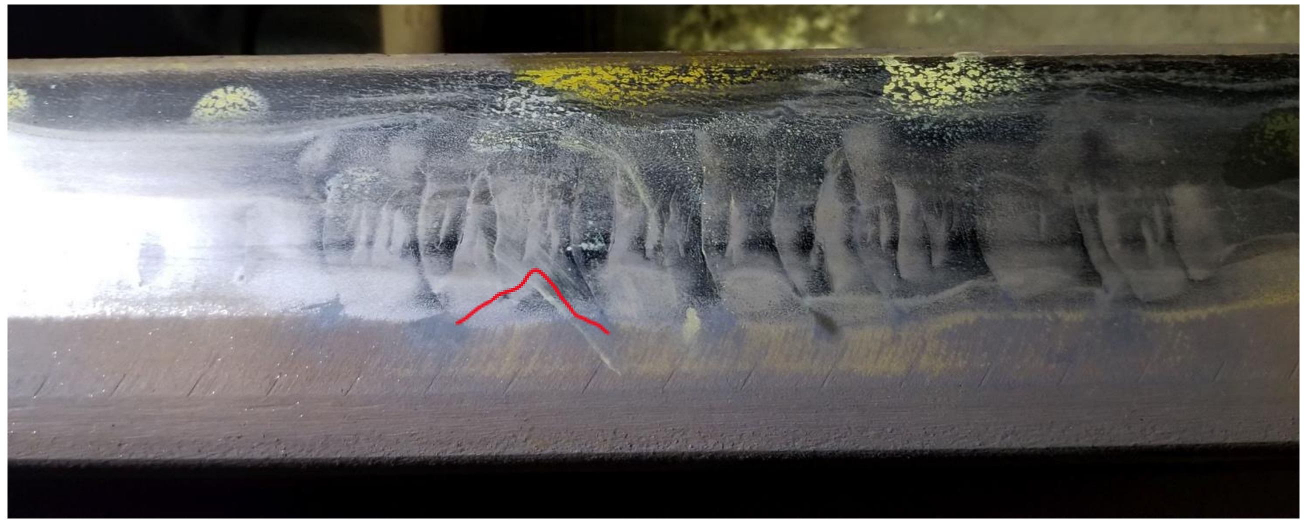
Other Metros

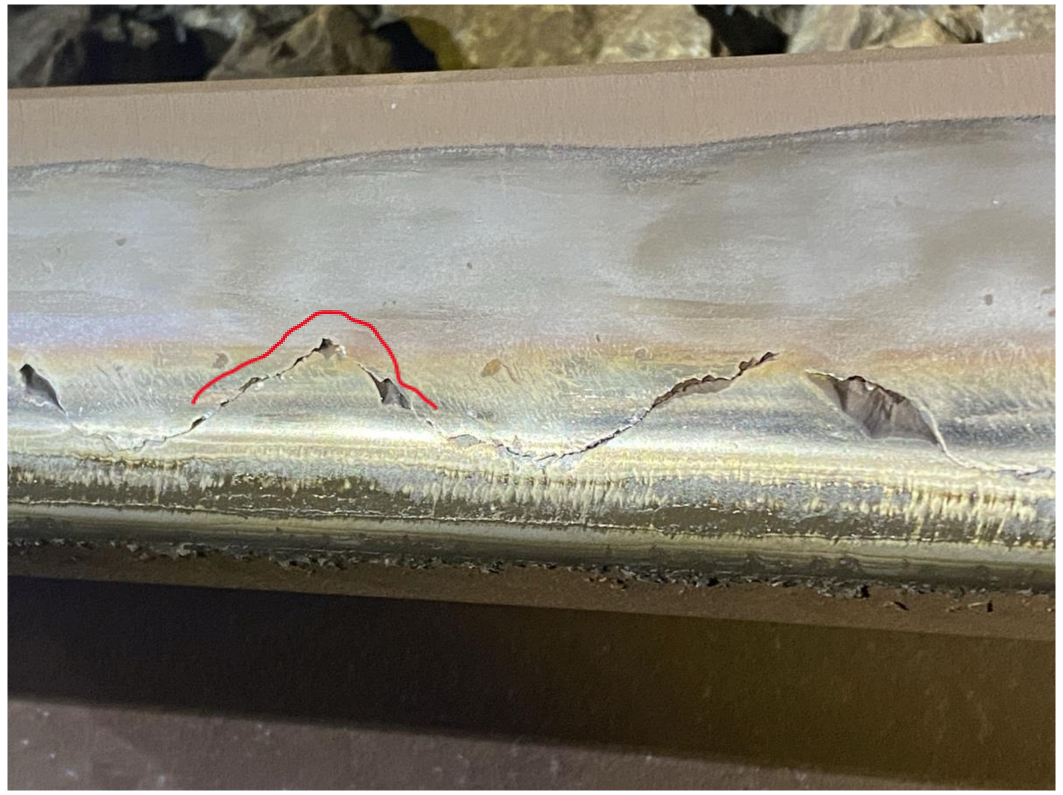
- Some evidence of similar type defects
    - Not as pervasive
    - No detailed study
- Annual preventive grinding
- Defects have not worsened in 5+ years
- Slowly being replaced as part of scheduled capital renewal

