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FINAL REPORT

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

3-Year Project Review
(March 2019 – March 2022)

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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 330 persons from 28 countries, including 36 railroads, 45 suppliers, 39 universities, 22 consultant and 9 government organizations.

The authors are grateful to organizations that provided financial sponsorship of the program during this reporting period:

- 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 for each of the past three years are listed below, in alphabetical order:

2021-2022:

- Advanced Rail Management (Canada)
- Central Queensland University (Australia)
- COWI (Denmark)
- CSX Railroad (USA)
- Huddersfield University (UK)
- Istanbul University - Cerrahpaşa (Turkey)
- LB Foster (Canada)
- Loram (USA)
- Monash University—Institute of Railway Technology (Australia)
- Plasser (Canada and USA)
- Sentient Science (USA)
- Sheffield University (UK)
- Simon Fraser University (Canada)
- Thornton Tomasetti (USA)
- Transportation Technology Center, Inc. (TTCI) (USA)
- Vehicle Dynamics (USA)
- Virtual Vehicle (Austria)
- Virginia Tech (USA)
- VTech CMCC Computing (Netherlands)

2020-2021:

- Advanced Rail Management (Canada)
- CSX Railroad (USA)
- Huddersfield University (UK)
- Istanbul University (Turkey)
- LB Foster (Canada)
- Sentient Science (USA)
- Sheffield University (UK)
- Virtual Vehicle (Austria)
- VTech CMCC (Netherlands)

2019-2020:

- Advanced Rail Management/Wheel-rail interaction (WRI) seminars
- CP Railway
- CSX Railroad (USA)
- Huddersfield University
- LB Foster (Canada)
- London Underground (UK)
- Loram Maintenance of Way, Inc. (USA)
- Monash University—Institute of Railway Technology (Australia)
- Norfolk Southern Railway (USA)
- Rohmann LP (USA)
- Sheffield University (UK)
- Vehicle Dynamics LLC
- Virtual Vehicle (Austria)
- VTech CMCC Computing (Netherlands)

Executive Summary

2019 started off strong with its annual conference drawing nearly 60 persons for two and a half days of presentations and discussion in Vancouver. The most exciting outcome was that two railroads announced field programs involving novel measurement technologies and unique test conditions. Although these programs have not yet come to fruition (due to COVID 19 restrictions and resource shortages) one of the railroads (Norfolk Southern Railway) has re-engaged and the project could start by mid-year 2022.

Plans were made for the 2020 workshop to be held in Istanbul Turkey in April of that year. The COVID-19 pandemic led to the workshop's cancellation. In lieu of the workshop, many presentations were provided remotely using an internet based platform. Between April 2020 and March 2021, 16 technical presentations and 2 workshops were given in 12 separate sessions. Attendance varied between 31 and 150 persons for any session, averaging 70 participants.

In 2021, an in-person workshop was not feasible so the ICRI webinars continued to serve the purpose of maintaining knowledge transfer and sharing between the ICRI members. Between April 2021 and March 2022, 11 technical presentations were given in 9 separate sessions. Attendance varied between 41 and 101 persons for any session, averaging 67 participants.

Planning for three in-person conferences/workshops is underway for 2022: 1) a three day in-person workshop is planned in Ottawa for April 26-28, 2022; 2) a half day workshop will be held during the WRI Transit Principles Course at the 27th annual Wheel Rail Interaction Conference in Vancouver on June 21st, 2022; 3) a full day workshop will be held during the 12th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems in Melbourne Australia on September 4th, 2022.

Coordination efforts were increased considerably in the second half of 2021 and into 2022; team meetings were organized for and progress has been made by each of the six research topics, with several new sub-topics emerging.

The Friction Modeling Studies are nearing completion after benefiting from supplemental Federal Railroad Administration (FRA) funding to ICRI partners and some results were presented at a July 2020 ICRI webinar. A follow-up project proposal has been submitted to FRA and two additional efforts have been added to this research topic; Friction Library and Tribometer Business Continuity Plan. The first involves the collection of existing and new friction related data into a centralized database to support modeling efforts under a range of conditions, while the latter seeks to continue the development and technical support of the new International Engineering (IE) Tribometer whose survival is currently uncertain following the death of its inventor.

The Quantify Surface Damage team continues to populate the matrix with rail samples sent by the community and a final report is expected by the beginning of 2023. The Wear Mapping and VTI Economics projects are nearing completion, although ongoing improvements and publications are expected. The Damage Modeling project made only incremental progress within the ICRI, though partners have continued to develop models within their own organizations. Profile Scoring Parameter

Working Groups are being developed for the new initiative to develop a methodology for rail profile scoring.

Building off the rail safety work and risk analysis that was completed in 2020-2021, a research framework for modelling broken rail derailments was developed. This is the largest ICRI project ever and involves several different modules that may eventually be integrated into a single model. Teams of interested individuals have been tasked to develop each of the seven distinct modules; identify the module inputs, algorithms and outputs, the current methods/understanding, and research gaps or new technology needs. A report and project proposal for the next step is expected in the beginning of 2023.

Membership in the ICRI continues to rise, with this most recent year being very successful from that perspective. The ICRI now numbers over 330 individuals from 160 organizations in 29 countries, a gain of over 130 persons, 57 organizations and 10 countries in the last three years period.

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1 Introduction

There are many persons and organizations working to understand the problems of wear and rolling contact fatigue (RCF), and 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.

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. This sharing would occur without the "carrot and stick" approach of funding and contracting that exhausts so much effort in its generation and accounting, but contributes nothing to new knowledge development.

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."

Key tasks for the 3-year project period (2019-2022), according to statements of work with both the FRA and Transport Canada, were to:

- Champion, coordinate and manage the ICRI's ongoing efforts. These include:
  - 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;
  - Specifically, NRC would:
    - Initiate and coordinate at least one new research project;
    - Continue 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;
      - Evaluating the relationship between surface fatigue and the effectiveness of ultrasonic detection;
      - Evaluating the cost of RCF and wear to the Canadian Railway Industry;
  - While identifying new topic areas, developing and guiding those with collaborative, in-kind contributions until they reach a state requiring direct funding;

- Recruiting additional organizations and researchers as required for participation in projects; and
- Organize and host an annual workshop, and regular web meetings (at least four per year) and events.

- Explore specific topics including:
  - Refining an economics model to understand the cost of wheel-rail issues to the Canadian railway industry;
  - Evaluating existing inspection tools and to develop new approaches for quantifying the severity of surface damage on rails and wheels; and
  - 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.
- Submit annual reports that review ICRI ongoing efforts and accomplishments and (for Transport Canada) present those each year to the 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 3 years.

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 website lists the following 7 research topics, with four new sub-topics —see Table 1. Each of these efforts will be discussed in further detail in Section 3.

Table 1: Ongoing and new ICRI topics

Title	Champion(s)	Status
Friction Modeling		
Friction Modeling Studies	Edwin Vollebregt (CMCC, Netherlands) Klaus Six (Virtual Vehicle, Austria)	Nearing completion and follow-up project proposal submitted to FRA.
Friction Library **(NEW)**	Davey Mitchell (LB Foster, Canada)	Framework or library being defined. Monthly meetings started in Jan 2022.
Tribometer Business Continuity Plan **(NEW)**	Ben White (Sheffield University, UK)	First meeting held Jan 2022.
Quantify Surface Damage	Daniel Szablewski (NRC, Canada)	Team continues to populate the matrix with rail samples sent by the community.

