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Final Technical Report

An International Collaborative Research Initiative on Rolling Contact Fatigue and Wear of Rails and Wheels

Yearly Project Review
(March 2022 – March 2023)

Prepared for: Kaveh Kahlilian, Engineer
Innovation Centre, Transport Canada

and

Ali Tajaddini, Program Manager
Federal Railroad Administration

Prepared by: Sylvie Chenier and Eric Magel

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Prepared by: And by:

_____   _____

Sylvie Chenier, PMP   **Eric E. Magel, P.Eng.**

Senior Project Manager, Automotive and Surface Transportation   Principal Engineer, Automotive and Surface Transportation

Reviewed by

_____

Jon Preston-Thomas, P.Eng.

Principal Engineer, Automotive and Surface Transportation

Approved by:

_____

Philip Marsh, P. Eng.

Director, R&D Transportation Engineering Centre

NRC.CANADA.CA

Acknowledgements

An International Collaborative Research Initiative (ICRI) by definition involves the contributions of many persons from many countries. At the time of this report, the ICRI membership included over 400 persons from 35 countries, including 39 railroads, 52 suppliers, 47 universities, 25 consultants, 14 research establishments, and 9 government organizations.

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- US Federal Railroad Administration
- Transport Canada
- National Research Council Canada

Many organizations have provided in-kind contributions and although it would be difficult to recognize all, those who provided direct support to the ICRI by hosting meetings and workshops, facilitating field investigations, leading workgroups and through regular participation in ICRI efforts deserve acknowledgement. Those who made contributions over the last year are listed below, in alphabetical order:

- Acoustic Studio (Australia)
- Athena Industrial (Canada)
- Advanced Rail Management (Canada)
- BNSF Railway (USA)
- British Steel (UK)
- Canadian National Railway (Canada)
- Canadian Pacific Railway (Canada)
- Chalmers University of Technology (Sweden)
- CSX Railroad (USA)
- Delft University (Netherlands)
- EVRAZ (North America)
- Federation University (Australia)
- Huddersfield University (UK)
- Jiatong University (China)
- KTH Royal Institute of Technology (Sweden)

- LB Foster (Canada)
- London Underground LUL (UK)
- LORAM (USA)
- Monash University—Institute of Railway Technology (Australia)
- MxV Rail (USA)
- Network Rail (UK)
- Plasser (Canada and USA)
- Rail Safety and Standard Board (UK)
- Sheffield University (UK)
- Simon Fraser University (Canada)
- Swedish National Road and Transport Research Institute VTI (Sweden)
- Transport for NSW (Australia)
- VTech CMCC Computing (Netherlands)
- Virtual Vehicle (Austria)
- Vehicle Dynamics (USA)

Executive Summary

In 2022, over 110 International Collaborative Research Initiative (ICRI) members gathered in-person during three organized conferences/workshops; the firsts to be held since the pandemic:

1. ICRI 2-day workshop in Ottawa, April 2022;
2. ICRI half-day workshop in Vancouver, June 2022, during the WRI Principles Course at the 27th annual Wheel Rail Interaction Conference (WRI 2022);
3. ICRI one day workshop in Melbourne, Australia, September 4, 2022, during the 12th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM 2022).

The ICRI also continued to host webinars, attracting over 350 viewers over 4 separate web-sessions. A total of 11 presentations were given during 2 web-based workshops and separate web-based presentations.

Planning is also underway for three more in-person conferences/workshops for 2023 in the United Kingdom (UK), Canada, and Brazil, and several web-based workshops.

In 2020 the ICRI initiated its most ambitious project ever — to develop a comprehensive model of broken rail and broken rail derailments. A framework was developed that breaks the problem into seven distinct modules; each of these was then tackled by volunteer teams. The teams were asked to identify the module inputs, algorithms and outputs, the current methods/understanding, and research gaps or new technology needs. Five of the seven modules were analyzed in this way and numerous research questions and needs were uncovered. While there is more work that can be done within the ICRI, some of the questions will require dedicated resources that are outside the capabilities of a volunteer organization. It is hoped that universities and research organizations will take on these challenges and develop their own research efforts to progressively fill in the gaps.

The Quantify Surface Damage team continues to populate a matrix relating visible surface damage to subsurface depth with rail samples sent by the community and have finally accumulated enough samples to allow a direct comparison and draw conclusions about crack angles vs. location across the rail head, and depth of rolling contact fatigue (RCF) cracks based on the curvature and accumulated million gross tons of rail traffic passing over a track in a year (MGT). A good correlation can be seen between (destructively) measured crack depth and transverse EC scans; however, the same cannot be said for the longitudinal EC scans.

An earlier ICRI field studies effort was renewed in October of 2022, when a different Class 1 railroad, BNSF, agreed to host ICRI field studies related to friction, wear, RCF and (internal) defects, which will include the onsite collection of post-grind and then pre-grind measurements, over roughly a 50 mgt cycle, of eddy current measurements, friction measurements, rail profiles, machine vision images and photographs. Six organizations will participate in the field work and the resulting data is expected to form the basis for several other ICRI project initiatives.

Membership in the ICRI continues to rise, and now numbers over 400 individuals from 186 organizations in 35 countries, a gain of 70 persons, 26 organizations and 6 countries in the last year.

Table of Contents

List of Tables

List of Figures

1 Introduction

Rolling contact fatigue (RCF) and wear are natural phenomena that serve to decrease both safety and economic viability of rails and wheels. They are the result of millions of contact cycles between the heavily loaded train axles and the running surface of rails. While the causes of both RCF and wear are generally understood, useful relationships between operating conditions, material properties and the rates of deterioration remain to be developed. With such relationships it will be possible to understand root causes of service failures (such as broken rails) and to undertake risk and economic analysis to justify the expense of improved components or more rigorous maintenance practices (including automated approaches) to improve safety and limit the cost penalty of wear and RCF.

There are many persons and organizations working to understand the problems of wear and rolling contact fatigue (RCF) and to develop solutions. Most often working in small groups within a single organization, they are at times developing models and test methodologies that are similar to others being developed elsewhere. Eventually—many months and sometimes years later—some small portions of their efforts show up in the public literature. The data being generated on test machines and in field experiments meets the needs of one researcher but, because of exclusivity concerns or differences in inspection and record keeping techniques, is unable to be used elsewhere by others. Excellent computer models are lacking data necessary to calibrate and validate models.

In 2011, an international collaborative research initiative (ICRI) was conceptualized, discussed and proposed. The premise was that by sharing data and ideas we might be able to develop higher quality deliverables for our clients, extend and enhance our professional relationships and ultimately leverage the collaboration for the development and winning of future projects.

The ICRI has been likened to a "coffee house" where people meet, share and learn what they can, and participate as much as they can for as long as they are seeing some benefit. The interactions are both web-based and through various locations worldwide of in-person workshops. The ICRI is founded on a model where all contributions to the research are made in-kind by researchers around the world working on problems of common interest.

The activities undertaken by the ICRI have evolved since it was founded in 2013. But there are two activities that have consistently received strong attention:

- Improving predictive models: Because of the expense, time, difficulty and safety hazards involved in virtually any form of field-testing ("controlled" or not), researchers, suppliers and railways are increasingly relying on numerical modeling in the design and validation of new processes and products. Multi-body dynamics models are increasingly detailed, and increasingly used to predict vehicle and track responses and forces at the contact patch. But algorithms to predict the impact that those forces have on wear, rolling contact fatigue and plastic flow need further development.
- Improving our understanding of friction: Arguably the most influential parameter affecting RCF and wear is friction. But for the most part researchers and engineers use arbitrary or very conservative models of friction to employ in otherwise very capable and appropriate models and safety analyses. One reason for this approach is the lack of true understanding of this highly variable and very complex phenomenon. But as computerized tools play an ever-increasing role in the development of performance and safety assessments, it is even more critical that science

and data are the basis for relationships and assumptions applied in the models, and that these are made available to the industry.

In addition to those two tasks, work has continued in mapping of wear, quantifying surface damage, modeling of broken rail and related derailments, and calculating how improvements to material and processes can reduce the economic cost of vehicle-track issues.

1.1 Objectives

The goal of the ICRI is:

> "To identify small and large research topics in the general area of RCF and wear of rails and wheels and then to form talented research teams (consisting of persons with similar or related interests) to resolve the problems."

The ICRI fosters international collaborations that address problems of rail safety and economics.

Key tasks for the project period (2022-2023), according to statements of work with both the Federal Railroad Administrration (FRA) and Transport Canada, were to:

- Champion, coordinate and manage the ICRI's ongoing efforts. These include:
  - o Identifying, scoping, guiding and initiating new topic areas and projects related to friction, quantifying damage, wear mapping, modeling of friction, and economic and safety modeling so that teams can be engaged to further develop and carry out work on these issues;
  - o While identifying new topic areas, developing and guiding those with collaborative, in-kind contributions until they reach a state requiring direct funding;
  - o Recruiting additional organizations and researchers as required for participation in projects; and to
  - o Organize and host an annual workshop, and regular web meetings (at least 4 per year) and events.
- Explore specific topics including:
  - o Evaluating existing inspection tools and to develop new approaches for quantifying the severity of surface damage on rails and wheels; and
  - o Understanding the contribution of rolling contact fatigue (RCF) and wear to safety and risk, including its impact on the reliability of ultrasonic defect inspection, broken rails and related derailments.
- Continue to drive the ICRI-Safety projects, including:
  - o Quantifying Risk; and
  - o modeling broken rails and broken rail derailments.
- Submit annual reports that review ICRI ongoing efforts and accomplishments and (for Transport Canada) present those each year to the Railway Research Advisory Board (RRAB) Technical Committee.

This report reviews the activities of both the coordinators and the research teams in fulfilling the responsibilities and goals of the ICRI over the last year.

1.2 Approach

Research topics are sometimes developed organically amongst ICRI members but usually are derived at the major workshops. Any topic that can gather enough support and has a champion can be brought under the ICRI banner. Regular workshops and web meetings are held to present ongoing work, solicit input, and develop new ideas. A website (https://www.icri-rcf.org/) is maintained to provide basic information on each topic, provide a place for storing and retrieving presentations and to announce new developments and opportunities.

At the time of this report, the ICRI projects include eight research topic, described below as projects, several of which also contain sub-projects as listed in Table 1. Each of these efforts will be discussed in further detail in Section 3.

Table 1: Ongoing and new ICRI topics

Project / sub-project title	Champion(s)	Status
Field Studies (NEW)	Eric Magel (National Research Council Canada (NRC), Canada), LB Foster, Athena, LORAM, ARM, EVRAZ, Plasser, and others	The team is preparing to send 3 representatives to the field to finalize the test locations on May 15, 2023.
Friction Studies		
Friction Modeling	Edwin Vollebregt (Vtech, CMCC, Netherlands) Klaus Six (Virtual Vehicle, Austria)	Presentation at ICRI workshop in Melbourne, Sept 2022. Research gaps identified.
Friction Library	Davey Mitchell (LB Foster, Canada)	Overview of project presented at ICRI workshop in Vancouver, June 2022. Framework of library is still being defined. Not much progress was made in the last year.
Tribometer Business Continuity Plan — *on hold*	Rob Caldwell (NRC, Canada)	Effort is on hold until the ownership of the Tribometer is resolved.
Quantify Surface Damage	Daniel Szablewski (NRC, Canada)	Report of findings submitted to FRA March 2023. ICRI web presentations is scheduled in April 2023.
Wear Mapping	Roger Lewis (Sheffield University, United Kingdom (UK))	Recent full-scale tests of laser clad layers have shown very good correlation with twin disc data
Damage Modeling	Wei Huang (NRC, Canada) Klaus Six (Virtual Vehicle, Austria) Adam Bevan (Huddersfield University, UK)	Ongoing project; collaborators are currently looking for a master's students to apply new data sets to their models.
VTI Economics	Wesley Thomas (LORAM, United States of America (USA))	To date, there have been 32 total users; railroads, service providers, and universities.

Project / sub-project title	Champion(s)	Status
Rail Profile Scoring	Ankur Ashtekar, (LORAM, USA)	Profile scoring parameter working groups are being developed.
Safety		
Broken Rail Modelling	Eric Magel (NRC, Canada)	Framework developed; broken down into 7 sub-sections.
1. Wear Model	Roger Lewis (Sheffield University, UK)	Workshop completed (Feb 7, 2022).
2. RCF Model	Richard Stock (Plasser, Canada)	Survey being developed to send to members.
3. Welds and Internal Defects Model	Peter Mutton (Monash University, Australia)	Workshop completed (March 2, 2022).
4. Stress-Strength /Resilience Model	Yan Liu and Chris Ladubec (NRC, Canada)	• Strength/Resilience workshop, led by David Fletcher (Sheffield University, UK) completed (Feb 16, 2022). • Stress-Strength workshop, led by NRC completed (Feb 17, 2022). • Stress-Strength /Resilience workshop, led by Chris Ladubec, completed (May 9, 2023).
5. External Loading Environment	Alex Woelfle (NRC, Canada)	Workshop completed (March 24, 2022).
6. Friction Characterization and Modeling	TBD	Searching for topic leader
7. Broken Rails and Derailments	Eric Magel (NRC, Canada)	Overview presented at ICRI workshop in Vancouver, June 2022.
Agent Based Modelling	Wei Huang (NRC, Canada)	Initial programing of model complete. Calibration task is ongoing.

2 Management Activities

The various activities undertaken by the coordinators to fulfill their responsibilities in managing the ICRI are reported in this section.

2.1 ICRI Project Coordination Activities

As part of the efforts to champion, coordinate and manage the ICRI's ongoing project, the ICRI coordinators from the National Research Council Canada (NRC) have:

o   Initiated and coordinated two new research efforts:

- the development of a framework for modeling broken rails that lead to derailments. This project is discussed in detail in Section 3.8;

- A field studies effort at the BNSF railroad to collect data that will support several of the other ICRI initiatives. This project is outlined in Section 3.1.1.

o   Continued to champion safety-related ICRI projects, particularly:

- Quantifying Risk—developing a methodology for evaluating the increase or decrease in risk or safety associated with adoption of new processes or technologies, discussed in Section 3.3:

  - Evaluating the relationship between surface fatigue and the effectiveness of ultrasonic detection.

- Evaluating the cost of RCF and wear to the Canadian Railway Industry:

  - This is being pursued in concert with the VTI-Economics effort, discussed in Section 3.6. There are currently five Canadian railways participating in this effort.

- Agent based modeling of broken rails and broken rail derailments. The next stage of this project is awaiting funding.

o   Facilitated the initiation of several new ICRI efforts (as shown in Table 1), and guided and coordinated those with collaborative, in-kind contributions until they reach a state requiring direct funding. The details of these efforts are discussed in more detail in Section 3;

o   Recruited additional organizations and researchers as required for participation in projects.

2.1.1 ICRI Leadership

With the approaching retirement of the ICRI's founder and current technical leader, an ICRI leadership committee has been formed to discuss the future leadership of the ICRI.

During the first ICRI leadership committee meeting, held October 12, 2022 members agreed that:

- The "coffee shop" aspect of the ICRI is great; where people to come together and talk, or even for a short collaboration, to exchange papers and ideas;

- Although it is sometimes difficult to progress some of the ICRI projects, especially the complex topics, because of other commitments, it is still beneficial to try to push these projects forwards; and that

- The ICRI leadership committee will meet every couple of months.

Subsequent meetings were held January 18, 2023 and March 1, 2023. The idea of recruiting an ICRI group leader for a period of six months was agreed upon. The ICRI Group Leader is expected to:

- Meet regularly (weekly/biweekly) with the ICRI secretariat (Sylvie Chenier, NRC) to review and update the list of ongoing activities and actions. The ICRI secretariat will maintain that list;

- Chair bi-monthly meetings of the ICRI leadership team;

- Conceive, promote, and host regular web meetings and web workshops. The ICRI secretariat will schedule the meetings and send out updates;

- Help drive the ICRI projects, including meetings with project leaders, reaching out for updates, encouraging presentations in webinars and workshops, and advising on approaches and actions;

- Review ICRI communications drafted by the secretariat as required (e.g., workshop announcements, meeting agendas, etc.) to be sent to the community through the ICRI email;

- Work with the ICRI secretariat and webmaster to ensure that the webpage is up to date (project status, events, workshops, etc.);

- Promote the ICRI and its events, for example by posting announcements on LinkedIn or through other social media platforms.

Several names have been proposed to date but a group leader has not yet been named.

2.2 ICRI Website

The ICRI website was created for disseminating ICRI outcomes (https://icri-rcf.org) and is regularly maintained by a volunteer (Dr. Richard Stock, Plasser) from within the ICRI. As in previous years, the subscription costs for the website have been sponsored by Plasser.

Table 2 summarizes the website activity. In general, activity has increased significantly, doubling from 2021 to 2022, and the number of different countries accessing the site has increased by 26. These results testify to the increasing reach of the ICRI.

Table 2: ICRI website activity summary by year

Year	Unique visitors	Number of visits	Pages	Hits	Countries
2019	10,411	19,587	52,659	128,159	67
2020	9,731	21,387	71,686	170,780	55
2021	21,169	46,071	233,206	322,949	76
2022	39,096	91,112	687,190	789,807	102
Increase (from 2021 to 2022)	185%	198%	295%	245%	134%

2.3 ICRI Annual Workshops

Many ICRI workshops and meetings have been held in the past to bring together groups of international researchers to discuss needs and priorities related to rolling contact fatigue and wear of rail/wheel systems. These workshops are normally organized to coincide with other technical meetings where large numbers of people are expected to already be attending. Past meetings have been held in conjunction with the Annual WRI seminars, American Railway Engineering and Maintenance-of-Way Association (AREMA) and FRA Railroad Safety Advisory Committee (RSAC) meetings, Contact Mechanics and other major conferences.

In 2022, three in-person conferences/workshops were held:
1. ICRI Workshop in Ottawa, April 26-28, 2022;
2. ICRI half-day Workshop in Vancouver, June 21, 2022, during the WRI Principles Course at the 27th annual Wheel Rail Interaction Conference (WRI 2022);
3. ICRI one day Workshop in Melbourne, Australia, September 4, 2022, during the 12th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM 2022).

Planning is also underway for three in-person conferences/workshops for 2023:
1. ICRI one-day workshop in Huddersfield, UK, March 22, 2023, held the day before V/T SIC & ADHERE[1] seminar in Manchester, UK;
2. ICRI one-day workshop in Ottawa, Canada, August 24, 2023, as part of the 28th International Association for Vehicle System Dynamics (IAVSD) International Symposium on Dynamics of Vehicles on Roads and Tracks Conference;
3. ICRI half-day workshop in Rio, Brazil, August 27, 2023, prior to the 12th International Heavy Haul Conference and will take place August 27-31, 2023.

2.3.1 ICRI Workshop in Ottawa, April 26-28, 2022

The first ICRI workshop to be held since the beginning of the COVID-19 pandemic was a three-day in-person workshop at the NRC Sussex location in Ottawa, Canada. Despite ongoing COVID-19 travel restrictions, 45 people were able to attend; 28 from Canada, 11 from the USA, 4 from Austria, 1 from the Netherlands and 1 from the UK.