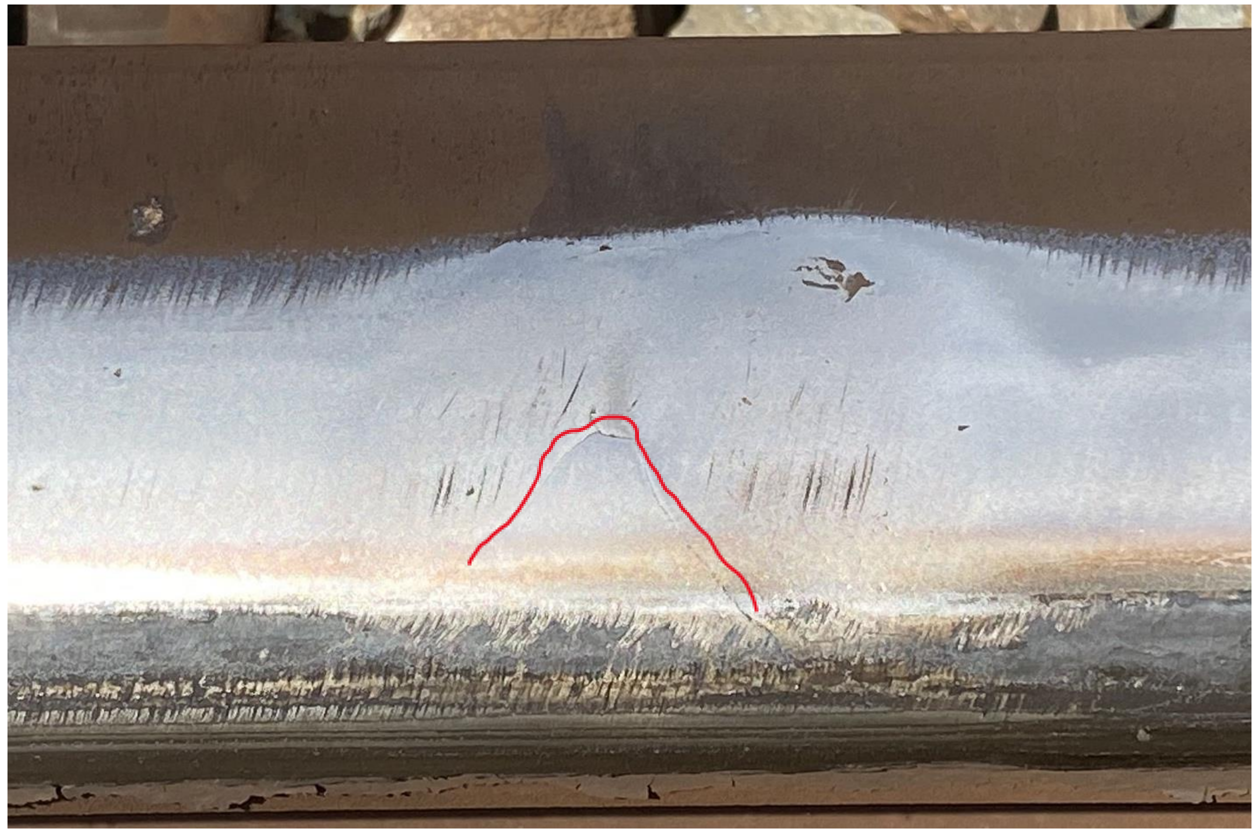
Other Metros

- Studs or squat-type defects have been observed elsewhere
  - Often in combination with increased tractive effort and premium steel
- Agencies are switching out older, softer steels for head hardened rail
  - Solves the wear issue but may be introducing a new set of issues if preventive grinding not employed

Other Metros







Sound Transit – Remediation Techniques

- Rail Grinding Program
  - Two-phase process for metal removal and leaving behind acoustically smooth rail
  - 3-year cycle (30 to 40 MGT), little rail wear, limited return of corrugation, some evidence of RCF, stud growth lower
  - Studs known to return within 10 MGT
- Milling programs
  - Attempt to reset rail (low wear) with rail replacement
- Rail replacement
  - KCM continues to implement rail renewal in infected areas

Sound Transit – Remediation Techniques

- Rail head weld repairs
  - Many shelling/spalling locations from studs were repaired with rail head welds (no longer a technique used)
  - Mapping out all welds (repair, flash butt, thermite)
- Rail hardness varies (as per specification) in high traction areas (harder rail)
- Friction Management
  - Lubrication has been effective, very little squeal and little to no gauge face wear (also a sign the wheel/rail interface is effective in steering)
  - Could TORFM help stabilize COF and reduce slip events

Knowledge gaps

- Martensite: A buildup of martensite layers or single events, most vehicles or rogue incidents. Thickness/depth is key?
- Crack growth – tonnage accumulation before detectable crack develops?
- Role of contact patch size, contact stress?
- Preventive grinding adequate for control?
- Is corrugation a contributor to or result of studs?
- What role do harder steels play?

Conclusions

Rail damage affects all metros:

- Corrugation and rolling contact fatigue are very pervasive, and solutions are (generally) well understood
  - Friction management, W/R profiles, rail grinding…
- Wheel burns (on rail) and wheel slides (on wheel tread) are also common, but more difficult to eliminate
- Dipped welds are a common “sore spot” and need regular attention (in addition to proper installation in the first place)

Conclusions - studs

- Are becoming increasingly common
- Although not known to cause rail breaks, they still pose risks and concerns
  - Noise and vibration
  - Damage to wheels, car components and rail
  - Potential to hide internal defects from detection as well as act as stress risers
- Root cause is still elusive but current theory is that they are associated with
  - Higher tractive effort and White Etching Layer (Martensite)
  - Outdoor track (probably because low friction under wet conditions)
  - Harder steels (?)
- Even small studs tend to be 2mm or deeper – prevention is the goal
- Preventive grinding has shown some success in arresting their development