Title	Champion(s)	Status
Wear Mapping	Roger Lewis (Sheffield University, UK)	Nearing completion.
Damage Modeling	Wei Huang (NRC, Canada) Klaus Six (Virtual Vehicle, Austria) Adam Bevan (Huddersfield University, UK)	This is a long-term, ongoing project.
VTI Economics	Wesley Thomas (Sentient Sciences, USA)	Ongoing improvements – 32 total users; railroads, service providers, and universities.
Rail Profile Scoring	Ankur Ashtekar, (Sentient Sciences, USA)	Profile scoring parameter working groups are being developed.
Safety		
Broken Rail Modelling **(NEW)**	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)	Workshop scheduled April 14, 2022. Survey sent to members.
3. Surface Fatigue to Internal Defects Model	TBD	Searching for topic leader.
4. Welds and Internal Defects Model	Peter Mutton (Monash University, Australia)	Workshop completed (March 2, 2022).
5. Strength/Resilience Model	David Fletcher (Sheffield University, UK)	Workshop completed (Feb 16, 2022).
6. Stress-Strength Model	Yan Liu and Chris Ladubec (NRC, Canada)	Workshop completed (Feb 17, 2022).
7. External Loading Environment	Alex Woelfle (NRC, Canada)	Workshop scheduled for March 24, 2022.
8. Friction Characterization and Modeling	TBD	Searching for topic leader.
Agent Based Modelling **(NEW)**	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 NRC have:

- Initiated and coordinated a new research project; the development of a framework for modeling broken rails that lead to derailments. This project is discussed in detail in Section 3.7
- 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 3.2.
        - 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 3.5. There are currently 5 Canadian railways participating in this effort.
- While identifying new topic areas, facilitated the initiation of several new ICRI efforts (as shown in Table 1), 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.
- Recruited additional organizations and researchers as required for participation in projects.

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. This year the website costs have been also been sponsored by Plasser.

Table 2 summarizes the website activity. In general, activity increased from 2019 to 2020, though the table shows that the number of different countries did decline in the second year. As for the number of unique visitors, the 2019 number is believed to be high since the website went from being unsecured (http) to secured (https) and the same person may have shown up twice if they visited before and after the transition. From 2020 to 2021, website activity increased significantly. This is likely due to the increased size of the community (more members), more project activity and greater accessing of the Downloads page.

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
Increase (from 2019 to 2021)	103%	135%	343%	152%	13%

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 Assocation (AREMA) and FRA Railroad Safety Advisory Committee (RSAC) meetings, Contact Mechanics and other major conferences.

In 2019 the ICRI held a stand-alone workshop in Vancouver that gathered nearly 60 participants for two and a half days, plus optional technical workshops on the third afternoon.

In 2020 and 2021 it was not possible to host any in-person workshops due to the COVID-19 pandemic. However, several virtual workshops were held in their place and are discussed in Section 2.4.

Planning for three in-person conferences/workshops is underway for 2022:

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

2.3.1 ICRI Workshop Vancouver, July 23-25 2019

Previous Vancouver workshops in 2017 and 2018 were held at the University of British Columbia but it was decided for 2019 to have a City Center location. The only significant impact was that the cost of accommodations for attendees. Fortunately sponsorships from Simon Fraser University, LB Foster, NRC, Linsinger, Wheel-rail Seminars and Whitmore helped to cover higher catering and facility costs, enabling the workshop to retain its very low registration fee and to generate a small surplus.

Forty-eight persons from 6 countries attended, with 15 being new to the ICRI. Over the two-and-a-half-day event there were 16 presentations that facilitated discussions in a single stream (i.e. there were no parallel sessions), with additional time for discussion and interaction. The final agenda is shown in Figure 1. While the bulk of the presentations were invited by the program organizing committee, other submissions were made that complemented the program. No technical papers were required but the organizers pledged to facilitate the distribution of presentations, documents and data to all participants. All presentations are available at http://icri-rcf.org/downloads.php.

start	end	Tuesday, Jul 23	Wednesday, Jul 24	Thursday, Jul 25
8:00				
8:15	8:35	Welcome and workshop outline ***Eric Magel***	**Paul Gies**, Athena Industrial Services *Detection & measurement of rolling contact fatigue with electro-magnetic field imaging*	**Harold Harrison** *Producing and Measuring the 3rd Body Layer*
8:35	9:20	**Maksym Spriyagin**, CQU *Locomotive traction and its effect on rail wear: methodology, measurements and simulations*	**Deborah DeGrasse**, Transport Canada *Transport Canada's Approach and Research following the Railway Safety Review* **Ali Tajaddini**, FRA *FRA Research plans and priorities*	**Kyle Mulligan**, CP Rail *The effects of wheel shelling on Canadian freight railways and risk mitigation strategies*
9:20	9:40	discussion/followup *(Eric Magel)*	discussion/followup *(Bob Tuzik)*	discussion/followup *(Joel Garrett)*
9:40	10:10	coffee break - sponsored by Linsinger	coffee break - sponsored by Whitmore	coffee break
10:10	10:40	**Gerald Trummer**, Virtual Vehicle *Modeling adhesion, carry-down and consumption of friction modifiers in the wheel-rail interface*	**Brad Kerchof**, Norfolk Southern Railway *RCF damage on curve rails*	**Sean Regehr**, Advanced Rail Management *Quality indices for rail grinding*
10:40	11:10	**Davey Mitchell**, LBFoster *Noise Mitigation using Friction Modifiers on Narrow Running Bands*	**Richard Stock**, Linsinger *Rail milling in North American context – opportunities and applications*	**Taking action: wrap up discussion** ***(Eric Magel and Kevin Oldknow)***
11:10	11:30	discussion/followup *(Briony Croft)*	discussion/followup *(Louisa Stanlake)*	
11:30	13:00	break for lunch		
13:00	13:30	**Alok Jahagirdar**, NRC Canada *Quantifying rail surface damage*	**Ben White**, Sheffield University *Assessing the economic costs and benefits of friction management products*	**Optional Technical Tours** Tour 1: BCRTC (Skytrain) Operations and Maintenance Center Tour 2: LBFoster's Friction Management Research and Manufacturing Center
13:30	14:00	**Alfredo Gay Neto,** University of Sao Paulo *Wheel-rail modeling efforts and needs in Brazil*	**Wesley Thomas**, Sentient Sciences *The ICRI's VTI Economics Model*	
14:00	14:20	discussion/followup *(Mark Reimer)*	discussion/followup *(Gary Wolfe)*	
14:20	14:50	coffee break - sponsored by WRS2020	coffee break - sponsored by NRC Canada	
14:50	15:35	**Chris Bosomworth**, CQU *Approach for the prediction of rail heat transfer under heavy haul train operation scenario: experiment vs simulation*	**Eric Magel**, NRC Canada *Quantifying Risk*	
15:35	16:00	discussion/followup *(Sheldon Green)*	discussion/followup *(Charles Franz)*	
16:30	19:00	**Buffet Dinner** *Grouse Mountain*	**WRI 2020 sponsored reception** *Top of Vancouver Restaurant*	
	22:30			

Figure 1: Final program for July 2019 ICRI Annual Workshop

As per its goals, this workshop was successful in bringing together researchers, suppliers and railways for practical discussions on topics having significant cost and safety implications for the railway industry. Compared with previous workshops, we were less successful with the Class 1 freight railroads as only two (Canadian Pacific Railway (CP) and Norfolk Southern Railway (NS)) sent representatives.