The main goals of the conference were to:

- Review ongoing ICRI efforts and obtain immediate peer feedback on current projects and future plans;
- Promote research collaboration by bringing "end users" together with research and technology providers;
- Provide a sharing and learning environment for all participants, discuss best practices and broaden perspectives;

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[1] Vehicle/Track System Interface Committee (V/T SIC), ADHEsion REsearch challenge (ADHERE)

- Identify and prioritize gaps in understanding and research needs and develop plans for advancing the subjects of RCF and wear, vehicle/track interaction, safety and economics.

The workshop program is shown in Table 3. The various presentations are available on the ICRI website at https://www.icri-rcf.org/downloads/.

Table 3: Final program for April 2022 ICRI Annual Workshop in Ottawa

start		Tuesday, April 26		Wednesday, Apr 27		Thursday, Apr 28	start
08:25	E. Magel (NRC)	Welcome and workshop outline	M. Slade (EllisDon)	5. noise and noise mitigation	K. Khallian (TC)	9. system models	
08:45		1. Keynote D. Hampton (CSX Railroad) Heavy Haul Rail maintenance: current practices, opportunities and needs		M. Reimer (ARM) - Noise and Vibration – Seattle/Vancouver/BART projects		W. Thomas (Sentient Science) - VTI economics modeling	8:30
				B. Croft (Independent Consultant) - Wheel roughness vs rail roughness and contributions to noise		E. Magel (NRC, Canada) - Broken Rails Modeling	9:00
09:30		discussion/followup		discussion/followup		discussion/followup	9:30
10:00		coffee break					10:00
10:30	E. Vollebregt (CMCC)	2. friction R. Caldwell (NRC) and K. Oldknow (SFU) ICRI friction library and tribometer intiatives	R. Stock (Plasser)	6. Simulation Techniques W. Huang (NRC, Canada) - Agent based modeling of broken rail derailments	K. Oldknow (SFU)	B. Kerchof (ARM) - Mitigating risk associated with broken rail derailments	10:30
11:00		M. Santoro (LBFoster) - The effectiveness of gauge face, restraining rail and Top-of-Rail friction modifiers in mitigating curving noise.		A. Woelfle (NRC, Canada) - Sensitivity Analysis to determine the relative impacts of various parameters on RCF and Wear		Brainstorming/wrap-up session E. Magel (NRC) and K. Oldknow (SFU)	11:00
11:30		discussion / followup		discussion/followup			11:30
12:00		lunch break				grab and go lunch	12:00
13:00	P. Klauser (consultant)	3. New Technologies H. Brunskill (Sheffield University) - VTI assessments using ultrasonic arrays.	A. Oberhauser (GRT)	7. case studies S. Chenier (NRC, Canada) and Mark Reimer (ARM) - Squats/Studs on Sound Transit		Technical tours	13:00
13:30		A. Berry (Canadian National) - Comprehensive Rail Management: Leveraging Autonomous Platforms for Risk Mitigation and Advanced Insight		S. Regehr and J. Rychtarczyk (ARM) - Migrating rail profiles and grinding practices at BART			13:30
14:00		R. Stock (Plasser) - Measurement technology to support rail maintenance: Technologies and applications		A. Doy (Network Rail Consulting) - Enhanced Rail Management Through Rail Milling: Network Rail's Rail Maintenance Journey			14:00
14:30		discussion/followup		discussion/followup			14:30
15:00		coffee break					15:00
15:30	A. Elbana (TC)	4. material performance A. Banerjee (MxV Rail) - Heavy haul testing of rail performance at TTC	G. Bachinsky (ARM)	8. Profile assessment S.DeBlois (Canadian Pacific) - correlating defects with profile data			15:30
16:00		D. Szablewski (NRC) - Quantifying rail damage		A. Ashteker (Sentient Science) - ICRI Profile Scoring Initiative			16:00
16:30		discussion/followup		discussion / followup			16:30
18:00		Guided walk (weather depending)		social event - "Oh Canada"			18:00

The two optional technical tours were hosted:

1. Tour of Area X.O: A state-of-the-art R&D facility, located in Kanata North (Ottawa), that offers a safe and secure environment to create, test, and demonstrate future mobility, autonomy, and connected technologies;
2. Tour of the NRC Uplands testing facilities: These are state-of-the art testing facilities for the rail industry, including a climatic testing research facility; compression and tension testing facility (squeeze frame); heavy structural dynamics lab research facility; rail vehicle impact ramp research facility; wheel bearing and brake research facility; and instrumented wheelsets.

2.3.2 ICRI Half day Mini-Workshop Vancouver, June 21, 2022

This half-day in-person workshop was held during the WRI transit Principles Course at the WRI 2022 conference with 12 members participating in the discussions. The agenda is shown in Table 4 and the presentations are available at https://www.icri-rcf.org/downloads/.

Table 4: Final program for June 2022 ICRI Workshop in Vancouver

start time	Wednesday June 22, 2022 at WRI
01:00	
	Reviews of some ongoing ICRI projects • VTI-Economics – Eric Magel (for Wesley Thomas) • Friction Library – Robert Caldwell (for Davey Mitchell) • Tribometer Continuity Plan – Robert Caldwell • Quantifying Surface Damage – Daniel Szablewski
	Presentation: "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	*coffee break*
	Presentation: "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 – Alexandre Woelfle • Wear modeling – Eric Magel (For Roger Lewis) • RCF modeling – Richard Stock • Rail Resilience – Chris Ladubec • Broken Rails and Derailment modeling – Eric Magel

2.3.3 ICRI One day Workshop in Melbourne, Australia, September 4, 2022

This one-day in-person workshop was held during the 12th International Conference on Contact Mechanics and Wear of Wheel-Rail Systems with 60 community members participating. The program is shown in Table 5 and the presentations are available at https://www.icri-rcf.org/downloads/.

Table 5: Final program for September 2022 ICRI Workshop in Melbourne

start time	Sunday September 4, 2022	Presenter
08:30	Welcome and workshop outline	Richard Stock (Plasser American)
08:45	Adding value to research and professional development through collaboration	Gopi Chattopadhyay (Federation University)
09:10	Lead: Eric Magel (NRC, Canada) ICRI review: webinars, workshops and projects	
	Wear Mapping	Roger Lewis (Sheffield University)
	Friction Modeling	Edwin Vollebregt (Vtech CMCC)
	Friction Library	Kevin Oldknow (Simon Fraser University)
	Quantify Surface Damage	Eric Magel (NRC, Canada)
10:00	coffee break	
10:30	Lead David Fletcher (Sheffield University) Modeling risk: broken rails and derailments	
	Some considerations regarding risk assessment for rail breaks in heavy haul and mixed traffic operations	Anders Ekberg (Chalmers University)
	TFL experience with rail breaks on HP335 rail	Andy Vickerstaff (Transport for London)
	Case studies of broken rails in Australian rail operations	John Cookson (IRT Monash)
12:00	lunch break	
13:00	Lead: Peter Mutton (IRT, Monash University) Squats/Studs	
	Squats - current knowledge gaps	Zili Li (Delft University)
	The rail squats problem at TfNSW	John McLeod (TfNSW)
	Rail treatment to mitigate squats and studs?!	Richard Stock (Plasser American)
14:30	coffee break	
15:00	Lead: Briony Croft (Acoustic Studio) Panel Discussion: W/R noise	
	Incorporating wheel/rail interface considerations in the planning and procurement stages of rail projects.	Darrien Welsby (Monash IRT) Dave Anderson (Acoustic Studio) Steve Allday (TSA Advisory)
16:15	Wrap up	Kevin Oldknow (Simon Fraser University)

2.3.4 Planning for ICRI one day Workshop in Huddersfield, UK, March 22, 2023

Table 6 shows a draft outline of the planned program for the ICRI workshop planned for March 22, 2023, at Huddersfield University.

Table 6: Planning for ICRI Workshop in Huddersfield UK

Start time	Wednesday March 22, 2023	Presenter
10:00	Coffee Served (15 minutes)	
10:15	Welcome and workshop outline	Adam Bevan (UoH)
10:30	Squats/Studs Lead: Gareth Tucker (UoH)	
10:30	Introduction to squats/studs R&D and challenges	Gareth Tucker (UoH)
10:40	State of the art and research challenges in squat research	Michael Steenbergen (TU Delft, via MS Teams)
10:50	Observations of squats/studs removed from service	Stephen Lewis (British Steel)
11:00	Modelling or rail squats on Network Rail	Mark Burstow (Network Rail)
11:10	Discussion session	All speakers, led by Gareth Tucker (UoH)
11:30	Noise and Vibration Lead: Jamie Wilkes (Network Rail)	
11:30	Introduction to N&V challenges and current Network Rail R&D	Jamie Wilkes (NR)
11:50	An engineering indicator of squeal noise risk based on falling friction contact	Elham Khoramzad/Sebastian Stichel (KTH, via MS Teams)
12:00	Corrugation on JLE - Why it is more than just noise	Chris Clarke (LUL)
12:10	Discussion session	All speakers, led by Jamie Wilkes (NR)
12:30	Lunch Break (45 minutes)	
13:15	Tour: IRR Research Facilities	
14:30	Adhesion Lead: Paul Gray (RSSB)	
14:30	Introduction to adhesion R&D and challenges	Roger Lewis (UoS)
14:40	The influence of particle characteristics on railway adhesion: a numerical perspective	Sadegh Nadimi Shahraki (Newcastle University)
14:50	Northern innovations for dealing with low adhesion	Rob Cummings (Northern)
15:00	Low adhesion testing on HAROLD	Julian Stow (UoH)
15:10	Discussion session	All speakers, led by Paul Gray
15:20	Rail Management Lead: Bleddyn-James Davies (Network Rail)	
15:20	Long-term rail surface damage	Sebastian Stichel (KTH, via MS Teams)
15:30	Optimising rail grinding practice for premium rail materials	Lucas Biazon Cavalcanti (UoS)
15:40	Ultrasonic B-scan inspections on London Underground	Daniel Harrison (LUL)
15:50	Automated repair of rail defects in plain line and restoration of worn crossings	Jay Jaiswal (AAR, UoH)
16:00	Discussion session	All speakers, led by Bleddyn-James Davies (NR)
16:20	Wrap up	Andy Vickerstaff (LUL)

2.4 Web Meetings

The ICRI webinars are a recent initiative that more recently were established to substitute for the in-person workshops that could not take place during the COVID-19 pandemic. Although many pandemic related travels and gathering restrictions have been lifted, the webinars continue to be a useful means of transferring and sharing information within the community, specifically for those with other travel or commitment restrictions, and for international participants.

As shown in Table 7, four separate web sessions were held between April 2022 and March 2023. This included 2 separate web-based presentations and 2 web-based workshops, with a total of 12 presentations.

Table 7: ICRI webinars held in 2022-23

Month	Date	Presenter(s)	Organization	Title	Attendance
April	13-Apr-22	W Wang, H Ding	SouthWest Jiaotong University	Experimental study on wear and RCF damage of wheel/rail materials under complex environment conditions	65
December	14-Dec-22	S Nia	KTH Royal Institute of Technology	Predictive maintenance in railway systems: MBS-based wheel and rail life prediction exemplified for the Swedish Iron Ore line	93
January	17-Jan-23	ICRI Web-Based Workshop - University of Sheffield Rail Innovation and Technology Center Research			100+
		J Whittle	University of Sheffield	ICRI Seminar Introduction	
		Dr. J Corteen	British Steel	British Steel Technical Talk & UKRRIN Collaboration	
		M O Folorunso	University of Sheffield	Artificial Intelligence & Low Adhesion	
		R Kempa	University of Sheffield	Switch Measurements & Laser Cladding	
		I Slodczyk	University of Sheffield	Fuzzy Logic & Rail Buckling	
		A Wilby	University of Sheffield	Twin Disc Optical Monitoring	
February	21-Feb-23	ICRI Web-Based Workshop - Wheel/Rail Noise			100+
		B Croft	Acoustic Studio	Introduction and overview of the recent International Workshop on Railway Noise (IWRN14) held December 2022	
		P Torstensson	Swedish National Road and Transport Research Institute (VTI)	Survey of curve squeal occurrence for an entire metro system	
		J Theyssen	Chalmers University of Technology	Optimizing components in the rail support system for dynamic vibration absorption and pass-by noise reduction	
		A Pieringer	Chalmers University of Technology	Transient modelling of curve squeal considering varying contact conditions	

Future plans for web sessions include:

1. ICRI Web Based Workshop Series:
   a. Rolling Contact Fatigue, led by Daniel Szablewski, April 18, 2023;
   b. Friction Modeling, led by Klaus Six and Edwin Vollebregt;
   c. Broken rails, led by Eric Magel;
2. ICRI Webinar recaps of the in-person ICRI Workshops:
   a. ICRI Huddersfield workshop, March 2023;
   b. ICRI IAVSD-Ottawa workshop, August 2023;
   c. ICRI International Heavy Haul Association (IHHA)-Rio workshop, August 2023.

3 Research Program Activities

3.1 Field Studies

Following the 2019 ICRI Workshop in Vancouver, two field research project proposals were developed with the support of two railroad partners:

1. Norfolk Southern indicated a willingness to host further research activities around the use of eddy current systems to quantify surface damage and how the resulting information can be used to best maintain rail; and
2. Canadian Pacific stated that they were initiating a monitoring program consisting of 7 miles of new rail that includes 54 curves, and would be willing to consider complementary research activities focused on friction management.

However, in 2020 under the conditions of the pandemic, neither railroad was able to support a project and due to changes in management, the champion at each of the railroads had left and further efforts to re-engage were not successful.

3.1.1 BNSF Field Studies

In October of 2022, BNSF railroad tentatively agreed (based on approval of the scope of work) to serve as host to an ICRI team undertaking field studies related to friction, wear, RCF and internal defects, which would start summer 2023 and last for about seven months on a section of track between Lind and Connell in the state of Washington.

The field study will include the onsite collection of post-grind and pre-grind data from the same grinding cycle and locations, including eddy current measurements, friction measurements, rail profiles, machine vision images and photographs. The current list of field participants includes NRC, LB Foster, Athena, LORAM, ARM, EVRAZ, and Plasser, with other organizations expressing interest in contributing to the analysis of the data collected. The technical goals of the project include are to:

1. Develop relationships between visible surface damage and depth of damage;
2. Develop relationships between surface damage and risk, particularly with respect to ultrasonic testing and service failures;
3. Develop methods for incorporating new inspection technologies into regular maintenance practices (in particular grinding and milling);
4. Establish a best practice for grinding of new rail;
5. Characterize friction conditions in railway operations;
6. Understand the rate of crack initiation and growth rates as a function of

Type of steel	Cant deficiency
Track curvature	Track geometry errors/roughness
Grade, tractive effort	Proximity to special trackwork (crossings, switches, bridges)
Rail (and wheel) profiles	Friction conditions

7. Develop and validate models of wear and surface fatigue;
8. Quantifying "The Magic Wear Rate" [1];
9. Quantify economic benefits of improved maintenance practices;

The team has selected potential test curves and locations and is preparing to send three representatives to the field to finalize the test locations on May 15, 2023.

That section of track in planned for grinding in June 2023. The full team of six persons will head out roughly two weeks later for a two-day data collection campaign.

Prior to grinding in December 2023, that same team will collect "pre-grind" data from the same test locations.

3.2 Friction Modeling Studies

3.2.1 Friction Modeling

Friction in wheel-rail contact is an important part of this complex tribological system and therefore has a strong influence on vehicle-track interaction (VTI). To realize high quality VTI predictions (vehicle/traction/braking dynamics, wear, damage, etc.), reliable friction models that consider the most important tribological phenomena are of great importance. A review was made of the friction modelling and the creep force characteristics article published by Volbregt, Six and Polach in 2021 in the Vehicle System Dynamics International Journal of Vehicle Mechanics and Mobility [2]. Virginia Tech used the model to simulate measurements on the Virginia Tech-FRA roller rig.

An overview of the state-of-the-art paper was presented at the ICRI workshop in September 2022 in Melbourne, Australia. Research gaps were summarized as:

•	Further friction measurements are needed, to get a better grip on the "surface conditions";

•	Detailed integrated simulation should be attempted for detailed measurement data, with a focus on identifying the creep forces involved.

For more details visit: https://www.icri-rcf.org/friction-modelling/.

Leaders: Klaus Six, Virtual Vehicle and Edwin Vollebregt, Vtech.

3.2.2 Friction Library

Vehicle-track interaction modelling and simulation typically require the coefficient of friction (COF) to be specified at the wheel-tread/top-of-rail interface and wheel-flange/gauge-face interfaces. Commonly the COF at each interface is defined as single, nominal value. Under real-world conditions, however, friction levels are known to vary substantially based on operating and environmental factors, and can change significantly with both space and time from a single point of measurement. The purpose of this project is to establish and populate a "Friction Library", with data sets collected from a range of operating scenarios and environmental conditions. Examples include friction (or proxy) data gathered from tribometers, lateral/vertical force measurement sites, and instrumented wheelsets, together with information describing the operating conditions (e.g., traffic type and patterns, track type and geometry, vehicle parameters, friction management status) and environmental conditions (e.g., temperature, humidity, precipitation, observed contaminants). It is expected that the resulting Friction Library could serve as a repository for various ICRI members and project groups, providing input data that would help in the selection of representative COF values for various VTI simulation scenarios, as well as longer-term efforts to model

and incorporate wheel-rail friction levels as stochastic variables. Expected benefits include improvements in VTI modeling and simulation to better understand and predict how changing friction conditions in a given situation might affect parameters of interest to the railway, whether transit or freight.

The next steps are to finalize the goals and framework for the Friction Library and to establish a usable data repository. The modeling community gave input on situations where a Friction Library could be useful, and where it would likely not. For example, it may help modelers make assumptions about friction levels but likely won't improve the modeling itself unless there is a physical model developed. Four categories of simulation that consider friction were discussed, as listed in Table 8.

Table 8: Simulation categories that consider friction.

Simulation category	How friction is used	Would a Friction Library be useful?
Design studies: Simulations done to qualify a new vehicle concept in advance of or in place of physical acceptance tests.	These simulations are usually based on a prescribed worst-case friction coefficient.	Not really — only to the extent that it might indicate if the prescribed value is either optimistic (and should be further increased) or too pessimistic (and could be reduced).
Life cycle studies: Simulation to assess vehicle or track life cycles. Profile evolution of wheels and rails is one example.	A Monte Carlo approach is used where friction coefficients are a random variable (e.g., several hundred or thousand simulations are done with a Gaussian distribution for left and right rail crown and flank COF values).	Yes — would provide guidance on the range of variation relative to the average condition (e.g., does "flange lubrication" give an average friction value of 0.20 ranging from 0.15 to 0.25 or is it 0.25 ranging from 0.10 to 0.40).
Evaluation studies: Simulations to specifically examine the effect of friction coefficient. Used to answer questions such as: -How much should we lubricate? -What is the optimal friction modifier characteristic? -How should we balance top of rail and flange lubrication? -Where should I place lubricators? etc.	As the parameter/variable being evaluated	Yes — would guide the range of friction values that should not be examined, because there is no evidence these conditions can be achieved or maintained in practice. Could identify the conditions under which target values are no longer achieved, meaning the assumed benefits are lost or at least reduced.
Specialized studies: Modeling that examines falling friction effects, constituent behavior of the third body layer, heating of that material, distribution of lubricant in the contact patch (at the transition between the clean rail crown and the lubricated rail flank), and so on.	Most codes allow the user to define a coefficient of friction (typically separate for tread, flange, and flange back contact) and a spatial variation of the friction coefficient or, e.g., as a function of position along track.	It could be useful, but the available measurement techniques (tribometers, etc.) may not yet be up to the task (or perhaps only in the lab but not in the real world) of supporting specialized studies.