The objective was to collect research ideas and gaps from the previous presentations and form corresponding research projects and teams. Several follow-on actions emerged, thanks largely to ongoing field research efforts by our railroad partners.

2.3.1.1 Norfolk Southern Field Studies

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. The eddy current data being collected 10 times per year by NS over large stretches of track is expected to be very valuable in analyzing the relationship of profiles, curvature, friction conditions, cant deficiency etc. on the rate of initiation and propagation of surface fatigue.

Recently NS has re-engaged and a new project proposal was sent to their management February 1st, 2022 (see Appendix A).

Participants: Brad Kerchof (Advanced Rail Management (ARM)) – Lead, NS, NRC, Sperry, Loram, Harold Harrison, Rohmann, and Virginia Tech University.

2.3.1.2 Canadian Pacific Field Studies

The CP Manager of Friction Management reported that his company was initiating a monitoring program consisting of 7 miles of new rail that includes 54 curves in the Thompson Region (near Kamloops, BC). Focused on friction management, he offered that CP would be willing to consider complementary research activities.

A test proposal (see Appendix A) was sent to CP for consideration in January 2020. CP reported in late 2020 that under the conditions of the pandemic they would not be able to support a project and asked that the ICRI reconnect with CP when things are “more normal”. Recent efforts to re-engage CP have not been successful.

Participants: CP, LB Foster, Loram, ARM, NRC, Harold Harrison.

2.3.1.3 BART Field Studies

The Bay Area Rapid Transit (BART) has an extensive program of rail/wheel monitoring underway that includes regular eddy current, corrugation, wheel and rail profile, and noise measurements. They are currently being used to track the progress of its rail grinding program. Quality indices are being developed related to profile, surface damage, and corrugation. A methodology has been devised to combine these into an equivalent grinding index (EGI).

This project is well underway and extensive data sets have been processed and plotted. The indices are in regular use to demonstrate project progress but not really yet being applied to the management of grinding. A review of the EGI was recently completed and it was found to be very sensible and to have good potential for use as a single condition parameter upon which to establish maintenance priorities.

Participants: BART, ARM, NRC

2.3.1.4 Other action items

Table 3 lists the other action items from the discussions that were had following the presentation sessions.

Table 3: Other action items from the July 2019 ICRI Workshop in Vancouver

	Action Item	Status
1.	**New York City Transit** has an instrumented revenue train running on its #7 Flushing Line collecting wheel/rail force, acceleration and noise data amongst others. NRC (E. Magel/R. Caldwell) and ARM (M. Reimer) will collect that data, along with others being collected as part of a friction management study, for use by ICRI teams involved in modeling friction and the carry down of friction modifiers.	Because of financial limitations, NYCT did not renew its contract with one supplier for the acceleration and noise data, which had previously been difficult to obtain as it involved a different vendor. The NRC-instrumented wheelset (IWS) ran until mid-2021 with large data gaps due to maintenance issues. The contract was not renewed due to financial limitations. The friction management testing is ongoing but has experienced several delays due to resource and travel limitations because of the COVID-19 pandemic. There may still be an opportunity to perform testing that will yield data about the carry of the products, should travel and site access resume. There is data available to determine product retentivity, which is not the same as carry down, but would still be of interest to the ICRI community.
2.	**Sentient Sciences** (W. Thomas) to host a web meeting where he walks users through the use of the VTI-Economics model by demonstrating a practical problem.	This demonstration was held March 25, 2020 and has become an ICRI project (see Section 3.5)
3.	**C. Bosomworth (CQUniversity (CQU))** volunteered to champion an effort related to data analytics and data mining.	Subsequent discussion found that it is difficult for this to be a generic activity but should instead be in support of other ICRI project activities (September 2019). C. Bosomworth will be invited to sit in on the other project teams with the aim of identifying data analytics needs and opportunities.
4.	On the topic of **risk and safety**, E. Magel will continue to develop a framework for its quantification.	An outline was developed and presented at an ICRI webinar in July 2020. The broken rails modeling framework has been refined, specific modules defined and leaders recruited, and several workshops have been held. See Section 3.7 of this report for more detail.

	Action Item	Status
5.	There is a need for **full-scale traction creepage curves**. These are currently collected by suppliers but are not publicly available. Is there any way the ICRI can help to liberate those—maybe in some anonymous or non-dimensionalized form? E. Magel to discuss with Sheffield University and Virtual Vehicle.	A friction library team (See Section 3.1.2) has been convened that seeks to collect available friction and traction/creepage data.
6.	The US FRA has supported the development of two substantial **wheel-rail simulation facilities**: one at Virginia Tech, and the other at TTCI. The FRA has available some funding to support testing.	An email was sent August 14, 2019 letting participants know that: *“The US Federal Railroad Administration has supported the development of a large-scale disc-on-disc wheel-rail contact simulator at Virginia Tech and a full-scale rail roller rig at TTCI. “If you have a research project that would benefit from tests on these rigs, please contact Ali.Tajaddini@dot.gov with your ideas.”*

The detailed summary of the July 2019 ICRI workshop can be found in the 2019-20 annual report [13].

2.3.2 2020 ICRI workshop

In the fall of 2019 it was confirmed that the 2020 ICRI workshop would take place in Istanbul at the Beyazıt Campus Rectorate of Istanbul University. Dr. Ozgur Bezgin would serve as the local host. Compared with previous workshops in Vancouver, it was hoped that Istanbul would better suit the large number of European ICRI members (which constitute 30% of its membership) and also encourage additional engagement from Africa and the Middle East. A quick survey of members suggested that potential European and African participants were comfortable with Istanbul as a destination, while some from North America expressed mild anxiety that it might not be a safe location. The schedule was amended compared with previous workshops to accommodate a larger number of speakers (21 instead of 16) and the resulting program was well developed—see Figure 2. Sponsorship was strong, with contributions from Advanced Rail Management, Linsinger, LB Foster, Loram, NRC, Simon Fraser University and Yapiray.

start	end	Tuesday April 7	Wednesday, April 8	Thursday, April 9
8:00		Welcome and workshop outline		
8:15	8:35		Istanbul Metro presentation	New Tech/Sponsor Seminar
8:35	9:15	**Henry Brunskill / Joe Hill - Sheffield University** Recent developments in wheel & rail stress measurement and monitoring using ultrasonic technologies	**Daniel Hampton - CSX Railroad** Optimizing grinding for NA freight railroads	**Andy Vickerstaff - London Underground** Initial experiences of Premium Rail Steels on London Underground
9:15	9:30	discussion/followup		
9:30	10:00	coffee break		
10:00	10:25	**Stasha Jovanovic - ENSCO** Autonomous Vehicle Track Interaction monitoring and railway infrastructure maintenance	**Richard Stock - Linsinger** TBA	**Kevin Oldknow - Simon Fraser University** Sustainable Energy Engineering at Simon Fraser University: An expanded campus, new academic programs, and emerging research in clean transportation.
10:25	10:50	**Deborah DeGrasse - Transport Canada** Automated Inspection Technologies	**Mark Reimer - Advance Rail Management** Monitoring the effectiveness of rail maintenance programs	**Eric Magel - National Research Council** Risk and risk management
10:50	11:15	**Feras Naser - FerasNaser.com** Applications of deep learning in railway applications specifically computer vision for track maintenance	**Beyazit Ölçer - Yapiray** Wheel Rail Interface Analysis for Ethiopia Awash Kombolcha Hara Gebeya Project	Taking action: wrap up discussion
11:15	11:35	discussion/followup		
11:35	13:00	lunch break		
13:00	13:25	**Christina Riley - Southampton University** Data driven damage modeling	**Edwin Vollebregt - Vtech CMCC** Survey of physical effects and modeling of wheel-rail creep forces	Possible workshop or technical tour
13:25	13:50	**Klaus Six - Virtual Vehicle** Model based assessment of rail RCF: impact of model assumptions on prediction results	**Jon Paragreen - LB Foster** Wheel squeal and flanging noise – Challenges in validation of friction management in the field and laboratory	
13:50	14:15	**Pelin Boyacioglu - Huddersfield University** Prediction of Rail Damage (RCF and Wear) in London Underground	**Şerafettin Dilaver - Istanbul Metro** Flange abrasions observed in Istanbul light city rail wheel flanges	
14:15	14:35	discussion/followup		
14:35	15:05	coffee break		
15:05	15:30	**Lyn Williams - Bay Area Rapid Transit** Rail/wheel performance data drives maintenance funding	**Haluk Gokman - Enekom** Using BIG DATA to manage track condition monitoring effectively through the Acoustic Domain, based on a fixed infrastructure of broken rail detection system	
15:30	15:55	**Wesley Thomas - Sentient** VTI Economics	**Ozgur Bezgin - Istanbul University** An analytical approach to estimate dynamic impact forces on railheads due to wheel flats	
15:55	16:10	discussion/followup		

Figure 2: ICRI 2020 workshop technical program as of February 28, 2020.

The COVID-19 pandemic coupled with geo-political issues in Europe (particularly the migration of Syrian refugees from East Turkey to Greece through Istanbul) led to a cancelling of the workshop on March 2nd, 2020. All registrations and sponsorship funds were refunded. Fortunately the ICRI did not suffer a significant financial cost with the cancellation—only fees associated with credit card processing that amounted to about $100. A cancellation in Vancouver would have been much more costly.

In place of the in-person workshop, several of the presentations initially scheduled for Istanbul were instead presented remotely at regular ICRI webinars. These are discussed in Section 2.4

2.3.3 2021 ICRI workshop

The ongoing pandemic prevented the holding of an in-person workshop in 2021. In place of the in-person workshop, several ICRI webinars were organized to continue knowledge transfer and sharing between the ICRI members. These are discussed in Section 2.4

2.3.4 2022 ICRI workshop planning

Planning for three in-person conferences/workshops is underway for 2022, as described below.

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

A three day in-person workshop is planned at NRC's Sussex Location in Ottawa, Canada. Attendance is expected to be largely Canada-US due to ongoing COVID-19 travel restrictions.

The main goals of the conference are to:

- Review on-going 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;
- 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.

Table 4: Planned presentations for April 2022 ICRI Annual Workshop

presenter(s)	Organization	Topic
Ankur Ashtekar	Sentient Science	ICRI Profile Scoring Initiative
Ananyo Banerjee	TTCI (now MxV)	Heavy haul testing of rail performance at TTC
Briony Croft	consultant	Wheel roughness vs rail roughness and contributions to noise
Brad Kerchof	Norfolk Southern (retired)	Mitigating risk associated with broken rail derailments
Ben White	Sheffield University	ICRI friction project - TBA
Daniel Hampton	CSX Railroad	Keynote
Alex Woelfle and Daniel Hampton	National Research Council, Canada CSX Railroad	Sensitivity Analysis to determine relative impacts of various parameters on RCF and Wear
Daniel Szablewski	National Research Council, Canada	Quantifying rail surface damage
Eric Magel	National Research Council, Canada	Broken Rails Modelling
Henry Brunskill	Sheffield University	VTI assessments using ultrasonics
Jon Paragreen, Davey Mitchell	LB Foster	The effectiveness of gauge face, restraining rail and Top-of-Rail friction modifiers in mitigating curving noise.
Mark Reimer	Advanced Rail Management	Noise and Vibration – Seattle/Vancouver/BART projects
Richard Stock	Plasser	The technologies, pros/cons and then also show some application examples and how these technologies can be used as input data for rail maintenance.
Sylvie Chenier and Mark Reimer	National Research Council, Canada Advanced Rail Management	Squats/studs on Sound Transit
TBA	Linsinger	Enhanced Rail Management Through Rail Milling: Network Rail's Rail Maintenance Journey
Wei Huang	National Research Council, Canada	Agent based modeling of broken rail derailments
Wesley Thomas	Sentient Sciences	VTI economics modeling

Two optional technical tours, based on registration/attendance have been proposed:

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 NRC Uplands Testing Facilities: State-of-the art testing facilities for the rail industry, including: 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.

2.3.4.2 ICRI Half day Workshop Vancouver, June 21st, 2022

This half day workshop will be held during the WRI transit Principles Course at the WRI 2022 conference. The technical content will be focused on the ICRI Broken Rail Monitoring Initiative, and tentatively, on the planned field studies at NS.

2.3.4.3 ICRI One day Workshop in Melbourne Australia, September 4th, 2022

This one day workshop will be held during the 12th International Conference on Contact Mechanics and Wear of Wheel-Rail Systems and will attract many of the international members of the ICRI, especially those from China and Australia.

2.4 Web Meetings

The COVID-19 pandemic prevented the holding of any in-person workshops in 2020 and 2021.In place of these workshops, ICRI webinars have been held to continue knowledge transfer and sharing between the ICRI members.

Between April 2020 and March 2021, 16 technical presentations were given in 12 separate sessions (listed in Table 5). Attendance varied between 31 and 150 persons for any session, averaging 70 participants.

Table 5: ICRI webinars held in 2020-21

Month	Date	Presenter(s)	Organization	Title	Attend-ance
May	28-May-20	F. Naser	FerasNaser.com	Potential Deep Learning Applications in Railway Maintenance and Operation	69
June	18-Jun-20	A. Vickerstaff D. Szablewski	Transport for London NRC, Canada	Initial experiences of Premium Rail Steels on London Underground Summary of the ICRI surveys on the use of Premium Rail steels and Untestable Rails	88
	30-Jun-20	R. Stock J. Paragreen	Linsinger LB Foster	Rail maintenance and its impact on Squat mitigation Wheel squeal and flanging noise – Challenges in validation of friction management in the field and laboratory	78
July	14-Jul-20	W. Huang A. Woelfle Eric Magel	NRC, Canada NRC, Canada	Rolling contact fatigue in heavy haul railroads - conclusions from an extensive pummelling simulation. ICRI Broken Rails	60
	28-Jul-20	E. Vollebregt Z. Lee G. Trummer	Vtech CMCC Sheffield University and Virtual Vehicle	Survey of physical effects and modeling of wheel-rail creep forces Benchmark Tests and Modelling of Top-of-Rail Product Behaviour in the wheel/Rail Interface	68
October	08-Oct-20	R. Lewis K. Six G.Trummer	Sheffield University and Virtual Vehicle	Predicting wheel-rail interface friction with leaves	55
November	03-Nov-20	Ozgur Bezgin	Istanbul University - Cerrahpasa	Introduction of Bezgin-Kolukırık Equations to estimate peak dynamic impact forces caused by wheel flats	31
December	02-Dec-20	ICRI BrokenRails Workgroup		Modeling risk and derailment	47
	09-Dec-20	Stasha Jovanovic	ENSCO	Autonomous Vehicle Track Interaction monitoring and railway infrastructure maintenance	72
January	27-Jan-21	Henry Brunskill	Sheffield University	Applications of ultrasonics to rail/wheel performance monitoring	49
February	24-Feb-21	Wesley Thomas Daniel Hampton	Sentient Science CSX	Profile Quality and Rail Life	150
March	24-Mar-21	Peter Mutton	Monash University	Australian experience in improving weld integrity	72

In early 2021 these presentations were reviewed to extract a list of all the research opportunities and data needs identified. Those are summarized in Table 6.