The Friction Library could also be used to help compare different measurement devices so that the measurements could be translated from one data set to another; since different sources of friction data are very difficult to compare to each other because there are so many parameters with inherent variability, including the method of measurement.

Leader: Davey Mitchell (LB Foster).

Participants: Marco Santoro (LB Foster), Kevin Oldknow (Simon Fraser University), Rob Caldwell (NRC Canada).

3.3 Quantify Surface Fatigue

Rail is currently inspected and its maintenance needs determined based primarily on visual observations from knowledgeable inspectors. But this approach is time consuming and labour intensive (and hence expensive), inconsistent in quality and interpretation, and places personnel in harm's way (e.g., on the track and in adverse weather conditions). However, various technologies are now available for automatically collecting information on rail surface health, including electromagnetic (e.g., eddy current (EC) and magnetic flux), machine vision, ultrasonic and acoustic means.

The objective of this project is to advance techniques for assessing the surface condition of rail that have relevance and application to remediation (e.g., through rail grinding) and risk assessment (by relating surface condition to inspection reliability and rail failure).

Electromagnetic technologies for measuring surface breaking cracks on rails are becoming increasingly common. Eddy current systems in particular have proven effective in assessing the length of cracks in rail. But since both safety and maintenance depend on crack depth, the FRA has been sponsoring work to develop relationships between RCF crack depth and EC probe measurements. Ultimately the goal is to support better grinding and rail inspection practices. The ICRI has supported this work through the provision of rail samples and as a forum for dissemination and application of the resulting information.

The project approach consists of two stages:

1. A destructive metallurgical analysis of RCF damage on the rail in both freight and transit systems, and
2. A non-destructive eddy current evaluation of the RCF surface damage in these same rails.

Each part consists of the following:

- Development of an "RCF matrix" quantifying rail running surface fatigue damage as a function of rail type and position in track, tonnage accumulation, traffic condition, as well as other environmental and maintenance conditions the rails are subjected to during their life-cycle;
- Inspection of the RCF surface damage through non-destructive EC technology in an effort to build a link between surface damage observed through destructive metallography and non-destructive EC inspection techniques.

A methodology for metallurgical analysis of RCF crack planes has been developed for implementation into the RCF matrix.

To date 33 rail samples have been analyzed and included in the RCF matrix. RCF metrics include crack position on the railhead, angle to surface, as well as crack length and depth. EC measurements are taken for each sample and Vickers micro-hardness traces collected on representative samples. Two bins in the RCF matrix have enough hi-rails samples analyzed to allow a direct comparison of RCF crack depths and crack angles; 4.0-4.9 degree curves with 500-599 MGT, and 5.0-5.9 degree curves with 600-699 MGT and the following main observations were made:

1. Results comparison for each of the selected bins indicates an increasing crack angle with increasing lateral position (i.e., distance from the gauge face). Cracks are shallow (i.e., small angle to the surface) at the gage-face (GF), but their angle increases as the position shifts toward top of rail (TOR), becoming orthogonal to the running surface at TOR. This trend can also be seen across the entire population of hi-rails found within the 33 rails that were analyzed.
2. Comparing the crack angles from the two bins indicates that in sharper curves the transition from GF to TOR crack angles occurred more rapidly, i.e., cracks approached the 90-degree orthogonal orientation sooner than they did in shallower curves.
3. For most samples analyzed, there is a good correlation between metallography and transverse EC scans. Longitudinal scans do not always provide a good correlation.

Lead: Daniel Szablewski (NRC).

Participants: Alok Jahagirdar (NRC), Sylvie Chenier (NRC).

3.4 Wear Mapping

Wear Mapping is collaborative project aimed at developing universal wear maps that take account of the full range of operating and environmental conditions prevalent for the wheel/rail contact. These can be integrated with multi-body dynamics simulation tools for predicting wheel or rail profile evolution with wear or as a stand-alone tool for assessing particular case study sites. A strong focus is being placed on effects of third-body layers and generating data for a wider range of wheel and rail materials.

This project is nearing completion, with the following outcomes achieved to date:

• Contact conditions have been gathered;
• A spreadsheet of available wear data has been created;
• Wear coefficients have been generated for premium rail materials across a range of contact conditions;
• Laser clad layers on rail have been investigated and are showing good wear and RCF resistance (clad layers will be inserted in track in 2023 to see how they perform in field conditions);
• Hardness effects on wheel and rail wear have been assessed;
• A standard approach to carrying out and reporting on small-scale twin disc tests has been published.

Current work is focused on full-scale tests on clad and premium rail materials to look at scaling effects. Recent full-scale tests of laser clad layers have shown very good correlation with twin disc data (for wear rates; roughness and hardness evolution). A new collaborative wear data spreadsheet has been updated recently with data from tests on a range of crossing nose materials. Analysis has also been carried out of the wear difference between driving and driven discs. This wear rate information could help improve modelling of braking/traction effects.

A project between Virtual Vehicle Research and The University of Sheffield is progressing that is aimed at studying fundamental aspects of wear. This is aimed at developing a physical wear model based on actual damage mechanisms to improve on the current semi-empirical models. Initial work has focused on modelling the deformed layer on the wheel or rail surface where the damage mechanisms initiate.

Another project is focusing on wheel and rail wear prediction using statistical approaches. Other ongoing work is looking at driving versus driven surfaces and the different wear rates and mechanisms and relating wear mechanisms to rail microstructure which has now been validated and is being implemented.

Proposals are being developed to set up some round-robin style twin disc wear testing to further progress the collection of wear data. Measurement points are also being established at test tracks to facilitate collection of field wear data.

Recent publications related to this ICRI project include:

1. Wear of Driving versus Driven Discs in a Twin Disc Rolling-Sliding Test [3]
2. Numerical Calculation of Wear in Rolling Contact Based on the Archard Equation [4]
3. Experimental Study on Wear Properties of Wheel and Rail Materials with different Hardness Values [5]
4. New Approach for Modelling Mild and Severe Wear in Wheel-Rail Contacts [6]
5. Comparison of Wear and Rolling Contact Fatigue Behaviours of Bainitic and Pearlitic Rails under various Rolling-Sliding Conditions [7]

Lead: Roger Lewis (Sheffield University).

3.5 Damage Modeling

The goal of the Damage Modelling project is to provide a prediction of the fatigue damage growth rate in wheels or rails. Models of this kind are becoming increasingly important for the prediction of component failure risk or expected life. To that end, this project supports the development, calibration and validation of damage models by providing realistic wheel/rail contact loading environments.

With CSX data collected under previous FRA funded ICRI activities, the NRC used a stochastic simulation approach to recreate the loading environment of two CSX curves. These environments were validated with a pummelling analysis compared to actual photographs and crack depth measurements. The NRC subsequently ran a sensitivity analysis on the loading environment to identify key factors that influence the risk of fatigue damage initiation. A final report covering the loading environment and the sensitivity analysis was submitted to the FRA during the first quarter of 2022. Once the report is published by the FRA, it will be linked on the ICRI website. The recommended next steps are to:

1. Process data from other test sites and compare key factor influence;
2. Run new simulations with a greater selection of stochastically-selected loading environment factors (ICRI broken rail loading environment characterisation initiative);
3. Convert relative metrics like RCF index into actionable metrics like crack growth rate (ICRI damage modeling initiative).

Virtual Vehicle and Huddersfield University have developed crack growth models from previous loading environments created by the NRC from different curves. They are currently reviewing the new loading environment data and will investigate how much calibration will be required to make the model work under these new conditions.

The latest update was presented at the ICRI workshop in April 2022 in Ottawa, Canada.

Leaders: Wei Huang (NRC), Alex Woelfle (NRC), Klaus Six (Virtual Vehicle), and Adam Bevan (Huddersfield)

3.6 VTI Economics

The goal for the Vehicle-Track Interaction (VTI) Economics research topic is to develop a model to enable railroads, suppliers and researchers to obtain fair and unbiased quantifications of the economic savings or benefits associated with a research, technology or process investment.

The model is currently being implemented by 32 users including 24 railroads, service providers, and universities. Five of the 24 railroads are Canadian. A case study of the Bay Area Rapid Transit (BART) using the VTI Economics Model to present the cost savings of their wheel life extension initiative to their Board of Directors was published in the *International Railway Journal* [8].

The most recent presentation on this project was given at the ICRI workshop in April 2022 in Ottawa, Canada.

Lead: Wesley Thomas (LORAM).

3.7 Profile Scoring

The goal for the Profile Scoring team is to develop a methodology to evaluate the performance/suitability of a rail profile for use under a specific set of conditions. This tool would provide scoring that helps determine what is the best profile, from available and new profile templates, given the current state based on performance with respect to wear, RCF, lateral and curving forces, stability and ride quality, noise and corrugation resistance, grinding, and frictional energy. Cost and economic implications would also be considered. The score would be used to rate if the current state is "good enough" and compare this value to an expected optimal.

Several parameter working groups have been identified, as listed in Table 9. Each group will be responsible for developing a scoring method that would feed into the overall profile scoring.

Table 9: Profile Scoring parameter working groups

Group	Lead
RCF/Wear	Kevin Oldknow (Simon Fraser)
Lateral Stability and Curving Forces/Dynamics	Peter Klauser (Vehicle Dynamics)
Corrugations Resistance/ Noise	Mark Reimer (ARM)
Grinding	Charles Rudeen (LORAM)
Frictional Energy	Rob Caldwell (NRC)

The project effort for this task is expected to build from the Field Studies data collection discussed in Section 3.1.

Lead: Ankur Ashtekar (LORAM)

3.8 Rail Safety

One of the NRC's objectives (according to statements of work with both the FRA and Transport Canada) is to explore specific topics including understanding the contribution of rolling contact fatigue (RCF) and wear to safety and risk, including their impact on the reliability of ultrasonic defect inspection, broken rails and related derailments.

A new safety initiative was started in 2019, inspired in part by the success of the VTI Economics activity. It is consistently the case that investments of resources must show a rate of return (hence the VTI Economics model) but in many or possibly even most cases, new technologies have both an economic and safety benefit. If the safety benefit could be quantified, it might help to further justify an investment. And maybe those safety benefits can be transformed into an economic benefit for direct application?

But safety is very difficult to quantify. For example, we intuitively know that improving surface condition will advance safety by reducing broken rails and improving the reliability of ultrasonic testing. But, until recently, there has been no reliable means to quantify surface damage. As inspection tools improve and surface damage data is collected over time and correlated to rail breaks, useful relationships should emerge.

There exists a premise that rail breaks are unsafe and so past efforts to address safety associated with broken rails have focussed on how to understand and reduce rails breaks. But FRA statistics show that less than one in a hundred rail breaks cause a derailment [9]. Other analyses (e.g., [10]) can show different numbers—probably because of differences that arise when all broken rails are considered (including at welds and all other causes), versus those breaks attributed to contact stress only. But regardless of the exact numbers, while the rail break clearly precipitated the derailment, most do not result in a derailment. So just as clearly, there were other factors at play. Reducing broken rails will reduce emergency maintenance and disruption to traffic but may not necessarily reduce the number of broken rail derailments or improve safety.

Compared with safety, risk is much more amenable to analysis, and the application of technologies to reduce risk can also be numerically evaluated. The approach being taken by this team is to identify the

track segments at highest risk of a broken rail derailment. For example, for a given 100 miles of track, can we identify the ten 0.1-mile track segments at highest risk? And then if these areas are targeted for remediation, it is strongly believed that broken rail derailments will measurably decline.

Notwithstanding the previous discussion, addressing broken rails requires us to understand what causes rail breaks. If we could eliminate all rail breaks, then there could be no broken rail derailments. Similarly, if there were no transverse defects, then there would be no (or almost no) breaks. And if there was no RCF and wear then there would be no associated transverse defects. In other words, [worn and cracked rail surface] leads to some [transverse defects] which causes some [rail breaks] which cause some broken rail [derailments]. We can interrupt the chain at any point through improved steels, friction management, improved rail support and track quality, rail grinding, more frequent and reliable rail flaw detection, etc. To visualize this process, an initial modeling framework was developed (Figure 1) that has since been refined and reworked several times (Figure 2). Specific modules have been defined, leaders recruited (see Table 10), and workshops held.
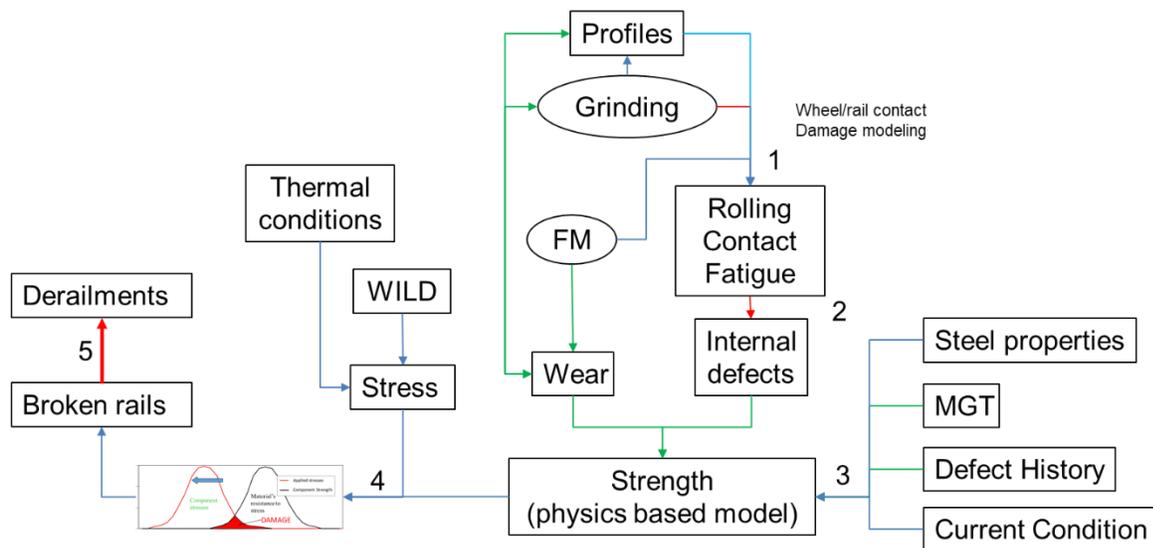

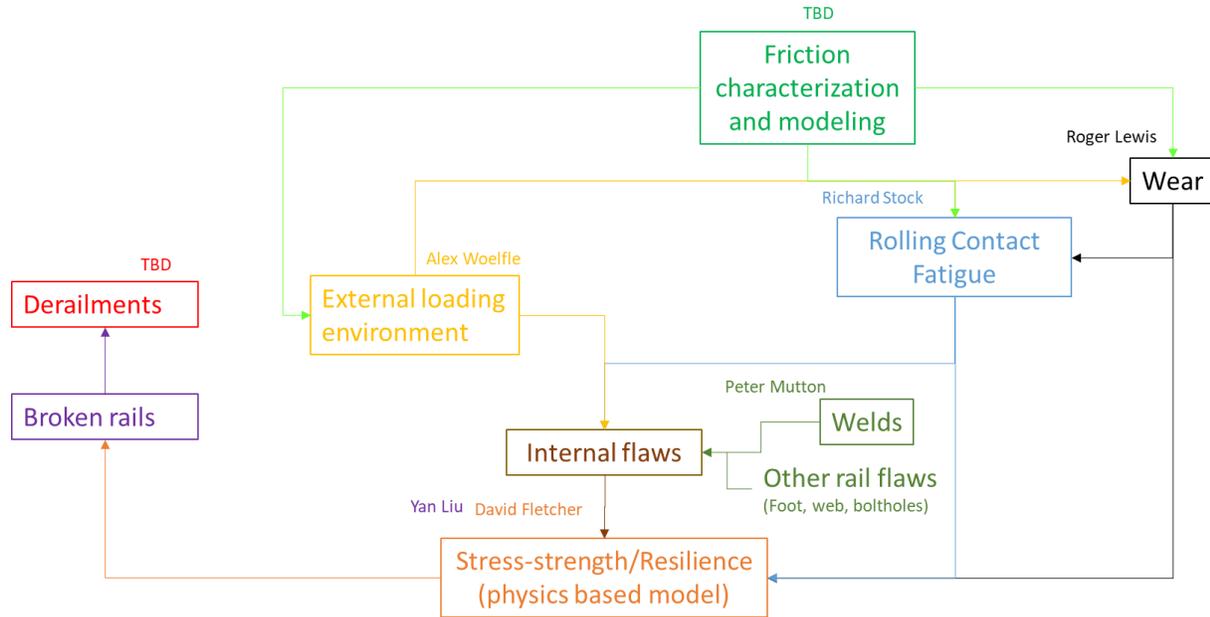Figure 1: The first ICRI-Broken Rail outline, presented in July 2020

Figure 2: Current ICRI-Broken Rail outline as of March 2023

Table 10: Ongoing Broken Rails Modules

Title	Champion(s)	Status
Broken Rail Modelling	Eric Magel (NRC, Canada)	Framework developed; broken down into 8 subsections.
1. Wear Model (Wear)	Roger Lewis (Sheffield University, UK)	Workshop completed (Feb 7, 2022).
2. RCF Model (Rolling Contact Fatigue)	Richard Stock (Plasser, Canada)	Survey sent to members.
3. Surface Fatigue to Internal Defects Model (Internal flaws)	TBD	Searching for topic leader.
4. Welds and Internal Defects Model (Welds/Other rail flaws)	Peter Mutton (Monash University, Australia)	Workshop completed (March 2, 2022).
5. Stress-Strength/Resilience (physics based model): - Strength/Resilience Model - Stress-Strength Model	Yan Liu and Chris Ladubec (NRC, Canada) - David Fletcher (Sheffield University, UK) - Yan Liu and Chris Ladubec (NRC, Canada)	Workshop completed (June 14, 2022 - Workshop completed (Feb 16, 2022). - Workshop completed (Feb 17, 2022).
6. External Loading Environment	Alex Woelfle (NRC, Canada)	Workshop completed (Mar 24, 2022).
7. Friction Characterization and Modeling	TBD	Searching for topic leader.

Title	Champion(s)	Status
Agent Based Modelling	Wei Huang (NRC, Canada)	Initial programing of model complete. Calibration task is ongoing.

3.8.1 Background

Rail Safety has been a topic of concern for the ICRI since its inception. Several activities have been performed under the auspices of the ICRI, including:

1. A. Ekberg and E. Kabo of Chalmers University (2014) developed a review titled: Surface fatigue initiated transverse defects and broken rails—an International Review [11]. The ICRI surveyed its many members and ultimately contributions (photos and incident descriptions) were received from China, Russia, South Arica, Sweden, UK and USA. The survey concluded that the depth when a rolling contact fatigue (RCF) crack deviates to a transverse propagation was found to be in the order of 5 mm with a fair amount of scatter. This was found to be reasonably consistent from an international perspective.