Table 6: Summary of research gaps or data needs extracted from ICRI web presentations

	Research Area	**Research Gaps**
1.	VTI Economics Demonstration	Add more users to ICRI Economics model Add more factors to the model
2.	Introduction of a new analytical method for a rapid estimate of dynamic impact forces due to track and wheel roughness	Models of the effects of secondary impacts on track stiffness Models of the effects of stiffness transition and profile variation on Entrance & Exit Force factors
3.	Potential deep learning applications in railway maintenance and operation	Labeled AI Training Data needed, including for railway surface defects AI data collection tools for data collection/research A comprehensive literature review of the progress of natural language processing (NLP)
4.	Summary of ICRI surveys on the use of premium rail steels and untestable rails	Cost analysis on grinding vs other options?
5.	Initial experiences of premium rail steels on London Underground	400 grade heat trial data
6.	Wheel squeal and flanging noise – challenges in validation of friction management in the field and laboratory	Track trials & case studies re: noise reduction & film thickness applications
7.	Rail maintenance and its impact on squat mitigation	Research re: squat WEL characteristics

	Research Area	Research Gaps
8.	ICRI Broken-Rails review	Research re: rail breakage likelihood by timelines/temperature (summer vs. winter) Research re ideal rail grinding timing/benefits Research re which rail breaks will cause a derailment Need for Low frequency/ high consequence data
9.	RCF-in-heavy-haul-railroads-conclusions-from-an-extensive-pummelling-simulation	Research re: non-stochastic methodologies? Expand and refine the selection of wheel-rail performance metrics Broaden range of simulation inputs
10.	Benchmark Tests and Modelling of Top-of-Rail Product Behaviour in the wheel/Rail Interface	Further develop high-friction rail models
11.	Survey of physical effects and modeling of wheel-rail creep forces	Models re: various lubricant's effects on rail friction
12.	Predicting wheel-rail interface friction with leaves	Models re: various effects of fallen leaves at changing decay levels on rail friction
13.	Introduction of Bezgin-Kolukırık equations to estimate peak dynamic impact forces caused by wheel flats	Further comparisons of predictive models vs field data re: wheel & rail fatigue

Between April 2021 and March 2022, 11 technical presentations were given in 9 separate sessions (listed in Table 7). Attendance varied between 41 and 101 persons for any session, averaging 67 participants.

Table 7: ICRI webinars held in 2021-22

Date	Presenter(s)	Organization	Title	Attendance
10-Apr-21	Pawel Woelke	Thornton Tomassetti	Modeling defect growth in rail steels	63
	Ananyo Banerjee	TTCI	Modeling defect growth in rail steels	
23-Jun-21	Sean Regehr	Advanced Rail Management	Quality Indices to Manage Rail Grinding	81
	Ankur Ashtekar	Sentient Science	ICRI Rail Profile Scoring initiative	
15-Sep-21	Wesley Thomas	Sentient Science	ICRI VTI-Economics updates	46
06-Oct-21	Erdem Balci and Ozgur Bezgin	Istanbul University	Introduction of the Concept of Apparent Track Stiffness: Variation of Railway Track Stiffness with Bogie Axle Spacing and Its Influence on Dynamic Impact Forces	41
27-Oct-21	Carsten Rasmussen	COWI	Grinding-induced Rolling Contact Fatigue in Rails.	101
17-Nov-21	Maksym Spiryagin and Esteban Bernal	Central Queensland University	Combination of simulation modelling process and experimental material testing program for shakedown analysis in locomotive studies	44
15-Dec-21	Briony Croft Mark Reimer Peeter Vesik	Consultant Advanced Rail Management Vancouver Skytrain	Quantifying friction modifier effects on roughness and corrugation growth	74
26-Jan-22	Mehdi Ahmadian	Virginia Tech	Long- and Short-term effect of Top of Rail Friction Modifiers (TORFM) on Traction	94
02-Mar-22	Ozgur Bezgin	Istanbul University - Cerrahpaşa	use of the Bezgin - Kolukırık Equation to Estimate Dynamic Impact Forces due to Abrupt and Rapid Changes in Track Profile at Rail Ends and Turnout Crossings	57

3 Research Program Activities

3.1 Friction Modeling Studies

3.1.1 Friction Modeling

Friction in the wheel-rail contact is an important part of this complex tribological system and therefore has a high influence on vehicle-track interaction (VTI). To realize high quality VTI predictions (vehicle/traction/braking dynamics, wear, damage, etc.), reliable friction models taking into account the most important tribological phenomena are of high importance.

VORtech received research funding from the US FRA for improved modeling of creep-forces. Physics-based sub-models for temperature and solid third-body layers have been developed and implemented into CONTACT. Further, CONTACT was implemented in GENSYS, UM, NUCARS and SIMPACK, and used to simulate measurements of NRC's full-scale wheel bearing and brake research facility. The final report was submitted to the FRA and has been going through an editorial process. The work was published in the *International Journal of Vehicle Mechanics and Mobility (Vehicle System Dynamics*) [19] in 2019. Vtech used the model to simulate measurements on the Virginia Tech-FRA roller rig.

Sheffield University, Virtual Vehicle, and LB Foster also received research funding from the FRA, for developing a model to predict carry down, consumption and related friction of TOR friction modifier products applied by field side application devices. Small-scale and full-scale experiments have been carried out. Furthermore, a theoretical model has been developed which has been parameterized and validated by the experimental data. The work was published at the TRB-2019 conference [20], the IAVSD-2019 conference [21] and in the Journal *Lubricants* [5] in 2021. Sheffield University, and Virtual Vehicle have applied for a FRA funded follow-up project with the aim to enhance and implement the developed model that takes account of falling friction at higher creep levels and the effects of third-body layers resulting from the application of a range of TOR materials. The decision is pending.

The latest update presentation "ICRI Webmeeting on Development of a Modelling Tool for Predicting Wheel/Rail Interface Friction with Leaves" was given to the ICRI community October 8th, 2020 (see Downloads).

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

3.1.2 Friction Library

Vehicle-track interaction modelling and simulation typically requires the coefficient of friction (COF) to be specified at each of the wheel tread/top of rail interface and wheel flange/gauge face interface. 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 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 first team meeting was held Jan 19, 2022, and has been followed by bi-weekly meetings. The team is currently creating a framework for the library to determine the data requirements; including useful parameters and measurement conditions.

The February 24th, 2022 meeting, included members from the modeling community (Maksym Spiryagin, Oldrich Polach, Peter Klauser, and Edwin Vollebregt) who shared their views on 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 as an 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).

Simulation category	How friction is used	Would a Friction Library be useful?
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 the 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.
The next steps are to finalize the goals and framework for the Friction Library and to establish a usable data repository.

Leader: Davey Mitchell (LB Foster)

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

3.1.3 Tribometer Business Continuity Plan

Portable tribometers allow the measurement of railhead friction in the field, useful for comparing laboratory friction testing to field data, as well as supporting modelling work and assessing railhead condition. This user group seeks to continue the development and technical support of the new International Engineering (EI) Tribometer whose survival is currently uncertain following the death of its inventor. The group will also continue the development and help troubleshoot the OnTrak railhead tribometer, whilst providing a platform to collaborate and share friction data.

The first user's group meeting was held January 17, 2022. Several next steps were established:

- Create an OnTrak/new Tribometer testing program to validate instrumentation;
- Develop a software to develop/support OnTrak tribometer;
- Determine the specific outcomes that this group is trying to accomplish and map how to get there;
- Find out if there any funding or grant programs that could be used for this Tribometer work?
- Create a "good practice guide" including an FAQ to help solve mechanical/software issues to be added to the ICRI Website.

A second meeting is expected to occur in April 2022.

Leader: Ben White (Sheffield)

Participants: Rob Caldwell (NRC), Paul Di Natale (Dispotel), Roger Lewis (Sheffield), Ryan McWilliams (International Engineering), Davey Mitchell (LB Foster), Josh Rychtarczyk (ARM), Ali Tajaddini (FRA), Nicholas Wilson (TTCI), Alexandre Keylin (TTCI)

3.2 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 labor 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). Leveraging RCF crack metallography measurements to calibrate EC probe settings, will ultimately yield more accurate EC results for on-track rail inspection and allow for better grinding decisions to optimize the rail life-cycles in variable track conditions.

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 13 rail samples have been analyzed and included in the RCF matrix. RCF metrics included crack position on the railhead, angle to surface, as well as crack length and depth. EC measurements were taken for each sample and Vickers micro-hardness traces were collected on representative samples. An additional 15 rail samples are awaiting processing and analysis over the next year.

Lead: Daniel Szablewski (NRC)

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

3.3 Wear Mapping

A 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 this year 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. A new collaborative 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.

Recent Publications related to this ICRI project include:

1. Comparison of the Damage and Microstructure Evolution of Eutectoid and Hypereutectoid Rail Steels under a Rolling-Sliding Contact [22].
2. Experimental Study on Wear Properties of Wheel and Rail Materials with different Hardness Values [23].
3. A New Approach for Modelling Mild and Severe Wear in Wheel-Rail Contacts [24].
4. Microstructure Evolution of Railway Pearlitic Wheel Steels under Rolling-Sliding Contact Loading [25].
5. Laser Cladding of Rail; the Effects of Depositing Material on Lower Rail Grades [26].
6. Benchmarking of Premium Rail Material Wear [27].
7. A Review on Wear between Railway Wheels and Rails under Environmental Conditions [28].

8. Investigation of the Influence of Rail Hardness on the Wear of Rail and Wheel Materials under Dry Conditions (ICRI Wear Mapping Project) [29].
9. Towards a Standard Approach for Wear Testing of Wheel and Rail Materials [30].
10. Microstructure Evolution of Railway Pearlitic Wheel Steels under Rolling-Sliding Contact Loading [31].
11. Comparison of Wear and Rolling Contact Fatigue Behaviours of Bainitic and Pearlitic Rails under various Rolling-Sliding Conditions [32].
12. Investigation on Wear and Rolling Contact Fatigue of Wheel/Rail Materials under Various Wheel/Rail Hardness Ratio and Slip Ratio Conditions [33].

Lead: Roger Lewis (Sheffield University)

3.4 Damage Modeling

Damage modelling provides a prediction of the fatigue damage growth rate in wheels or rails. Models of this kind are becoming increasingly important for members of the railroad industry who want to predict 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 the FRA's funding and CSX data, the NRC used a stochastic simulation approach to recreate the loading environment of two 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.

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 presentation "Rolling contact fatigue in heavy haul railroads – conclusions from an extensive pummelling simulation" was given to the ICRI community July 14th, 2020 [34].

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

3.5 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 railways 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* [35].

Several features have been added to the model over the past 3 years such as:

- Switch and crossing (S&C) Grinding added in September 2021;
- Turnout and special track work added in February 2019;
- Track access charges added in January 2019.

The latest update presentation on this project was given to the ICRI community September 15th, 2021.

Lead: Wesley Thomas (Sentient Science)

3.6 Profile Scoring

The goal for the Profile Scoring research topic team was to develop a methodology to evaluate the performance/suitability of a rail profile for use under a specific set of conditions through profile scoring. 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 actual 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 which would feed into the overall profile scoring

Lead: Ankur Ashtekar, Sentient Science

Table 9: Profile scoring parameter working groups

Group	Lead	Status
RCF/Wear	Kevin Oldknow (Sheffield)	First meeting held February 10th, 2022
Lateral Stability and Curving Forces/Dynamics	Peter Klauser (Vehicle Dynamics)	Being scheduled
Corrugations Resistance/Noise	Mark Reimer (ARM)*	TBD
Grinding	Charles Rudeen (Loram)*	TBD
Frictional Energy	Rob Caldwell (NRC)*	TBD

* To be confirmed

3.6.1 RCF/Wear

The goal of this specific group is to consider RCF/Wear part of the equation and determine a parameter to evaluate the score of resistance to Wear/RCF performance. The team is currently establishing a terms of reference for this activity to be finalized at the March 29th meeting.

Lead: Kevin Oldknow (Sheffield)

Participants: Mark Reimer (ARM), Charles Rudeen (Loram), Maksym Spiryagin (CQ), Richard Stock (Plasser), Darrien Welsby (Monash), Ankur Ashtekar (Sentient Science), Rob Caldwell (NRC), Eric Magel (NRC).

3.7 Rail Safety

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 [3]. 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 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 [4]. 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 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?
3. BNSF Railway (BNSF) analysis of rail break data [6]. 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 being 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 [6]. Broken rail derailments are the leading cause of severe derailments—those that derail the highest number of cars per incident [7].

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. The Norfolk Southern initiative discussed in Section 2.3.1 and Appendix A would be ideal for advancing this work.

There remains a premise that rail breaks are unsafe. But FRA statistics show that less than one in a hundred rail breaks cause a derailment [8]. Other analyses (e.g. [9]) 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, there were just as clearly other factors at play.

3.7.1 Analysis of Broken Rail Derailments

An analysis of broken rail derailment information from the literature (Figure 3) 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.
- The ratio of derailments to broken rails is eight times higher in the summer compared with the winter.

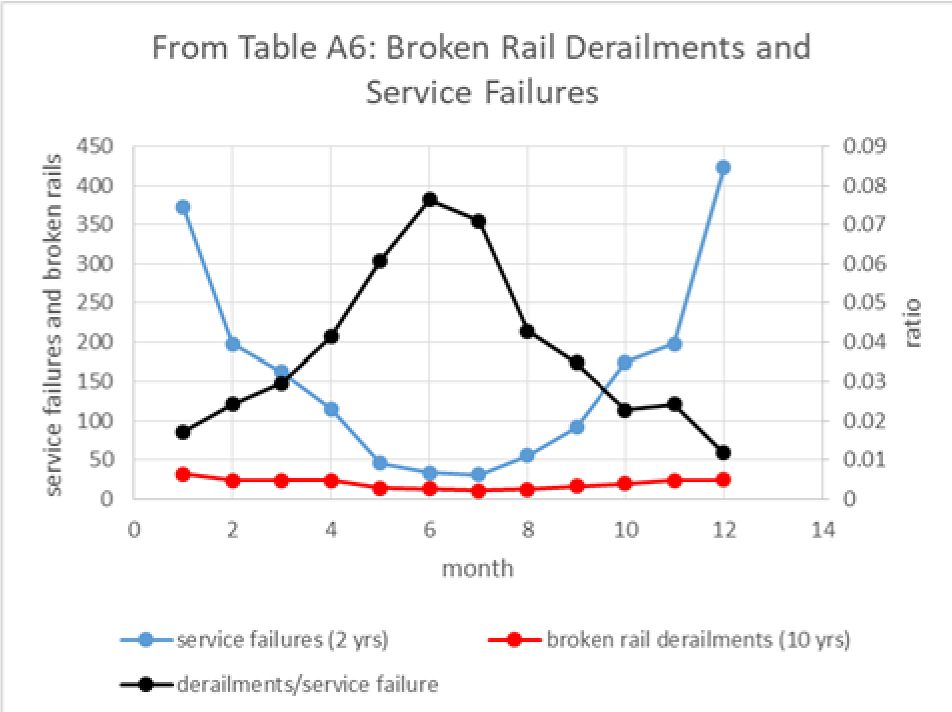


Figure 3: Broken rail data from Reference [9]