2. E. Magel, P. Mutton, A. Ekberg and A. Kapoor developed a paper titled *Rolling contact fatigue, wear and broken rail derailments,* that was submitted and presented at the Contact Mechanics 2015 Conference in Colorado Springs [12]. In this paper it is recognized the RCF is hazardous because it can initiate transverse defects and compromises rail flaw detection. Wear, on the other hand, reduces bending strength, may expose different metallurgy, cause periodic wear (corrugation) that can increase track forces, and changes profiles that typically increase stresses. Each of these aspects was reviewed. The paper concluded by listing the following series of questions that needed further exploration:
   - Is it possible to quantify a severity of surface fatigue cracking at which the effectiveness of ultrasonic detection is seriously compromised?
   - What are the crack driving forces when there are multiple cracks in close proximity, and when/why does a dominant crack form?
   - What are the conditions under which a long, but otherwise dormant crack deviates deep into the rail and precipitates a break?
   - Which is more dangerous: widely spaced cracks or densely spaced cracks?
   - While the mechanism of fluid entrapment and subsequent crack face lubrication and hydraulic crack propagation appears to be sound theory, is there any way—experimentally or otherwise—to distinguish the contribution of these two phenomena in an operating railway, and to establish the volume of water or lubricant in an operational crack and thereby model and quantify its effect?
   - What happens with cracks that are not fully removed during a rail grinding cycle? Are these residual cracks benign or are they more or less dangerous than new cracks?

3. BNSF Railway (BNSF) analysis of rail break data [13]. The BNSF data showed that on a per foot basis:
   - Tangent rail is more likely to break than low rails;
   - Crossings are 50% more likely to develop detected defects or service failures than open track;

- Turnouts are 500% more likely to develop detected defects or service failures than open track;
- Also, broken rail derailments peak in the fall, not at the coldest months of the year but rather at the start of the cold season.

A review of the FRA data for mainline derailments between 2008 and 2014 found that those due to surface fatigue (FRA Code T207) amount to roughly 21% of all FRA reportable track caused derailments and 26% of the reportable damage costs [13].   <u>Broken rail derailments are the leading cause of severe derailments—those that derail the highest number of cars per incident [14].</u>

3.8.2 Analysis of Broken Rail Derailments

Figure 3 shows a useful example of seasonal broken rail derailments from a 2013 paper [10] that used 10 years of broken rail derailments and 2 years of service failures. The authors revealed that:

- Unsurprisingly there are considerably more broken rails (service failures) and broken rail derailments in the winter season compared with all the other seasons;

- However, the <u>ratio of derailments to broken rails</u> is eight times higher in the summer compared with the winter.
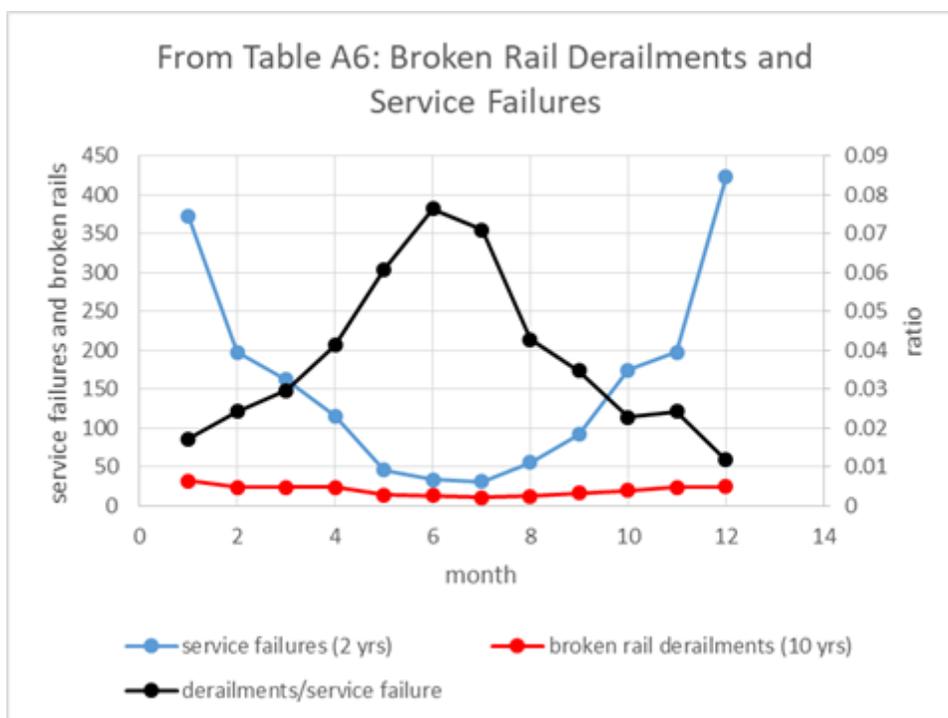

Figure 3: Broken rail data from Reference [10]

The second finding was cause for a separate discussion and the creation of an ICRI working group called Broken Rails Modeling (discussed in Section 3.8.4). Some members cautioned the reliability of the results, since the numbers of derailments used in the analysis was so few. For example, the number of broken rail derailments in the summer months might be as low as one per month over the entire class 1 industry in North America. Also, it was noted that, in the interests of time, derailments are often attributed

to the easiest to find culprit, such as a broken rail, even if the root cause might have been a car, wheel or track issue.

Nonetheless, a vigorous email discussion was held and several general points of agreement emerged:

- The rail support system is not as stiff in the summer as it is in the winter. Thus, for the same impacting wheels, the resulting stresses that contribute to rail fracture will be lower;
- In the winter, a clean break is more likely because the tensile thermal stresses will cause a significant gap that is readily detected by track circuits. Those breaks will be addressed before additional trains can pass over;
- Neutral or compressive longitudinal (thermal) stress in warmer months means that even with a break, a gap might not appear. The rail break might not be detected by track circuits and therefore have a chance to remain in track, being pounded by passing trains until eventually separating and causing a derailment;
- The favorable warm weather thermal stresses and softer foundation mean that the rail can probably sustain more damage before breaking. The rail can tolerate more, longer and deeper cracks and larger transverse defects before actually breaking. Clusters of internal defects can develop before the rail eventually breaks. But when it does, it is easier for a short length of the rail head to break out, and in the winter even a smallish transverse defect is likely to break.

In a separate effort, Transportation Safety Board of Canada (TSB) (Canada) incident reports from 1994-2020 and National Transportation Safety Board (NTSB) (USA) incident reports from 1996-2020 were reviewed and attempts were made to plot these against temperature. Figure 4(A) shows the Canadian results, with each bar giving the temperature at the times of each of the 27 major broken rail derailments suffered in Canada. The average of those temperatures is -6°C. Figure 4(B) includes only those major Canadian broken rail derailments caused by RCF. The average temperature at the time of the incident is close to 0°C.

Figure 5 shows that there were no serious broken rail derailments in the summer months in Canada and that most occurred in the fall.

Some broken rail data for CP Rail is shown in Figure 6. Although it peaks in January, the retired CP Rail person responsible for that data contends that the most rail breaks happen during the "first good cold snap". Latent defects in vulnerable rail fail when exposed to the large tensile stresses and these are then removed in bulk from the system. With those gone there are far fewer defects remaining and subsequent broken rails develop from either newly initiated defects or those that have grown from a very small size.
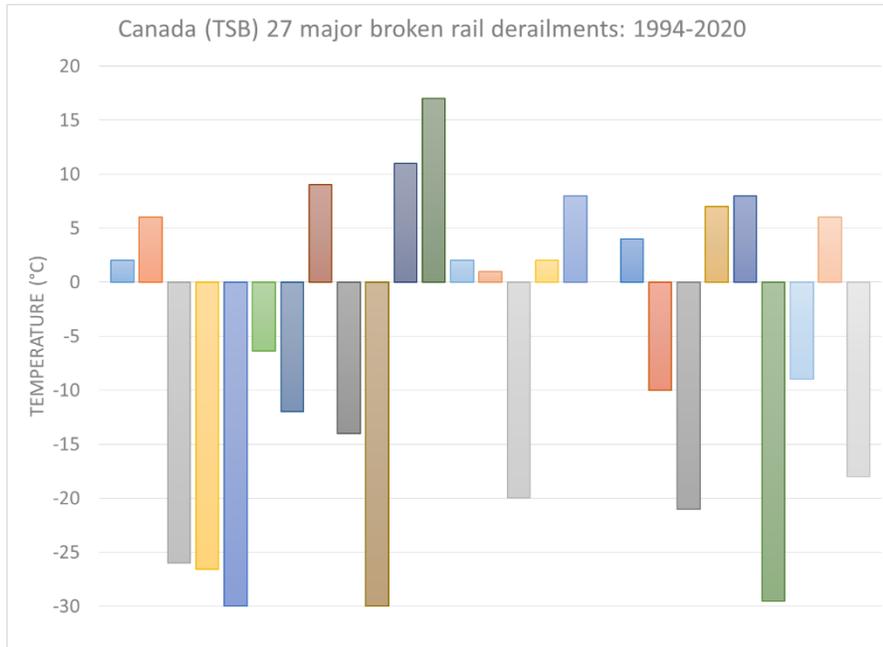
A)
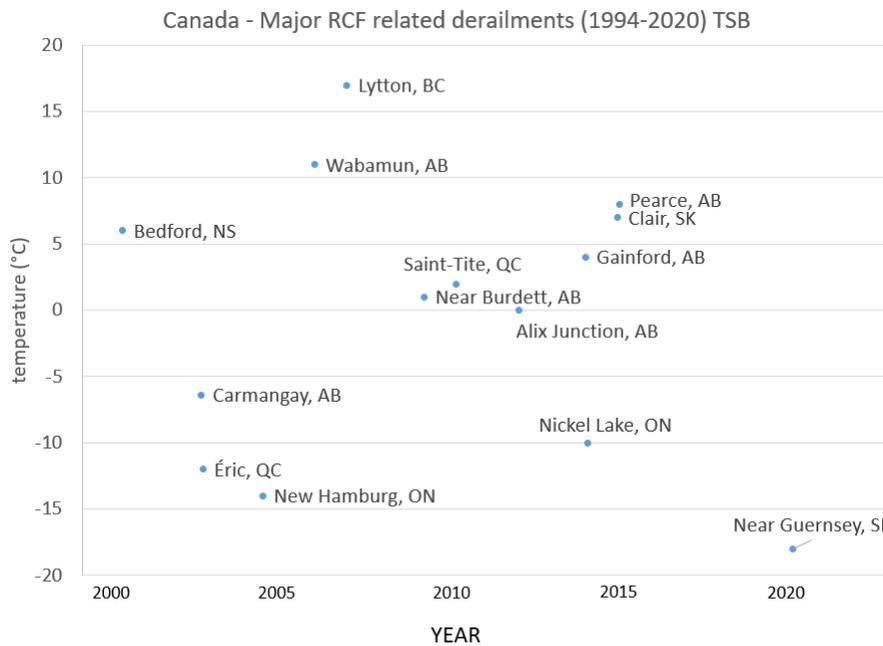
B)

Figure 4: Results from 1994-2020 TSB incident reports: A) temperature at the time of each of the 27 major broken rail derailments B) only those broken rail derailments believed to be a result of rolling contact fatigue.
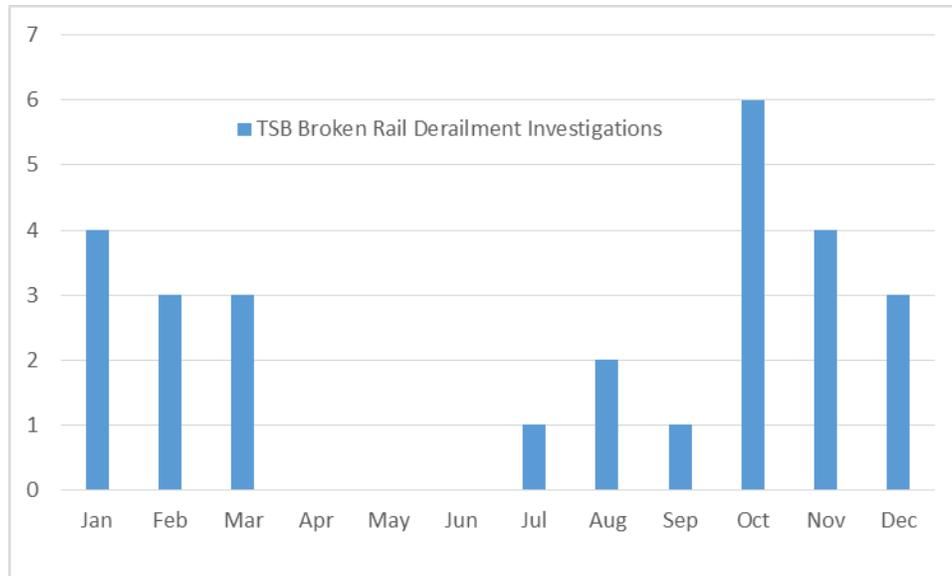
Figure 5: TSB broken rail derailments by month for all incidents between 1994 and 2020

A review of the NTSB incident reports was not nearly as enlightening. It appears that the NTSB investigates far fewer incidents, even though it oversees a much larger total mileage of railroads. Between 1996 and 2020, we found only 14 reports on broken rail derailments and only 6 of those were associated with RCF. The average temperature at the time of rail fracture and derailment was 5°C. The results have not been plotted in this report.

CP Service Areas - Percentage Frequency of Service Failures (TD/BR/DW)

Figure 6: Some broken rail data for CP Rail [15]. Note the inverted temperature scale

3.8.3 Risk

Risk is usually defined as being composed of two features: probability and consequence (or severity) (see Figure 7). The consequence or severity is relatively 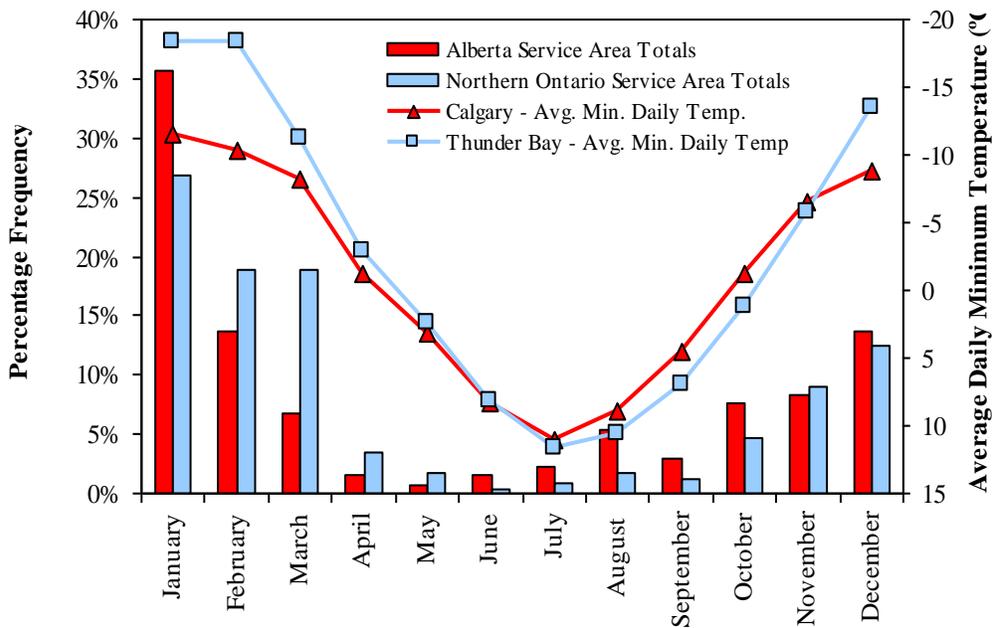straightforward to assess (given good data), based on proximity to human populations and bodies of water, type of good being transported, etc. The bigger challenge for risk assessment in railroads is the probability. While it might be able to do so in a generic sense, for example by using historical data to understand how many derailments it can expect in a subdivision, but to be useful, the probability needs to be evaluated with the same resolution as the consequence/severity. This might be based on track segment (e.g., a curve, length of tangent, an interlocking), or mile of track, or tenth of a mile, for example.

SAFETY RISK		Severity				
		Catastrophic	Hazardous	Major	Minor	Negligible
Probability		A	B	C	D	E
Frequent	5	5A	5B	5C	5D	5E
Occasional	4	4A	4B	4C	4D	4E
Remote	3	3A	3B	3C	3D	3E
Improbable	2	2A	2B	2C	2D	2E
Extremely improbable	1	1A	1B	1C	1D	1E

Figure 7: Risk assessment map to identify high priority regions

In a Transport Canada initiative called "Study of Definition of Key Routes for the Transportation of Dangerous Goods by Rail in Canada" from 2016 [16], the probability issue was addressed as follows:

> … the probability portion of the analysis focused on the likelihood of derailments based on factors such as rail age, car weight, characteristics of railway facilities, track class, train speed and number of grade crossings, correlated with traffic volume in terms of carloads.

> Models representing derailment probabilities were developed, using publicly and peer reviewed methods and algorithms, incorporating derailment probabilities from broken rails, other track-related causes, crossings and a fourth category of other causes, such as equipment, human factors and climatic conditions.

> The probability of derailment on a route calculated in the models is a function of total carload on the route.

… the big variation of the risk gradient is due to the other conditions such as rail age, car weight, characteristics of railway facilities, track class, train speed and number of grade crossings, etc., that differ from subdivision to subdivision.

During the course of the work, it became clear that the methodologies developed in this project can be used as a framework or foundation for a sophisticated tool to perform risk assessment of rail infrastructure in a segment-by-segment manner.

Ultimately, the derailment model developed was based on the use of broken rail statistics and the ratio of derailments to service failures. Approaches to date have consistently looked at the historical data, particularly with respect to broken rails statistics, and tried to project or assign risk on that basis, e.g., [17].

A problem is that derailments are, statistically speaking, low-probability events. FRA reported that from 2014 to 2018 there were 291 main-line track derailments that may have had RCF as a key contributor. This is shown in Table 11 where codes T220 and T207 represent derailment causes with surface fatigue as a root cause. That average of 58 per year (291 derailments in 5years) is for all the Class 1 railroads over all their many subdivisions, at various train speeds, age of rails, grades, curvatures, times of year, rail grinding histories, track geometry conditions, etc. How does a railroad assign the expected 8 (for example) mainline derailments to the many thousands of segments? While the challenge may seem daunting, it is the objective of this ICRI project to at least explore the problem.

Table 11: FRA Accident Statistics: 2001-2018 and 2014-2018

Description	Code	2001-18	2014-18
T220 Transverse/compound fissure	T220	860	77
T207 Detail fracture - shelling/head check	T207	753	214
T221 Vertical split head	T221	411	70
T210 Head and web sep (outside of joint bar limit)	T210	343	70
T202 Broken base of rail	T202	294	66
T201 Bolt hole crack or break	T201	135	23
T212 Horizontal split head	T212	89	13
T204 Broken weld (field)	T204	85	15
T203 Broken weld (plant)	T203	15	4
Broken rail derailments - Total		2985	552
All Track Cause derailments		10256	1873
		29.1%	29.5%

The long-term goals of the ICRI Safety task are to:

A) Provide a methodology for quantifying the risk reduction or safety improvements associated with new technology or process adoptions. This methodology should be generic and work with any safety issue, but particularly with wheel-rail interaction, rolling contact fatigue and wear;

B) Then work with the VTI Economics team to cost that value.