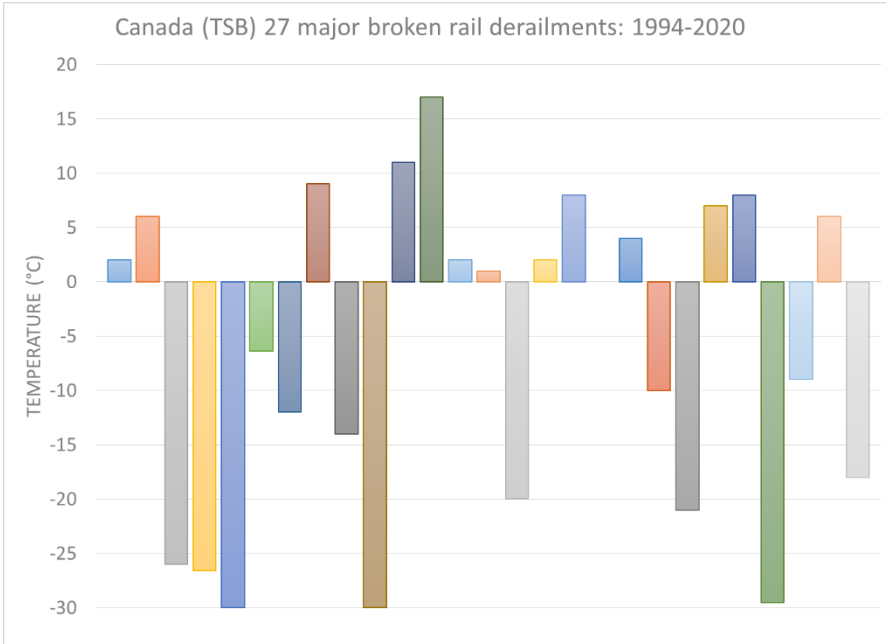
The second finding was cause for a separate discussion and the creation of an ICRI working group called Broken Rails Modeling (discussed in Section 3.7.3). Some members cautioned the reliability of the results, since the numbers of derailments used in the analysis is so few. For example, the number of 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:

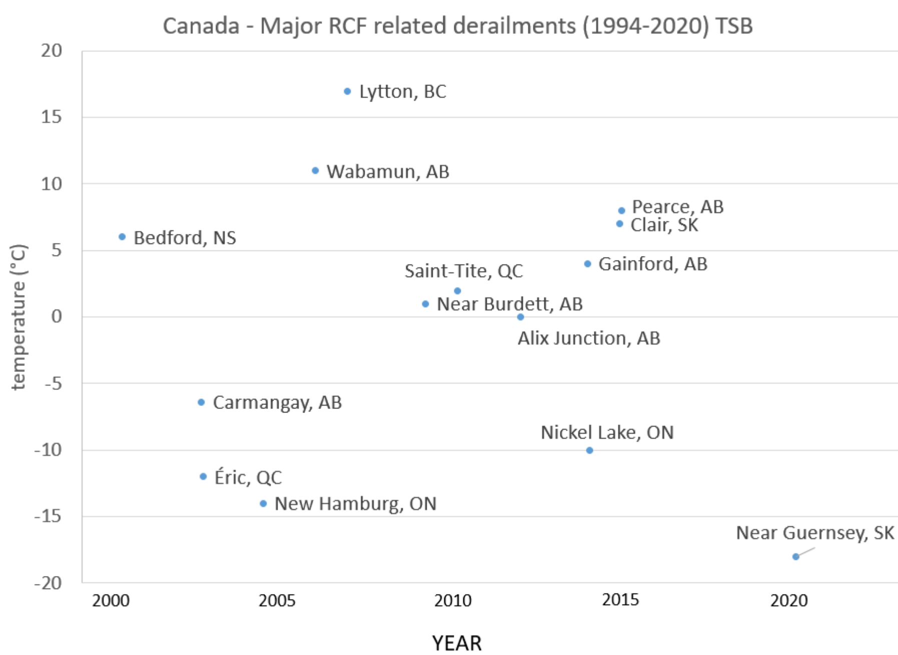
- The rail support system is not as stiff in the summer as it is in the winter. Thus for the same impacting wheels, the resulting stresses that contribute to rail fracture will be lower.
- In the winter, a clean break is more likely because the tensile thermal stresses will cause a significant gap that 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.

Transportation Safety Board of Canada (TSB) (Canada) and National Transportation Safety Board (NTSB) (USA) incident reports were reviewed and these were plotted 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 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 rail surface fatigue.

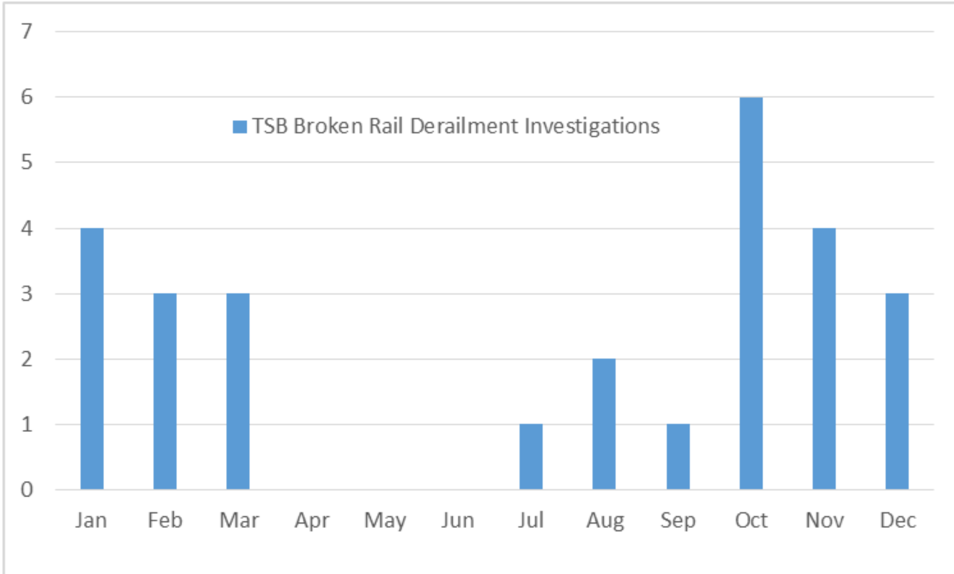


Figure 5: TSB broken rail derailments by month for all incidents between 1994 and 2020

A review of the NTSB incident reports was not nearly as enlightening. It appears that the NTSB investigates far fewer incidents, even though it is in charge of 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.