In the near term, the intention is to narrow the project focus to strictly broken rail derailments, with the expectation that the methodology will then be extended to other derailment types.

3.8.4 Broken Rails Modeling – Phase 1

An outline of the broken rail derailments problem was shown in Figure 1; shown as a flow chart of stress strength approach to quantify risk of broken rail derailment. Five models were identified in order to fulfill the requirements:

1. Damage Modeling including Profiles, Grinding and Friction Management

    Damage modeling is already an activity within the ICRI. But for the broken rails project we need to assure that both rail grinding and friction management are explicitly addressed along with material properties and contact mechanics (i.e., wheel and rail profiles, loading conditions, creepage).

    A) Rail grinding

    In the practice of rail grinding, freight railroads rarely grind for RCF—they are instead focussing on shape, anticipating that during that process the RCF will also be addressed. One reason for this is that there is no reliable way to know the presence or severity of RCF over long stretches of rail, and thus no way to include it as an automated data stream into planning software.

    Transit/passenger systems meanwhile commonly chase RCF. In Europe it is common practice to have an eddy current system mounted onto the rail grinder and to require that grinding continue until no detectable RCF remains. In North America, portable eddy current systems are being applied to ensure that RCF remains in control and is being progressively removed through rail grinding.

    Some work has been done to understand how various levels of grinding have affected the measured RCF (e.g., [17]) with mixed results. Frequently the eddy current systems measure large crack depths that are rapidly truncated even with modest grinding (e.g., 5 mm cracks that later measure 2 mm deep after only 0.5 mm of metal has been removed). The ICRI-Quantify Surface Fatigue project seeks to understand this problem.

    The results coming from eddy current systems are interesting, in that sometimes the measured crack lengths can increase as a result of grinding. This has been attributed to the rail grinding process "opening up" or exposing subsurface steel with cracking that did not previously reach to the surface. More experience is needed with the eddy current systems but that is being achieved as more units gain more miles and experience on North American railroads.

    Several research questions have been identified that refer to the relationship between grinding and RCF:

    - How soon should new rail be ground?

    - Is mill scale grinding really necessary?

    - What happens with residual cracks — are these more or less "dangerous" than newly initiated cracks of the same length?

    - Is there any evidence that coarse grinding can initiate RCF?

    B) Impact of friction modifiers (FM) on RCF

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It is generally accepted that by managing friction on the top of rail, excessive shear stresses can be avoided and RCF minimized. Some physical testing and simulation results support this belief. Friction modifiers also reduce wear rates and in-track forces, providing further advantages. It remains to:

- Develop (or collect, if they already exist) relationships between the amount of product applied and the RCF and wear reductions;

- Understand the differences, if any, between the different types of friction modifiers available;

- Understand the impact of short-term system failures (e.g., short periods of "dry" rail).

2. Relationship between RCF and Internal Defects

Crushed heads and transverse defects commonly develop from surface breaking cracks. But why, amongst the billions of surface cracks in rail, do only a few dive downwards and precipitate a rail fracture? Besides the existence of a crack, there are many other features that might contribute to an internal defect, including metallurgical imperfections (inclusions), adverse residual stress patterns, unfavorable profiles and the resulting contact stress conditions, and rail bending stresses arising as a result of local loading conditions. Those remain to be understood.

3. Strength Model (resistance to rail breaking)

The key properties affecting the resistance of rail to breakage are:

- Material properties - the strength properties of a given batch or type of steel are generally known. Ductility and fracture toughness are likely to be key properties.

- Million gross tons of traffic in a year (MGT) - this number is very useful when it is combined with WILD data to estimate the fatigue crack growth.

- Defect history - there is an assumption that a segment of track that has a historical rate of defects per mile will continue to have the same into the future. Over a longer length of rail this might be true, but if an internal defect or vulnerability is removed from a stick of rail (e.g., a 39 or 78 foot length) then should not that stick be more resistant to further failure? Of course, the introduction of another weld might increase the probability of failure. Further understanding needs to be developed.

- Current condition—If we believe that the probability of breakage is related to the severity of surface damage, then the emerging capabilities to quantify surface fatigue are key.

These need to be combined and contribute to a physics-based model of rail "strength" or at least the relative resistance to breakage.

4. Rail Break Model

The rail break model already developed by Liu for the Canadian Pacific Railroad [15] can be used for this purpose. That model was created to support the development of cold weather speed limits and included measured wheel impact load detector (WILD) values in determining whether a specific train should be slowed to reduce the probability of breaking a rail at low temperatures. A

stress versus strength method was employed (see Figure 8). The stress was determined from the applied impact loading as measured from nearby WILD systems. Since "strength" could not be directly measured, it was calculated through a statistical simulation based on fracture mechanics principles.
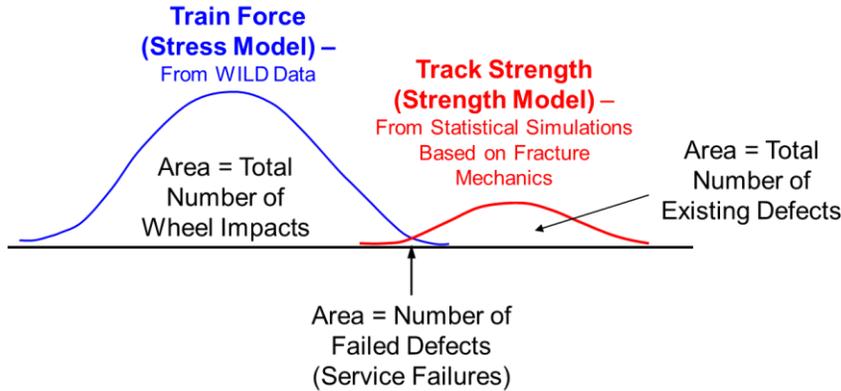

Figure 8: Stress vs. strength approach used for modeling potential rail breaks [15]

The strength model is outlined in Figure 9. A statistical simulation approach evaluates the subdivision "strength" using the population of known defects within that subdivision. The allowable impact load for each transverse defect was determined as the allowable stress remaining after the thermal and residual stress contributions have been subtracted. In the model, I is the moment of inertia of the rail, M_1 is a factor to account for the finite dimensions of the rail, M_S accounts for the defect having an elliptical rather than circular shape, and M_G accounts for stress gradients in the head of the rail. σ_R is related to the defect size. For a given subdivision, the distribution of defect sizes is developed based on the values recorded by the ultrasonic inspection vehicle. Once calibrated for a subdivision, the model could then be applied to specific track segments based on local conditions.
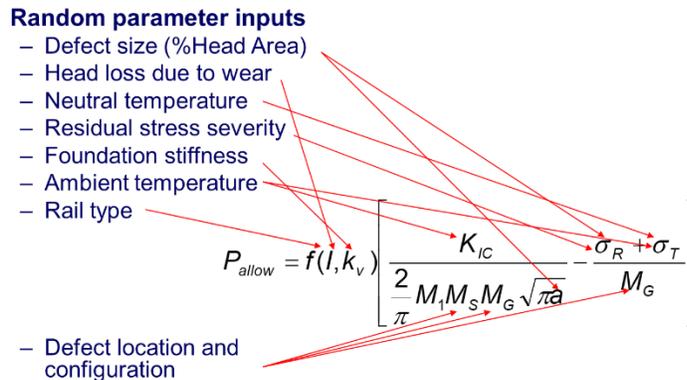

Figure 9: Strength model—statistical simulation approach [15]

5. Derailment Modeling

Under what conditions does a broken rail lead to a derailment? This will undoubtedly require a detailed review of derailment incidents, but is expected to include the existence of defect clusters, inadequate fastening and high local forces (e.g., track geometry perturbations) as contributing

factors. Proximity to crossings, switches and bridges may be exacerbating factors, though those may more affect derailment severity rather than probability.

It has already been noted that "clean breaks" have a low probability of causing a derailment. Multiple fractures over a short length, leading to a loss of the bearing surface, is a clear causal factor for a derailment.

Seasonality is also a factor. A review of FRA data (Reference [10] and also Section 3.8.2) shows that the number of broken rails is considerably higher in the winter than in the summer and that broken rail derailments peak in the fall. But interestingly, the ratio of derailments to broken rails is about five times higher in the summer than the winter. Data from the BNSF generally supports that finding, though as Figure 11 shows, there are both summer and fall peaks in this case. The reason for this is not yet understood.

The summer peak was the cause of a vigorous email thread within the ICRI and one of the most promising explanations that emerged is that compressive thermal forces in the summer lead a rail break to NOT be detected by an interrupted signalling system, since the rail does not pull apart. In warmer months, a broken rail may remain undetectable in track for some time, leading to local deterioration of fasteners, ties and ballast and increased potential of a multiple break (Figure 10) scenario.

Figure 10: Multiple breaks can lead to loss of a significant length of the rail head and a subsequent derailment.

Figure 11 shows the monthly distribution of broken rails, broken rail derailments and their ratio for the BNSF Railway from 2004 to 2014.
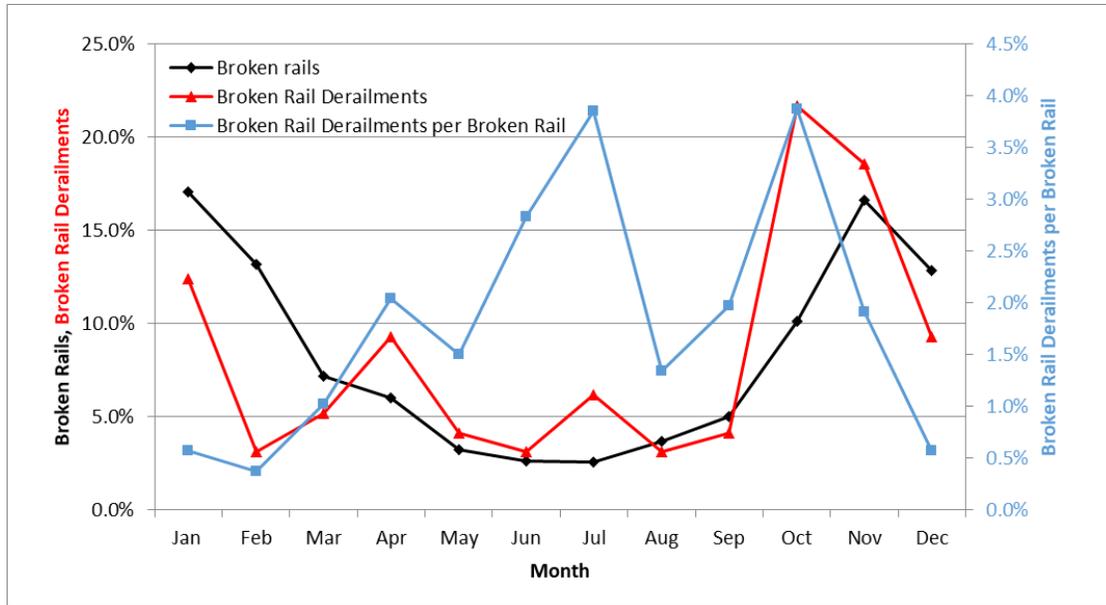
Figure 11: Seasonal BNSF broken rail derailment distribution

Lead: Eric Magel (NRC)

3.9 ICRI Broken Rails Modeling Initiative

Building off the Phase 1 rail safety work and risk analysis that was completed in 2020-2021 discussed in Section 3.8 above, the framework for a broken rail derailment model was extended (Figure 12) but then simplified into the modules shown in Figure 13, and discussed below.

Figure 12: Stress-strength approach to modeling broken rails

Figure 13: Outline of broken rails to derailment model

3.9.1 Broken Rails Module Framework Development

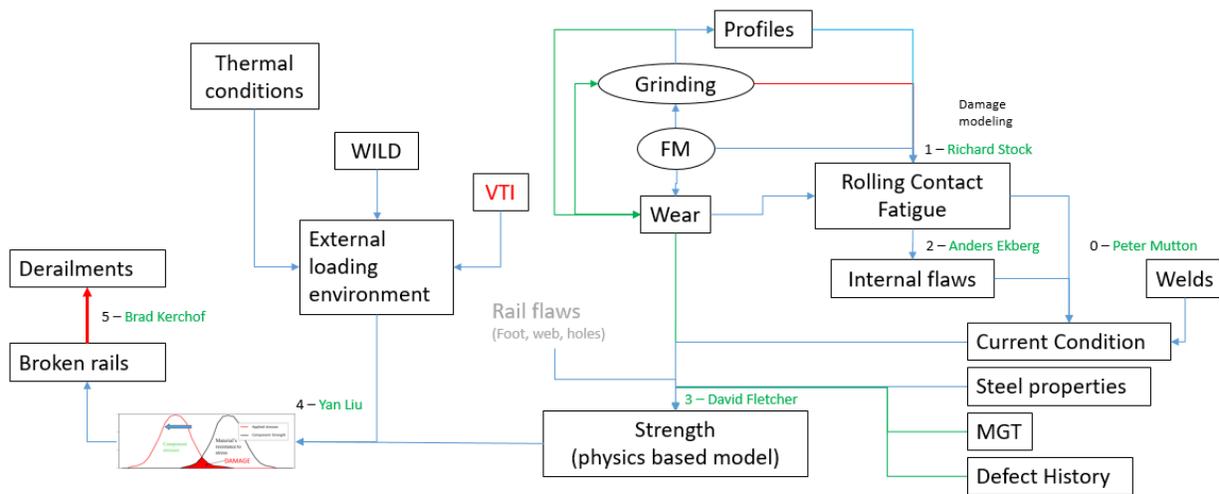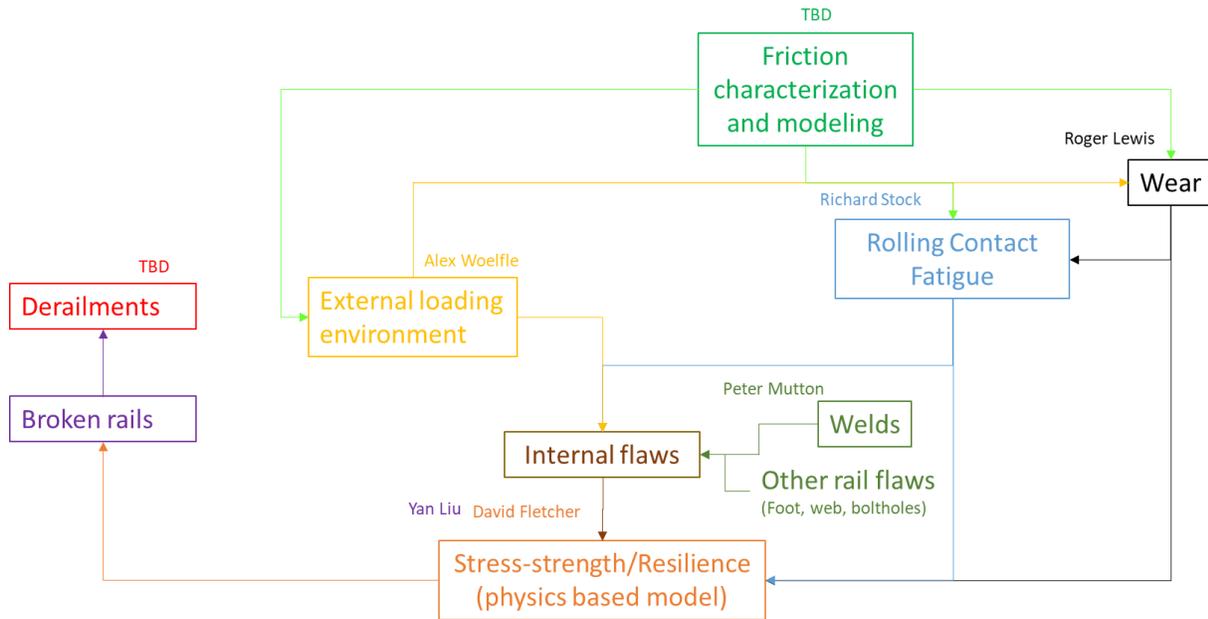Leaders and teams of interested individuals have been or are developing each module shown in Figure 13. Each team was asked to undertake a two-hour workshop/discussion aimed at identifying the module inputs, algorithms and outputs as shown in Figure 14. During these workshops, the teams would also identify current methods/understanding and research gaps or new technology needs. The intention in the immediate term was to narrow the project focus to strictly broken rail derailments, with the expectation that the methodology could then be extended to other derailment types later.
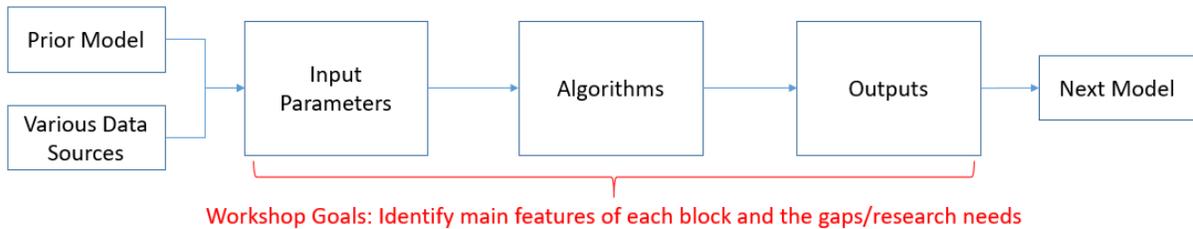
Figure 14: Generic approach to the broken rails modules workshops

Table 12 shows a summary of the broken rails modeling modules from Figure 13 and the status of each.

Table 12: Broken rails modeling modules

Sub-model	Technical Lead	Team Size	First Workshop
1. External Loading Environment	Alex Woelfle (NRC)	TBD	Mar 24, 2022
2. Friction Characterization and Modeling	TBD	TBD	TBD
3. RCF Model	Richard Stock (Plasser)	TBD	TBD
4. Surface Fatigue to Internal Defects	TBD	TBD	TBD
5. Wear Model	Roger Lewis (Sheffield University)	7	Feb 7, 2022
6. Welds and Internal Defects Model	Peter Mutton (Monash University)	19	Feb 22, 2022
7. Stress-Strength/Resilience Model	Chris Ladubec (NRC)	8	June 14, 2022
a. Strength/Resilience Model	David Fletcher (Sheffield University)	15	Feb 16, 2022
b. Stress-Strength Model	Yan Liu and Chris Ladubec (NRC)	8	Feb 17, 2022
8. Broken Rail Derailments	Eric Magel (NRC)	TBD	Presentation at ICRI Vancouver Workshop 2022

3.9.1.1 External Loading Environment

In understanding and modeling of RCF, wear and broken rails, it is important to have a credible loading environment. While WILD data might be sufficient for some tangent running scenarios, in curves the steering and traction forces can lead to a dramatic variation in the stress applied to the rail by any one passing wheelset. Multibody dynamics models can be used to calculate the load distributions on rails/wheels from hundreds or thousands of passing wheels/rails. Car and truck types, friction conditions, wheel profiles, wheel loads and other relevant parameters must be considered, and the resulting load cycles presented for inclusion in subsequent wear, RCF and fracture models.

A workshop was held March 24, 2022 to consider how the loading environment could be established. The results are summarized below.

Figure 15 shows the main input parameters, algorithms, and output parameters identified for characterizing the loading environment.
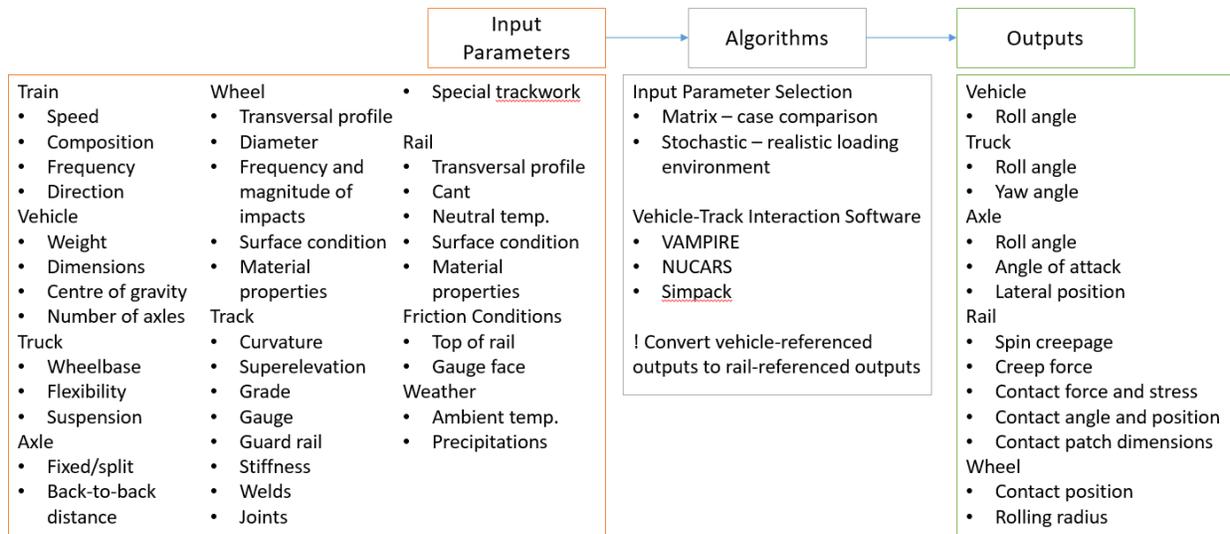

Figure 15: Outline of characterizing the external loading environment module 7.

Table 13 shows all the input parameters from Figure 15 and highlights the **key ones in bold,** and shows the less known ones in red.

Table 13 Identified loading environment input parameters with key ones shown in bold and less known ones in red.

Train	Wheel	Track Substructure
• Speed	• **Transversal profile**	• **Vertical stiffness**
• Composition	• Diameter and **out of**	• **Lateral stiffness**
• Frequency	**roundness**	• **Vertical displacement**
• Direction	• **Frequency and**	**such as track void**
Vehicle	**magnitude of impacts**	Rail
• Weight	**such as wheel flats**	• **Transversal profile**
• Dimensions (truck spacing,	• Surface condition (such as	• **Cant and roll**
wheelbase)	geometrical stress raiser)	• **Surface condition**
• Centre of gravity	Track	**Friction Conditions**
• Number of axles	• **Curvature**	• **Top of rail**
Truck	• **Superelevation**	• **Gauge face**
• Wheelbase	• **Grade**	• **3rd body layer**
• **Flexibility**	• **Gauge**	**contaminants**
• Suspension	• **Track geometry**	Weather
• **Component degradation**	**irregularities**	• Ambient temp.
Axle	• **Irreg. wavelength**	• Precipitations
• Fixed/split	• Guard rail	Operational factors
• Back-to-back distance	• Welds	• **Traction & braking**
	• Joints	
	• Special trackwork	
	• Track damage (such as	
	pull-aparts)	

Wheel and rail material properties were removed from the loading environment input parameters as they are only needed further downstream in the broken rail modeling flowchart.

The next steps identified are to:

1. **Revisit the output definitions and categories** after discussing with the broken rail modeling topics leader downstream of the loading environment in the flowchart.
2. **Define Algorithm flowcharts**. Ask participants of the workshop to create an Algorithm flowchart for their own tools and possible intermediary steps. This information will be used to identify commonalities during the next workshop.
3. **Broken Rail Modeling meeting.** Topic leaders must discuss the outcome of the individual workshops to properly align goals and establish cooperation when sections intersect (e.g., establish what the Wear team needs from Loading Environment team).
4. **Create a Questionnaire** aimed at people who need to recreate the loading environment as part of their own modeling work. The input characteristics would be listed and users asked which ones they consider essential, which can be replaced by assumptions, which aren't used, and which are missing. Answers would help assign a priority to the characteristics which may be vital for future data gathering as part of the broken rail modeling.
5. **Truck suspension degradation.** Do we need to establish the impact of truck component degradation at the wheel/rail interface? Discuss with the industry and, if needed, perform a literature review to identify the gaps.

Lead: Alex Woelfle (NRC)

Participants: Georg Schnalzger (MCL), Werner Daves (MCL), Adam Bevan (Huddersfield), Gerald Trummer (Virtual Vehicle)

3.9.1.2 Friction Characterization and Modeling

Both wear and RCF depend considerably upon friction, including the specifics of the traction-creepage characteristic. There are three ICRI projects underway to investigate friction:

1. Friction modeling (see Section 3.2.1): Klaus Six and Edwin Vollebregt have been leading a project wherein the tribological properties of 3rd body layers are modelled in order to realize high quality VTI predictions.
2. Friction Library (see Section 3.2.2): Davey Mitchell of LB Foster leads an effort to establish and populate a "Friction Library", with data sets collected from a range of operating scenarios and environmental conditions.
    - Past Meetings:
        i. Jan 5, 2022: Kick off meeting.
        ii. Jan 19, 2022: Development of project framework
        iii. Feb 3, 2022: Continue development of project framework
        iv. Feb 24, 2022: Meet with modeling community to determine their needs
        v. Mar 24, 2022: Incorporate modeling community input into project framework
3. Tribometer continuity plan: Ben White of Sheffield University has led this project to continue the development and help troubleshoot the OnTrak railhead tribometer, whilst also providing a platform to collaborate and share friction data. Several meetings have been held with the project team:
    - Past Meetings:
        i. Jan 17, 2022: Kick off meeting.

Unfortunately, there is a lot of uncertainty around this project as the OnTrak tribometer is a commercially developed and owned device and for whom its owner is currently seeking a buyer. Pending resolution of its ownership, this group's efforts are on hold.

Lead: TBD – No leader has been identified for this topic.

3.9.1.3 Rolling Contact Fatigue (RCF) Model

The RCF modelling group has taken on the challenge of, for a given loading environment consisting of many passing wheel contacts, modelling the response of the rail with respect to surface fatigue, considering the interaction with wear (which is a separate but obviously related module).

A survey has been sent out to the team members with the following questions:

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

A workshop has not yet been planned for this topic.

Lead: Richard Stock (Plasser)

Participants: Peter Mutton (Monash), Jay Jaiswal (ARR), David Fletcher (Sheffield), Albert Joerg (Voestalpine), Joe Kristan (Evraz), Gerald Trummer (Virtual Vehicle), Ananyo Banerjee (TTCI), Carlos Casanueva Perez (KTH), Anders Ekberg (Chalmers), Zili Li (TUDelft), Kevin Oldknow (SFU), Maksym Spiryagin (CQ), Almira Meshcheryakova (MIPT)

3.9.1.4 Surface Fatigue to Internal Defects Model

This team recognizes that amongst billions of cracks, only some develop into transverse flaws that cause a broken rail. Can we understand and model how stresses (contact, residual, temperature and bending) interact with surface fatigue cracks to progress to a transverse defect.

Only recently it was determined that the modelling methods for deep cracks are unlike those for shallow cracks and the need for this group was confirmed. It remains to form a research team around this topic.

3.9.1.5 Wear Model

The wear modeling team has been asked to develop algorithms to model the metal removal associated with wear that can be applied to any given loading environment, current surface condition, third-body layers and metallurgical properties.

This workshop was held February 7th, 2022. The results are summarized below in Figure 16 listing the input parameters, algorithms and outputs that would be required to build the wear model.
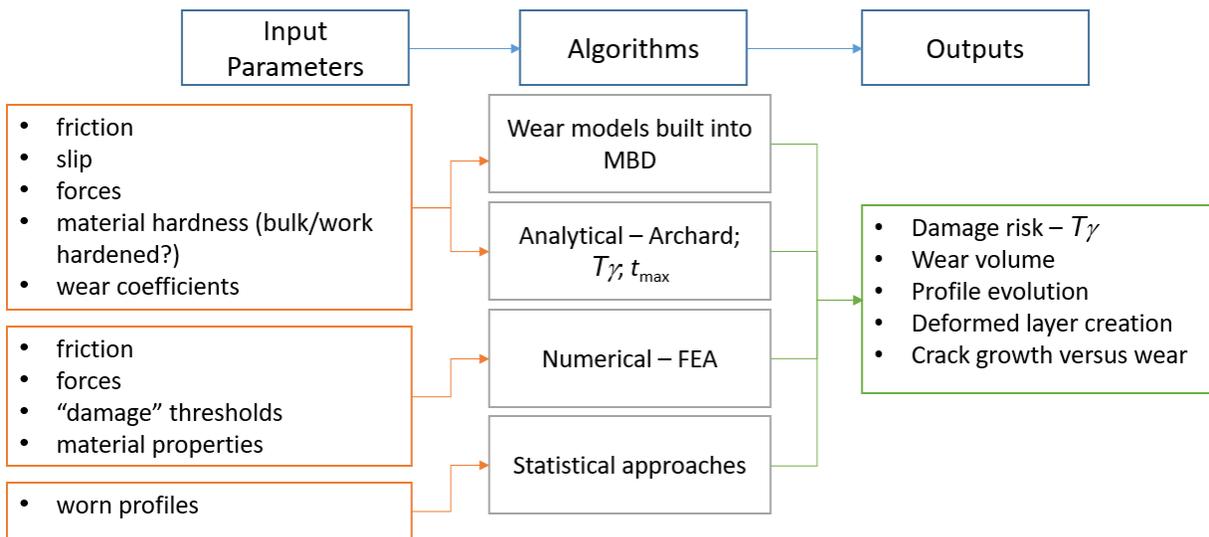

Figure 16: Wear module input, algorithms, and outputs

Where

$T\gamma$ = damage risk
t_{max} = peak traction value (limiting friction coefficient)

Inputs

Table 14 lists the inputs discussed by people in four different stakeholder categories.

Table 14: Inputs to wear models, separated by stakeholder.

Stakeholder	Inputs
Industry	• Worn profiles from wheel and rails. • Friction coefficients and creep curves from rail. • Data on damage – e.g., crack depths in wheels and rails.
Research – Experimental	• Wear coefficients for different materials and operating conditions. • Wear coefficients for third-body layers (3BL). • Measurement techniques for assessing damage/deformation in real time. • Properties of deformed layer.
Research – Dynamics Modelling	• Multi-body dynamics (MBD) simulations to generate wheel/rail interface conditions for wear testing. • Modelling frameworks for using damage algorithms (e.g., Archard/$T\gamma$).
Research – Damage Modelling	• New more physically based modelling approaches.

Gaps:

- Friction data needed – can instrumented wheelsets be used to get this data in the field?
- Real world traction creepage curves at various conditions.
- 3BL properties (shear strength; hardness possibly).
- Material properties of deformed layer.
- More data on transience of all variables.
- While there is good data for some material combinations, more data for different material combinations and 3BLs and contact conditions.
- To reduce wear test demands, critical wheel/rail interface conditions to focus on need identifying (via MBD simulations).

Next Steps

- Collect friction data via ICRI – e.g., data from OnTrak tribometer available.
- OnTrak can also measure traction creepage curves, collect these via user group where possible.
- Projects running to collect properties of deformed layer – this data will feed into discrete element method (DEM) models – keep track of progress.
- Challenge the research world to develop techniques for real time monitoring of deformed layer and damage evolution (can surface observations tell us what is happening subsurface?).
- Look at initiating projects to capture more information on transience.
- Use MBD pummelling data to focus areas for wear investigations.

- Gather more wear data by setting up mini-projects for Masters students (set-up test protocol and list needs and distribute).
- While there is good data for some material combinations, more data is needed for different material combinations and 3BLs and contact conditions.

Algorithms

Table 15 lists the four algorithm types discussed during the workshop.

Table 15: Algorithms discussed during the wear modeling workshop.

Algorithms	Discussion
Wear models built into MBD	− Locally predict wheel (or rail) profile evolution – or globally, material removed. − MBD typically incorporates third body materials incorporated by changing COF; − Friction is a result of the contact conditions! ▪ This can mean errors in force predictions. − Problems with wear predictions. − Need to have better friction data/prediction.
Analytical – Archard; $T\gamma$, t_{max}	− Wear coefficients are usually for dry conditions. − Limited material combinations investigated. − Need more creep force data and wear data for 3BLs. − Need more wear data for different wheel and rail materials.
Numerical – finite element analysis (FEA)	− Brick model; DEM; peri-dynamics (new approach – see Appl. Sci. 2018, 8, 2299; doi:10.3390/app8112299), boundary element layer model. − Can deal with wear and crack growth interaction. − Microstructure and material properties of deformed layer very important. − Damage thresholds, bond strength between grains, etc. − Need more data on deformed layer properties. − Need more data to define damage thresholds.
Statistical approaches	− Based on measured wheel or rail profiles. − Needs MBD alongside, combined with material loss models. − Needs a lot of measured wear profiles.

Gaps:

- Existing models give good wear predictions for wheels under certain conditions (can be expanded with more input data – wear coefficients, etc.) – there is a need for more physically based models though – using material properties as inputs, rather than wear coefficients.
- Wear prediction tools need to consider additional factors: braking/traction; bidirectional running.
- Wear and RCF behavior need to be integrated.

- Existing models give good wear predictions for wheels under certain conditions (can be expanded with more input data – wear coefficients, etc.) but more physically based models are needed that use material properties as inputs, rather than wear coefficients.
- Models of rail wear are not as well developed as those for wheels, the impact of wheel wear on rail wear is important as well.

Next Steps:

- Wear and RCF model integration – Discrete Element Modeling is a good route for this, but is so far only in the early stages of application.
- Most models focus on wheels – rails are more of a challenge – focus on specific wear/RCF hotspots initially?
- More needed on the impact of worn wheel on rail wear/damage.
- Consideration of bidirectional running.
- Consider effects of traction and braking (there is some work being done on driving versus driven discs in twin disc testing, that could help).
- A good starting point would be to model small-scale tests initially to overcome full-scale modelling and validation complexities.

Outputs

Outputs from the wear model will feed into several other elements of the model. These outputs include:

- Damage Risk – $T\gamma$: refers to the wear energy which is used in many models to arrive at a wear volume.
- Wear volume – is the predicted loss of material at any point on the wheel tread or railhead.
- Profile evolution – is the prediction of profile changes as a result of that material loss.
- Deformed Layer creation – a prediction of how the properties of the near-surface layer change as a result of the combined effects of wear and $T\gamma$ loading.
- Crack growth vs. wear – for existing surface cracks, do they propagate (grow deeper) faster than they are worn away?

Gaps and next steps:

- Validation – more field data needed– build data sandboxes?
  - formal route through the Rail Safety and Standards Board (RSSB) may be an option.
- Understand wear versus RCF – monitoring in lab tests initially – need non-destructive testing techniques to see deformation/cracks (Barkhausen noise?).
- Monitoring of wheels – turning carefully to look at crack depth.

Lead: Roger Lewis (Sheffield)

Participants: Adam Bevan (Huddersfield), Simon Groom (Alstom), Eric Magel (NRC), Haohao Ding (SouthWest Jiaotong University), Wenjian Wang (SouthWest Jiaotong University), Alan Lawton (RSSB)

3.9.1.6 Welds and Internal Defects Model

FRA statistics show that the welds are the cause of 30-50% of reported rail breaks. Although the initial interest was to consider breaks due to RCF, it was decided that breaks from welds are too important to ignore and should be considered in this ICRI effort. The question to be answered is: What conditions cause some welds to develop cracks that then grow into large internal flaws that can cause a rail break?

A workshop was held February 7th, 2022. The results are summarized below.

Key aspects for discussion:

- Is there a need to clearly differentiate between broken rails (welds) related to RCF and other (related) phenomena in the rail head, and those due to defects and fatigue in other parts of the rail section, as only the former may be relevant to the ICRI initiative?
- Are RCF-related defects in welds a major consideration in terms of broken rails, and if so, what stress/strength models (for welds) already exist (or require development) that could be incorporated into the overall stress-strength modelling approach?

Discussion points:

- Eric Magel:
  - FRA North American service failure statistics (example shown during the discussion was for 2014-2016 summer/winter periods)
    - Are a primary motivator for ICRI-RCF initiative on Stress-Strength Approach to Modelling Broken Rails.
    - Identified welds as a major contributor (40% in summer, 60% in winter).
  - Weld failures, even in the absence of RCF, account for a large number of rail breaks, and hence should be considered in the modelling approach, perhaps to the extent of identifying what actions can be implemented to reduce broken welds.
- Peter Mutton:
  - Rail welds exhibit a range of physical attributes that differentiate them from parent rails; these include residual stresses, microstructure, strength and hardness, fracture toughness, and for thermite/aluminothermic welds, external geometry and dimensions. Welds may also contain surface or internal defects that result from the welding process itself.
- Weld reliability (John Stanford, BNSF):
  - Industry experience (based on comments from John Stanford (BNSF), Jay Jaiswal (UK) and others) is that flashbutt welds are generally not a problem in terms of service failures.
  - BNSF experience is that rolling contact fatigue and other forms of fatigue damage in the rail head are an important issue, but if you consider this in terms of broken rail prevention, that becomes much less of a factor as ultrasonic rail inspection equipment is extremely effective at finding those kinds of defects. Either you have visual failures or transverse type defects initiating from such cracks and these are found with the rail detector cars. When you look at service failures, what breaks is a very small proportion directly attributed to fatigue of the rail crown and gauge corner, and it is failures in the

non-detectable zones and in the base, web and in the fillet areas that tend to drive the service failures, particularly in thermite welds. Service failures in flashbutt welds really aren't an issue.

- Flashbutt welds:
    - Full grinding of welds (over the complete rail section) to completely restore surface condition (the "invisible weld") results in improved fatigue performance as demonstrated by staircase fatigue tests (Jay Jaiswal, UK)
    - Changing welding conditions to produce welds with narrow heat-affected or softened zones has been examined in the UK and Europe:
        - Reducing the weld width to no more than about 25 mm compared to the 40 mm in normal welds resulted in improved bending strength and fatigue performance (staircase tests). Residual stresses would be expected to be higher, but were not measured. Jay Jaiswal (UK).
        - Use of reduced preheating and higher forging force reduces heat-affected zone width by approximately one third; however, no improvement on RCF performance over standard welds was identified in track testing. Residual stresses in the narrower welds were higher, and this may have been a factor in terms of the observed RCF behaviour (Erik Stocker, Voestalpine).
        - Post-weld heat treatment to reduce residual stress levels has also been found to improve fatigue behaviour, particularly in terms of horizontal split web failures, and is used by one Australian heavy haul system (P Mutton).
- Thermite/aluminothermic welds:
    - Industry experience generally is that these welds have historically been more problematic in terms of service failures, and continue to be problematic in some industry sectors.
    - European experience has been that defect and failure rates have been reduced to a very large extent by improved welder training and close control of welding procedures in the field (i.e., ensuring welds are made correctly). This is consistent with the experience in heavy haul systems, where it is very important that weld installation procedures be properly defined in the first place, and then followed in the field, taking out as much variability as possible.
    - Wide gap welds may be more sensitive to procedural variations than standard gap welds (John Stanford, BNSF), and have shown inferior fatigue performance under laboratory test conditions (P. Mutton).
    - Modelling approaches have been used to examine fatigue behaviour of thermite welds, including sensitivity to weld collar geometry, etc. (Maryam Tavakoli (Texas A&M), Iman Salehi (Swinburne University, Australia)).
    - Peening treatments to improve fatigue performance of thermite welds, in particular fatigue-prone regions at edge of weld collar, include:
        - Ultrasonic peening, Kerry Jones (TTCI);
        - Pneumatic peening technique from Pandrol (Peter Mutton).

- Behaviour of welds in wheel-rail contact and RCF damage
  – Previous research on deformation and dipping behaviour of welds and resultant impact loading was done at Southwest Jiaotong University (China) and University of Huddersfield (UK).
  – Some research is being done in Australia on modelling RCF behaviour in softened zones; however, in general there is not much interest in this topic.
  – Other initiatives to address higher sensitivity of softened zones to welds include:
    ▪ TTCI research on mitigating the hardness differential at the heat-affected zones by means of weld or laser-cladding overlays (Dan Szablewski, NRC).
    ▪ An automated repair technique that excavates the whole width of the weld, whether it be flashbutt or aluminothermic, and automatically deposits a material that is far more rolling-contact-fatigue resistant. An important feature is that after the deposition, the profile is restored to the original profile by milling, not grinding. The whole process is automated and the end product provides much better service. Network Rail is taking this through the organization's product approval system at the moment (Jay Jaiswal, UK).
- Stress-strength modelling
  – (Chris Ladubec, NRC):
    ▪ In regard to later stages of the modelling approach, some aspects of interest in relation to the parent rail and risk of failure are fracture toughness, residual stresses and rail neutral temperature. Hence it would be of high value to understand how those aspects differ for a weld material versus parent rail material.
    ▪ As we think largely in terms of statistical distributions, these distributions for the welds would have much more scatter, but perhaps also differ between weld types, and can be quantified to some degree using existing data. A statistical model could be used to determine distributions for weld defects.
  – A possible next stage could involve identifying and sharing data on the above aspects, perhaps by means of a couple of internal discussions with a smaller focus group. Some guidance may be required in terms of the data types, data formatting, etc.
  – The stress-strength team will develop a general approach that first ignores welds, but later adds in special considerations needed to extend the model to welds, i.e., tweak the model to include welds, including failure modes in welds that do not occur in parent rail.
  – Additional data on North American weld failure statistics (failure types and numbers) should also be examined.
    ▪ Action: Eric Magel to follow this up with John Stanford (BNSF) and Dan Szablewski (NRC).

Lead: Peter Mutton (Monash University)

  – **Participants:** John Stanford (BNSF), CR Battisti (BHP), Feras Naser (Emergence FZE), Jürgen Ju Reinhardt (Deutsche Bahn), Kerry Jones (TTCI), Ananyo Banerjee (TTCI), Frédéric Delcroix (Pandrol), Lionel Winiar (Pandrol), Taryn Peterson (Pandrol), Eric Magel (NRC), Daniel Szablewski (NRC), Philip Shackleton (Huddersfield), Ilaria Grossoni (Huddersfield), Yann Bezin (Huddersfield), Alexander Zlatnik (Voestalpine),

Stephen Lewis (British Steel), Erik Stocker (Voestalpine), Maryam Tavakoli, Chris Ladubec (NRC)

3.9.1.7 Strength/Resilience Model

The questions to be addressed by this team are as follows:

- For a segment of rail, what is its resistance to rail fracture?
- Also – why do some internal defects grow very rapidly (catastrophically) while others do not?
- Considering its worn section, defect history, support and other conditions, can we establish a measure of "strength" that can be compared with the applied stress and establish whether and by how much damage will increment with each passing load?

This workshop was held February 16, 2022. A follow-up meeting with the ICRI coordinators and the Stress vs. Strength module leaders suggested that the System Strength and Stress vs. Strength modules should be combined into one since the underlying technical approach – fracture mechanics – is the same, whether we are talking about damage increments or rail failure. Figure 17 shows the initial concept of the interaction between the separate strength and stress models.
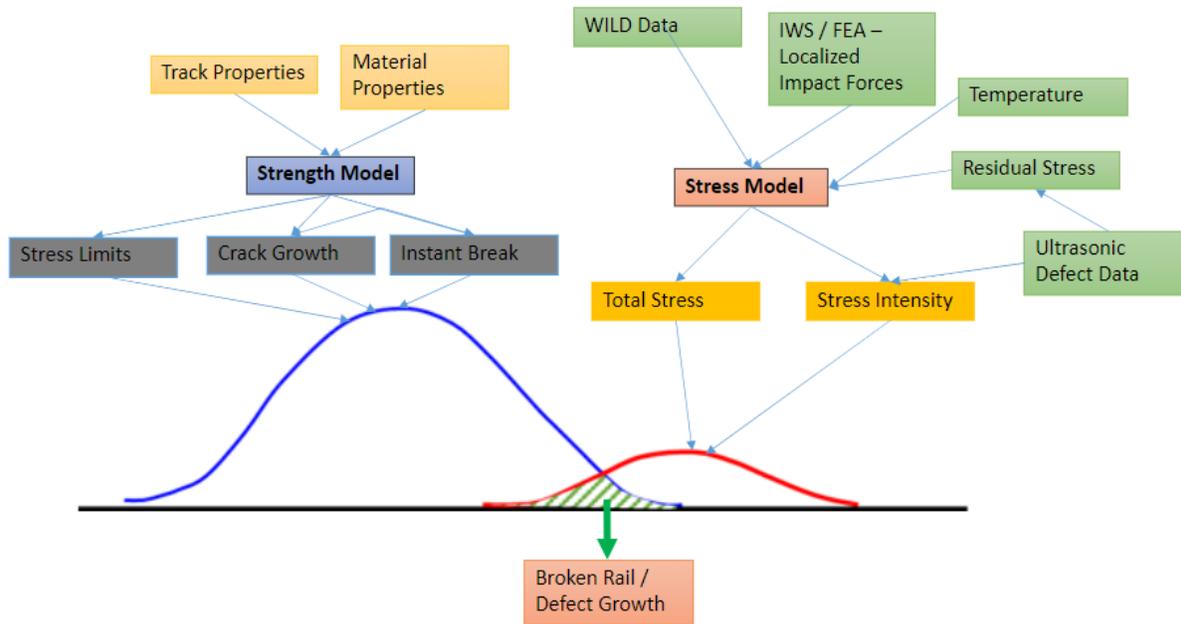
Figure 17: Initial concept of the interaction between the separate strength and stress models.

Lead: David Fletcher (Sheffield)

Participants: Ananyo Banerjee (TTCI), Peter Mutton (Monash), Anders Ekberg (Chalmers), Mark Burstow (Network Rail), Brian Whitney (Network Rail), Stephen Lewis (British Steel), Masahiro Tsujie (RTRI), Hua Chen (RTRI), Richard Stock (Plasser), James Taylor (Thornton Tomasetti), Martin Hiensch (DEKRA), Zili Li (TU delft), Uwe Zerbst (BAM), René Heyder (Deutsche Bahn)

3.9.1.8 Stress vs. Strength

The topic being addressed by this team is as follows:

- Can we combine the loading environment with other stress influencers (residual stress, longitudinal stress, bending, etc.) and compare with the current strength of the rail to determine whether fracture is imminent?

A workshop was held February 17, 2022 and resulted in the creation of a Draft Framework of the Combined Strength and Stress Modules (Figure 18). A follow-on workshop to this is discussed in the following Section (3.9.1.9).
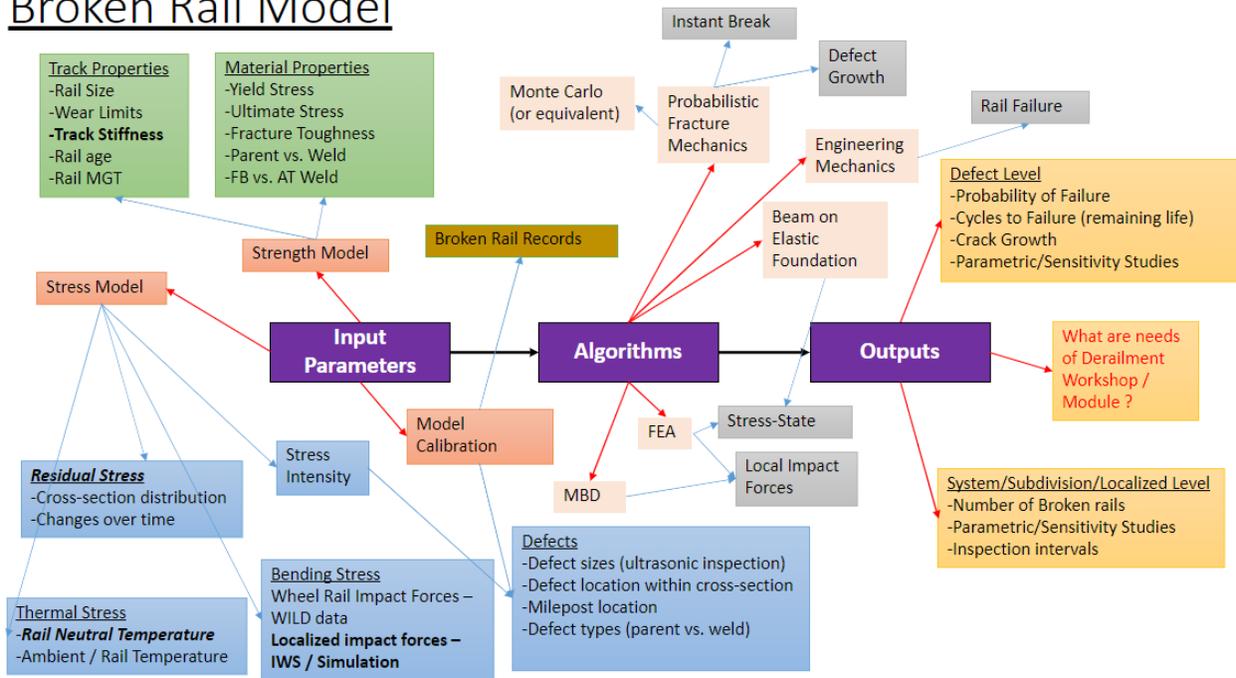

Figure 18: Draft Framework of the Combined Strength and Stress Modules

Leaders: Yan Liu (NRC), Chris Ladubec (NRC)

Participants: Shao Guang Li (Eurailscout), Irina Goryacheva (RAS), Almira Meshcheryakova (MIPT), Hamed Ronasi (Motosel), James Taylor (Thornton Tomasetti), Eric Magel (NRC)

3.9.1.9 Rail Resilience Workshop

Based on the results of the Strength/Resilience Model and Stress vs. Strength workshops, the module leaders suggested that the two efforts be combined into one.

A workshop was held June 14, 2022. The physics-based broken rail model concept (Figure 17) from the strength/resilience workshop was combined with the physics based broken rail model (Figure 18) from the stress vs. strength workshop. The result was a combination of data-driven and physics-based features shown in Figure 19.
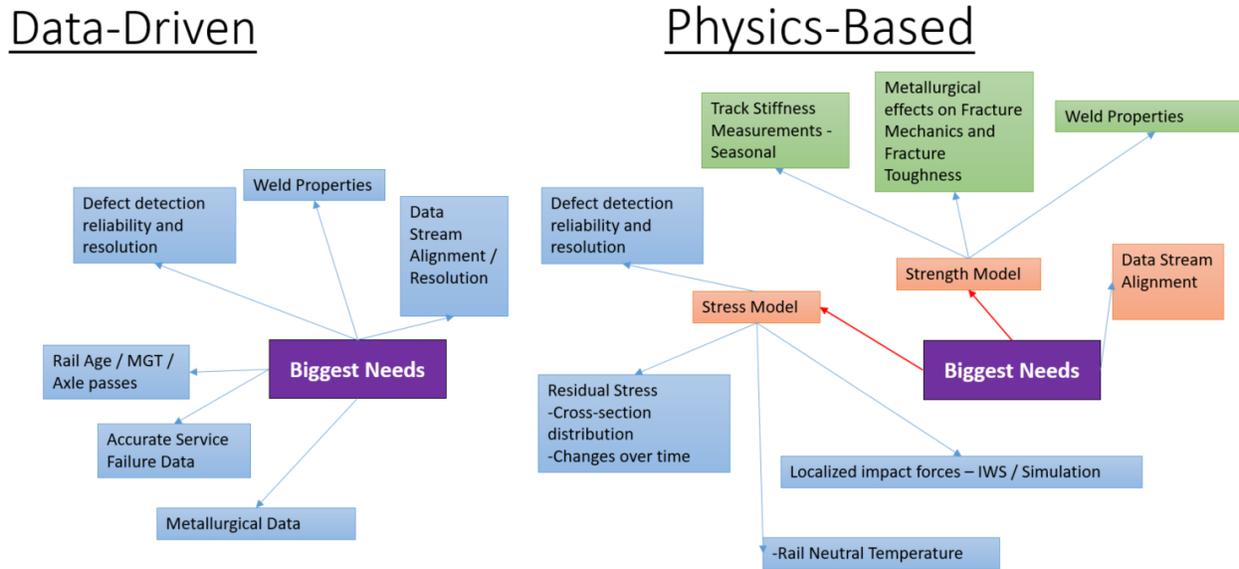
Figure 19: Data Driven Broken Rail Model

The proposed approach shown in Figure 20 uses the defect location (rail head, rail foot, or other) to determine which type of model (physics-based, or data-driven) should be used.
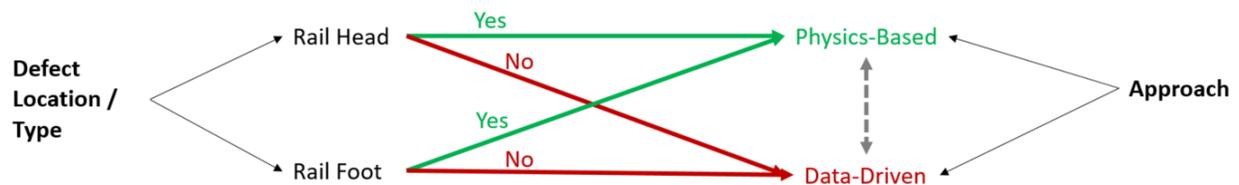
Figure 20: Defect Location and Model Approach

Key points discussed at this workshop included:

- Localized impact forces and track support conditions
- Residual stress
- Improved defect detection technologies
- Wear measurements
- Data alignment – track stiffness, defect location, broken rails, etc.
- Track stiffness measurement
- Combinations of faults
- Combination of Physics based-Data driven models

- Axlebox accelerometer data
- IWS data
- Numerical simulation of localized forces
- Data driven models to predict critical locations

The key areas for future research were identified:

- Residual Stress – understanding its magnitude and distribution through the rail for different metallurgies, in different curvatures, and at varying levels of accumulated tonnage and wear.
- Rail Neutral Temperature – having a measurement or knowledge of the neutral temperature enables accurate calculation of the thermal stresses.
- Defect detection – Improving the reliability and resolution of defect detection for different defect types and positions (e.g. head vs. foot) is important so that defects can be removed before they reach a critical size.
- Better alignment of data streams – data inputs to the loading environment model (e.g. geometry, profile, IWS, track stiffness, etc.) may come from different systems at different times and accurate alignment of those data sets is crucial to the development of credible models.
- Track stiffness measurements – local variations in track stiffness will affect the bending stresses and impact forces the rail must withstand.
- Better understanding of localized forces – characterizing localized wheel rail impact forces using tools such as IWS/Axlebox Accelerometers/FEA/MBD can help identify and remediate high risk track locations.
- Weld quality assessment is another important aspect to identify high risk locations and mitigate broken rail risk. Manual inspections to many welds made in different years are difficult and there is a need to develop an automation process based on new or existing technology.

NRC has submitted a proposal to the FRA for "Defect Growth and Allowable Wheel Rail Impact Forces using Statistical Models of Residual Stress". The objectives of this project are to:

- Extend the existing NRC defect framework to evaluate the contribution of a wheel population that has moderate impact forces, lower than the WILD threshold used by the industry, on the incremental defect growth and the broken rail risk.
- Assess the effect of different residual stress patterns on defect growth. If sufficient data is available, statistical representations of the stress distribution can be approximated.
- Integrate defect growth and residual stress distribution into the existing stress - strength model.

Leader: Chris Ladubec (NRC)

Participants: Hua Chen (RTRI), Ananyo Banerjee (TTCI) James Taylor (Thornton Tomasetti), Hamed Ronasi (Motosel), Brian Whitney (Network Rail), Stephen Lewis (British Steel), Richard Stock (Plasser, Canada)

3.9.1.10 Broken Rail Derailments

Amongst thousands of broken rails that occur, only a handful result in a broken rail derailment. We need to first understand what those factors are and then try to model them. Such a model would facilitate a

derailment risk assessment based on (hopefully) measurable parameters that could be used to focus maintenance and upgrades, ultimately reducing derailments and improving safety.

A web meeting was held June 7, 2022 that explored contributing causes. An important conclusion was that railroads should analyse their defect types in terms of survivable and fatal, and then concentrate on the fatal defects that the signalling system fails to detect.

The next steps for this team are:
- To get three Class 1 railroads to agree to provide defect and derailment data for such a project. Grouping and analyzing the data would enable the ICRI to develop a credible story that reflects industry experience.
- As there is "huge operator discretion" when it comes to establishing whether an ultrasonic test is valid, we should try to eliminate subjectivity from the process.

Leader: Eric Magel (NRC)

Participants: Mike Roney, Brad Kerchof, John Stanford (BNSF), Gary Wolf, and Norm Hooper

3.9.2 ICRI Broken Rails Modeling Phase 2

Through a series of on-line workshops, various elements of a comprehensive model conceived to facilitate predictions of broken rails and related derailments were explored. As each team worked through their respective elements, they summarized the key requirements and highlighted many research questions and needs.

3.9.2.1 External Loading Environment

A detailed model of the loading applied to the rail(s) and wheel(s) requires a number of initial inputs to be defined. The more accurately each parameter can be characterized, the more credible will be the resulting predictions.

Table 13 above shows all the input parameters from Figure 15 and highlights the **key ones in bold,** and shows the less known ones in red.

Table 16 shows the input parameters (determined in Section 3.9.1.1 above) and highlights **in bold the measurable and highly variable ones**, while those in red would benefit from new measurement systems.

Table 16: Identified loading environment input parameters with measurable and highly variable ones shown in bold and parameters that would benefit from new measurements systems in red.

Train	Wheel	Track Substructure
• Speed	• **Transversal profile**	• **Vertical stiffness**
• Composition	• Diameter and **out of roundness**	• **Lateral stiffness**
• Frequency	• **Frequency and magnitude of impacts such as wheel flats**	• **Vertical displacement such as track voids**
• Direction		
Vehicle		Rail
• Weight	• Surface condition (such as gsr)	• **Transversal profile**
• Dimensions (truck spacing, wheelbase)	Track	• **Cant and roll**
• Centre of gravity	• **Curvature**	• **Surface condition**
• Number of axles	• **Superelevation**	**Friction Conditions**
Truck	• **Grade**	• **Top of rail**
• Wheelbase		• **Gauge face**

• **Flexibility** • Suspension • **Component degradation** Axle • Fixed/split • Back-to-back distance	• **Gauge** • **Track geometry irregularities** • **Irreg. wavelength** • Guard rail • Welds • Joints • Special trackwork • Track damage (such as pull-aparts)	• **3rd body layer contaminants** Weather • Ambient temp. • Precipitations Operational factors • **Traction & braking**

The next steps identified by the group are:

1. Develop approaches to collect lesser-known inputs
2. Revisit the output definitions and categories after discussing with the broken rail modeling topics leader downstream of the loading environment in the flowchart.
3. Define Algorithm flowcharts.
4. Assign a priority to the characteristics
5. Further explore the issue of truck suspension degradation. Do we need to establish the impact of truck component degradation at the wheel/rail interface? Discuss with the industry and, if needed, perform a literature review to identify the gaps.

3.9.2.2 Friction Characterization and Modeling

Recruit a module leader and define next steps.

3.9.2.3 Rolling Contact Fatigue (RCF) Model

Plan a workshop to discuss potential survey questions:

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

3.9.2.4 Surface Fatigue to Internal Defects Model

It remains to form a research team around this topic.

3.9.2.5 Wear Model

Table 17 shows the list of identified gaps and next steps for the wear model module divided by inputs, algorithms, and outputs.

Table 17: Identified gaps and next steps for the wear model module

	Gaps	Next Steps
Inputs	• Friction data needed – can instrumented wheelsets be used to get this in the field? • Real world traction creepage curves at various conditions; • 3BL properties (shear strength; hardness possibly); • Material properties of deformed layer; • More data on transience of all variables; • While there is good data for some material combinations, more data is needed for different material combinations and 3BLs and contact conditions; • To reduce wear test demands, critical wheel/rail interface conditions to focus on need identifying (via MBD simulations).	• Collect friction data via ICRI – e.g., data from OnTrak available; • OnTrak can also measure traction creepage curves, collect these via user group where possible; • Projects running to collect properties of deformed layer – this data will feed into discrete element method (DEM) models – keep track of progress; • Challenge the research world to develop techniques for real time monitoring of deformed layer and damage evolution (can surface observations tell us what is happening sub-surface?); • Look at initiating projects to capture more information on transience • Use MBD pummelling data to focus areas for wear investigations • Gather more wear data by setting up mini-projects for Masters students (set-up test protocol, list needs and distribute) • While there is good data for some material combinations, more data is needed for different material combinations and 3BLs and contact conditions

	Gaps	Next Steps
Algorithms	• Existing models give good wear predictions for wheels under certain conditions (can be expanded with more input data – wear coefficients etc.) – there is a need for more physically based models though – using material properties as inputs, rather than wear coefficients; • Wear prediction tools need to consider additional factors: braking/traction; bi-directional running; • Wear and RCF behavior need to be integrated; • Models of rail wear are not as well developed as those for wheels, the impact of wheel wear on rail wear is important as well.	• Wear and RCF model integration – DEM is a good route for this, but is so far only in the early stages of application; • Most models focus on wheels – rails are more of a challenge – focus on specific wear/RCF hotspots initially? • More needed on the impact of worn wheel on rail wear/damage; • Consideration of bi-directional running; • Consider effects of traction and braking (there is some work being done on driving versus driven discs in twin disc testing, and that could help); • A good starting point would be to model small-scale tests initially to overcome full-scale modelling and validation complexities.
Outputs	• Validation – more field data needed– build data sandboxes? o formal route through the Rail Safety and Standards Board (RSSB) may be an option; • Understand wear versus RCF – monitoring in lab tests initially – need non-destructive testing techniques to see deformation/cracks (Barkhausen noise?); • Monitoring of wheels – turning carefully to look at crack depth	

3.9.2.6 Welds and Internal Defects Model

A workshop was held to discuss the influence of welds on broken rails. The following questions arose:

- Is there a need to clearly differentiate between broken rails (welds) related to RCF and other (related) phenomena in the rail head, and those due to defects and fatigue in other parts of the rail section, as only the former may be relevant to the ICRI initiative?
- Are RCF-related defects in welds a major consideration in terms of broken rails, and if so, what stress/strength models (for welds) already exist (or require development) that could be incorporated into the overall stress-strength modelling approach?
  - A possible next stage could involve identifying and sharing data on the above aspects, perhaps by means of a couple of internal discussions with a smaller focus group. Some guidance may be required in terms of the data types, data formatting, etc.
  - The stress-strength team will develop a general approach that first ignores welds, but later adds in special considerations needed to extend the model to welds, i.e., tweak the model to include welds, including failure modes in welds that do not occur in parent rail.
  - Additional data on North American weld failure statistics (failure types and numbers) should also be examined.

3.9.2.7 Stress-Strength/Resilience Model

The key areas for future research are:

- Residual stress – understanding its magnitude and distribution through the rail section for different metallurgies, in different curvatures, at varying levels of accumulated tonnage and wear.
- Rail neutral temperature – having a measurement or knowledge of the neutral temperature will enable accurate calculation of the thermal stresses.
- Defect detection – understanding the reliability and resolution of defect detection for different defect types and position (e.g., head vs. foot)
- Better alignment of data streams – data inputs to the loading environment model (e.g., geometry, profile, IWS, track stiffness, etc.) may come from different systems at different times and accurate alignment of those data sets is crucial to the development of credible models.
- Track stiffness measurements – local variations in track stiffness will affect the bending and impact forces the rail must withstand.
- Better measurements and understanding of localized forces – will require measurements with instrumented wheelsets and or finite element analyses and/or multi-body dynamics modeling.

3.9.2.8 Broken Rail Derailments

Because derailments are relatively rare events, it is difficult to amass sufficient relevant data for analysis. FRA statistics do cover derailments but that data set is devoid of details required for analysis and correlation. The most useful sets of data are owned by the railroads. A possible approach to advance this topic would be to:

- get three Class 1 railroads to agree to provide defect and derailment data for such a project. Grouping and analyzing the data would enable the ICRI to develop a credible story that reflects industry experience.
- Recognizing that there is "huge operator discretion" when it comes to establishing whether an ultrasonic test is valid, approaches should be developed to eliminate subjectivity from the process.

3.10 Rail Defect Simulation Using Agent Based Modelling (ABM)

Agent-based models are microscale models that simulate the simultaneous operations and interactions of multiple agents to recreate and predict complex phenomena. They combine elements of complex systems, emergence, multi-agent systems, and evolutionary programming. Agent-based modelling is much more computationally efficient at reproducing the complex systems than classical approaches based on solving numerous partial differential equations.

Most agent-based models are composed of:

- many agents specified at various scales
- decision-making heuristics
- learning rules or adaptive processes
- an interaction topology
- an environment

Using agent-based modeling is especially beneficial when:
- Large number of entities of different fidelity and properties are involved
- Entities will dynamically change during the simulation
- Extremely large numbers of simulation scenarios are needed

3.10.1 Broken Rail Prediction Model

A broken rail prediction model was developed by University of Illinois at Urbana-Champaign and funded by BNSF to assist in risk analysis and accident prevention [19]. The expected broken rails per mile per year is expressed as follows:

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

(1)

$$u = Z^* + c_1 S + c_2 R + c_3 A + c_4 T + c_5 L + c_6 I + c_7 G + c_8 B$$

(2)

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 in the last three years (1 if present, 0 otherwise)

G = presence of a geometric defect in the last three years (1 if present, 0 otherwise)

B = presence of a bridge within 200 feet of segment (1 if present, 0 otherwise)

$C_1, C_2, C_3, ..., C_8$ = coefficients

In the original model, the values for the adjusted model constant Z^* and coefficients $C_1, C_2, C_3, ..., C_8$ were based on data from the BNSF railway in the USA. The model was modified based on Canadian railway traffic and track data and used to predict broken rail service failure numbers for some Class 1 and shortline subdivisions in Canada [22] [23].

An agent-based model and simulation tool is being developed to predict rail defects which can be used in the aforementioned broken rail prediction model.

3.10.2 Rail Defect Simulation Using Agent Based Modelling

Over the course of several months, the NRC simulation team reviewed the capabilities of ABM, identified an instance in the literature where ABM was used for simple derailment modeling, and developed a basic

framework for more advanced modelling using the NetLogo modelling system. A powerful feature of the agent-based approach is that by using a randomized process, very interesting phenomena can emerge that you might not discover using other approaches.

A preliminary study was conducted and presented at an ICRI workshop in April 2022 on agent-based modelling of rail defect development and broken rail probability. A screenshot of the tool demonstration is shown in Figure 21 below. A generic track profile (curvature, grade, gauge, speed, superelevation) was developed to represent typical Canadian mountain railway systems. This profile was applied to a railroad subdivision 100 km in length that was then broken down into 10,000 segments (of 10m each) shown in the right hand of the screen. Each segment is then assigned properties based on a probability distributions of rail section, friction conditions, levels of wear, geometry, location of welds, etc. Then over that track we run trains whose properties also come from probability distributions that cover chiefly wheel nominal and impact loads. And at the same time, rail temperature fluctuates according to probability distributions harvested from historical temperature data.

Figure 21: NRC ABM Model in progress

Model inputs can be adjusted with buttons, sliders, input boxes on the upper left side of the window. Sliders allow a variety of parameters to be adjusted, including:

- Annual traffic (MGT)
- Rail neutral temperature, track modulus, severity factor
- Rail inspection and maintenance periods
- Train length
- General friction conditions
- Train speeds

Parameters and factors considered in the modelling include but are not limited to:

- Train types
- Weather condition (temperature, rain, snow)
- Curvature, superelevation, train speed, rail hardness, rail age, rail weight, rail type, car weight, etc.

- Friction coefficients and their seasonal variation
- Special trackwork and bridge locations

The model is run hundreds of times in the NetLogo environment to predict the number of broken rails and derailments. On the lower left part of the window are two plots showing the sizes of the rail defects along the track and the time history of total number of defects currently in track (blue) and the accumulated number in red. Steps in the defect number correspond to inspections and immediate removal of detected defects. The predicted values are compared with historical or expected numbers and the model refined. Where available, physics-based relationships are included. While the results are encouraging, they are of exploratory nature. Further development of the models and the tool is required before they can be used to study the effects of various factors on rail defects, broken rails and broken rail-related derailments.

The next steps are to add the following capabilities to the modelling of rail defect development and modelling of broken rail prediction:

- Rail defect initiation
- Physics-based rail defect development
- Data-driven rail defect development
- Rail defect detection and removal
- Physics-based broken rail prediction
- Data-driven broken rail prediction

4 Summary of Research Questions and Needs

The many efforts of the ICRI over the last few years were reviewed and the research questions and identified gaps in knowledge have been extracted and summarized here. The plan is for these to serve as the basis for future research plans.

4.1 RCF, Wear and Broken Rail Derailments

A paper was published by several ICRI members on the topic of rolling contact fatigue, wear and broken rail derailments [12]. It concluded by listing a series of questions that needed further exploration:

- Is it possible to quantify a severity of surface fatigue cracking at which the effectiveness of ultrasonic detection is seriously compromised?
- What are the crack driving forces when there are multiple cracks in close proximity, and when/why does a dominant crack form?
- What are the conditions under which a long, but otherwise dormant crack deviates deep into the rail and precipitates a break?
- Which is more dangerous: widely spaced cracks or densely spaced cracks?
- While the mechanism of fluid entrapment and subsequent crack face lubrication and hydraulic crack propagation appears to be sound theory, is there any way—experimentally or otherwise—to distinguish the contribution of these two phenomena in an operating railway, and to establish the volume of water or lubricant in an operational crack and thereby model and quantify its effect?
- What happens with cracks that are not fully removed during a rail grinding cycle? Are these residual cracks benign or are they more or less dangerous than new cracks?

4.2 Wear modelling

From the wear modeling team come the following needs:

- Improved models of rail wear, as the bulk of work to date has been for wheel wear.
- Stronger integration of Wear and RCF behavior.
- More physically based models are needed that use material properties as inputs, rather than wear coefficients.
- Inclusion of bidirectional running, traction and braking.

4.3 Damage Modeling/Rail Grinding

A reliable way of knowing/measuring the presence or severity of RCF over long stretches of rail is needed so that this can be included as an automated data stream into planning software.

Several research questions have been identified to help in establishing the relationship between grinding and RCF:

- How soon should new rail be ground?
- Is mill scale grinding really necessary?

- What happens with residual cracks—are these more or less "dangerous" than newly initiated cracks of the same length?
- Is there any evidence that coarse grinding can initiate RCF?

There is a need for techniques for real time monitoring of deformed layer and damage evolution (can surface observations tell us what is happening subsurface?).

4.4 Friction

Some generic and practical questions and research gaps that arise for a given scenario:

- How much should we lubricate?
- What is the optimal friction modifier characteristic?
- How should we balance top of rail and flange lubrication?
- Where should I place lubricators?

Some data and research gap have been identified:

- Meaningful, real-world friction data (e.g., IWS, locomotive traction curves)
- How to best characterize 3BL properties (shear strength; hardness possibly)
- Transience of all variables.
- While there is good data for some material combinations, more data is needed for different material combinations and 3BLs and contact conditions.

With respect to the impact of friction modifiers (FM) on RCF, we need to:

- Develop (or gather, if they already exist) relationships between the amount of product applied and the RCF and wear reductions.
- Understand the differences, if any, between the different types of friction modifiers available.
- Understand the impact of short-term system failures (e.g., short periods of "dry" rail).

4.5 Relationship between RCF and Internal Defects

Why, amongst the billions of surface cracks in rail, do only a few dive downwards and precipitate a rail fracture? Besides the existence of a crack, there are many other features that might contribute to an internal defect, including metallurgical imperfections (inclusions), adverse residual stress patterns, unfavorable profiles and the resulting contact stress conditions, and rail bending stresses arising as a result of local loading conditions. Those remain to be researched.

4.6 Strength Model (resistance to rail breaking)

The following key properties affecting the resistance of rail to breakage need to be combined and contribute to a physics-based model of rail "strength" or at least the relative resistance to breakage:

- Material properties—the strength properties of a given batch or type of steel are generally known. But:

- How well understood is the impact of different metallurgies on performance with respect to RCF? While shakedown modeling using hardness is common, hardness alone is not a sufficient indicator of real-world performance. What other properties should we be measuring? Ductility and fracture toughness are likely to be key properties.
  - Can we measure the relevant metallurgical properties with confidence?
  - How well understood is the impact of those metallurgical/mechanical properties on RCF initiation and propagation?
  - How does metallurgy interact with other factors (e.g., contact mechanics, friction management etc.)?

- Million gross tons of traffic in a year (MGT) - this number is very useful to estimate the fatigue crack growth, combined with WILD data. But what is the role of MGT? Is a recently ground and clean rail with 200 MGT of accumulated tonnage expected to perform any differently than a new, recently ground and clean rail of the same metallurgy? Should MGT since last ground be a more important parameter? But what if cracks were not fully removed by the grinding?

- Defect history—there is an assumption that a segment of track that has a historical rate of defects per mile will continue to have the same into the future. Over a longer length of rail this might be true, but if an internal defect or vulnerability is removed from a stick of rail (e.g., a 39 or 78 foot length) then should not that stick be more resistant to further failure? Of course, the introduction of another weld to remove the defect might increase the probability of failure. Further understanding needs to be developed.

- Current condition—If we believe that the probability of breakage is related to the severity of surface damage, then the emerging capabilities to quantify surface fatigue are key.

4.7 Derailment Modeling

Under what conditions does a broken rail lead to a derailment? This will undoubtedly require a detailed review of derailment incidents, but is expected to include the existence of defect clusters, inadequate fastening and high local forces (e.g., track geometry perturbations) as contributing factors. Proximity to crossings, switches and bridges may be exacerbating factors, though those may affect derailment severity more rather than probability.

The biggest challenge is that derailments are relatively low frequency (i.e., rare) events and detailed data from any event is not publicly available. The railroads would be the best source for data but are reluctant for it to be used for a public activity.

5 Conclusions

The International Collaborative Research Initiative continues to work in areas of rolling contact fatigue, friction modeling, wear, damage modeling and measurement, and rail safety; including a broken rails modeling initiative and a new field studies initiative. The current status of these projects has been reported. The summer 2023 BNSF field study is expected to foster further collaboration between ICRI members and renew participation in some of the project initiatives.

The rail safety topic has progressed through rail defect simulation using Agent Based Modelling and the ICRI broken rails modeling initiative that seeks to develop a comprehensive model of broken rail and broken rail derailments. The framework breaks the problem into seven distinct modules, with teams for five of the seven modules having identified the module inputs, algorithms and outputs, the current methods / understanding, and research gaps or new technology needs.

A major function of the ICRI is to bring together researchers to discuss and formulate collaborative research opportunities, which was achieved through both in-person and web-based workshops. Over 110 members gathered across the 3 in-person workshops which took place in Ottawa, Vancouver and Melbourne. Four separate web sessions were held, including 2 workshops, attracting over 350 viewers.

The ICRI continues to grow, having added 70 members, 6 countries and 26 new organizations to its membership list in 2022-23. It now numbers over 400 individuals from 186 organizations in 35 countries.

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Abbreviations and Acronyms

3BL	third-body layer
ABM	agent-based modelling
ADHERE	ADHEsion REsearch challenge
ARM	Advanced Rail Management
AREMA	American Railway Engineering and Maintenance-of-Way Association
BART	Bay Area Rapid Transit
BNSF	BNSF Railway
CM 2022	12th Int'l Conference on Contact Mechanics and Wear of Rail/Wheel Systems
COF	coefficient of friction
CP	Canadian Pacific Railway
DEM	discrete element method
EC	eddy current
EGI	equivalent grinding index
FEA	finite element analysis
FRA	Federal Railroad Administration (USA)
GF	gauge face
GQI	grinding quality index
ICRI	International Collaborative Research Initiative
IAVSD	International Association for Vehicle System Dynamics
IE	International Engineering
IHHA	International Heavy Haul Association
IP	intellectual property
IWS	instrumented wheelset
MBD	multi-body dynamics
MGT	million gross tons of rail traffic passing over a track in a year
MWR	magic wear rate
NRC	National Research Council Canada (Canada)
NTSB	National Transportation Safety Board (USA)
RCF	rolling contact fatigue
RRAB	Railway Research Advisory Board
RSAC	Railroad Safety Advisory Committee (USA)
RSSB	Rail Safety and Standards Board
TC	Transport Canada
TOR	Top of rail
TSB	Transportation Safety Board of Canada
TTCI	Transportation Technology Center, Inc.
UK	United Kingdom
USA	United States of America
VTI	vehicle-track interaction
V/T SIC	Vehicle/Track System Interface Committee
WPD	wheel profile detector
WILD	wheel impact load detector
WRI	wheel-rail interaction
WRI 2022	27th annual Wheel Rail Interaction Conference