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

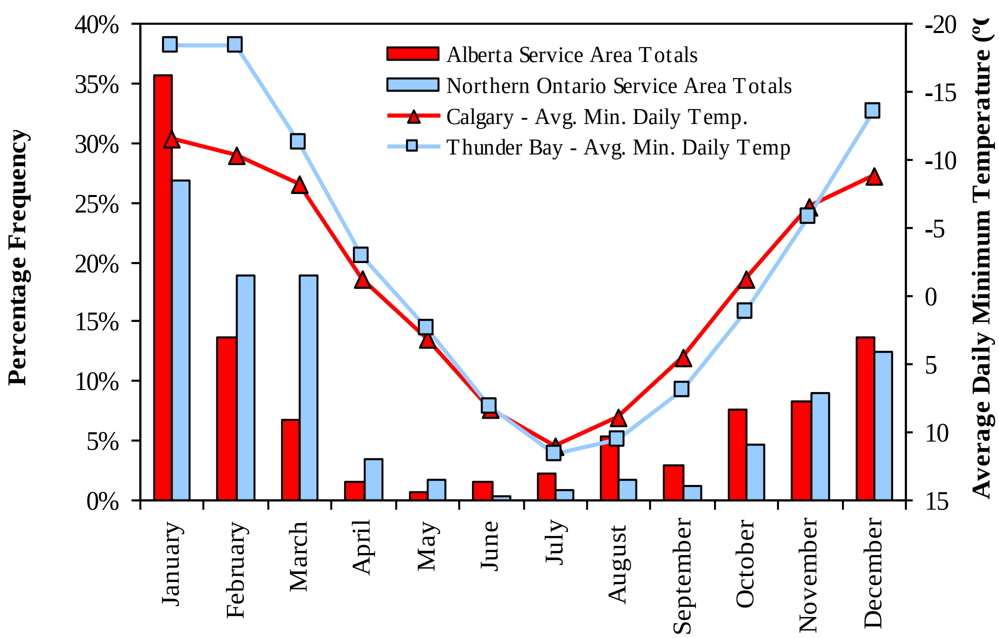


Figure 6: Some broken rail data for CP Rail [12]

3.7.2 Risk

Risk is usually defined as being composed of two features: Probability and consequence (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 challenge for risk assessment in railroads is the probability. Not in a generic sense—a railroad might be able to predict or use historical data to understand how many derailments it can expect. 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				
Probability		Catastrophic	Hazardous	Major	Minor	Negligible
		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 recent Transport Canada initiative called “Study of Definition of Key Routes for the Transportation of Dangerous Goods by Rail in Canada” from 2016 [10], 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. [13].

The problem with derailment data is that derailments are, statistically speaking, low probability events. FRA reported that, from 2014 to 2018, there were 291 main-line track caused derailments that may have had RCF as a key contributor (see Table 10). That average of 73 per year 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 12 (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 10: FRA Accident Statistics: 2001-2018

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.

3.7.3 Broken Rails Modeling – Phase 1

An outline of the broken rail derailments problem is given in the form of a flowchart in Figure 8. Five models are required in order to fulfill the requirements.

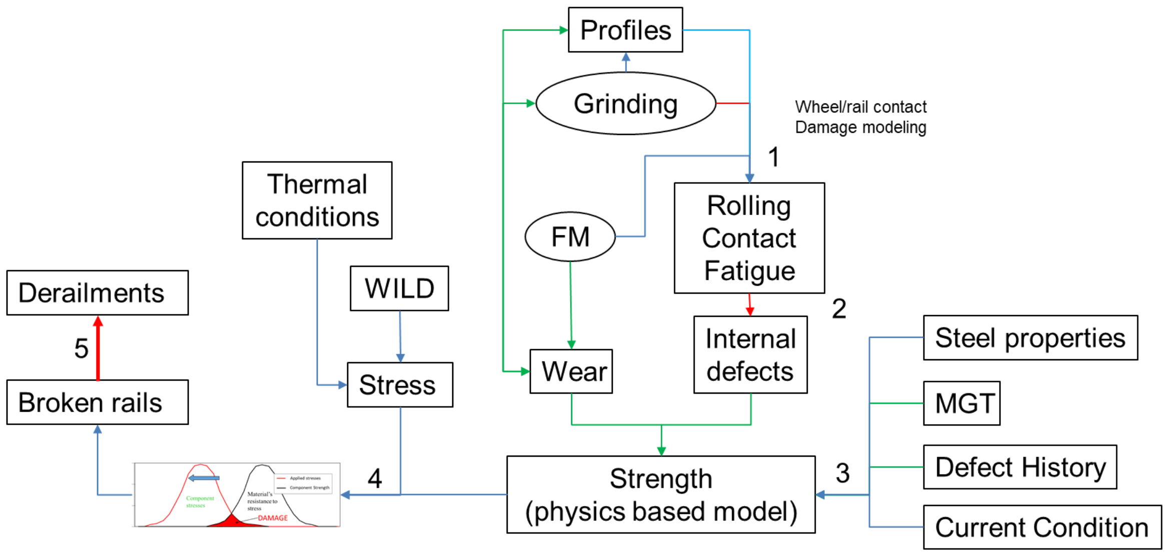


Figure 8: Flow chart of stress strength approach to quantify risk of broken rail derailment and improved models 1 to 5 that need to be developed

1. Damage Modeling including Profiles, Grinding and Friction Management

   Damage modeling is already an activity within the ICRI. But we should 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 exercise the RCF will also be addressed[1]. Surely 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 demand 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.

[1] The exception is track locations documented as SSC (shelling, spalling, corrugation) where a valid ultrasonic test was not possible. These locations must be rectified such that a valid ultrasonic test can be achieved, otherwise a slow order is imposed.

Some work has been done to understand how various levels of grinding have affected the measured RCF (e.g. [11]) 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 Quantify Surface Fatigue project (Section 3.2) seeks to address 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 reach to the surface. More experience is needed with the eddy current systems but that is being achieved as more units and more miles gain experience on North American railroads.

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?

B) Impact of friction modifiers (FM) on RCF

It is generally accepted that by managing friction on the top of rail, excessive shear forces are reduced and thus minimize RCF development. 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 (i.e. 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 researched.

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 to estimate the fatigue crack growth, combined with WILD data.
- 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 [11] can be used for this purpose. That model was created to support the development of cold weather speed limits and used measured wheel impact load detector (WILD) values to determine 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 9). 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.

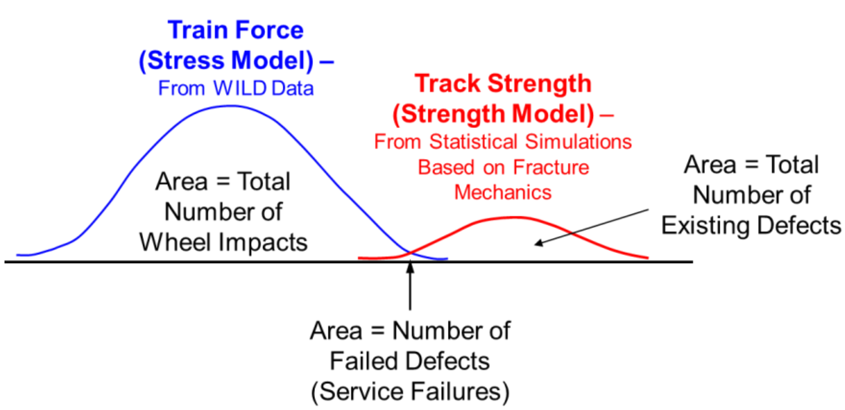


Figure 9: Stress vs. strength approach used for modeling potential rail breaks

The strength model is described in Figure 10. Here; 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.

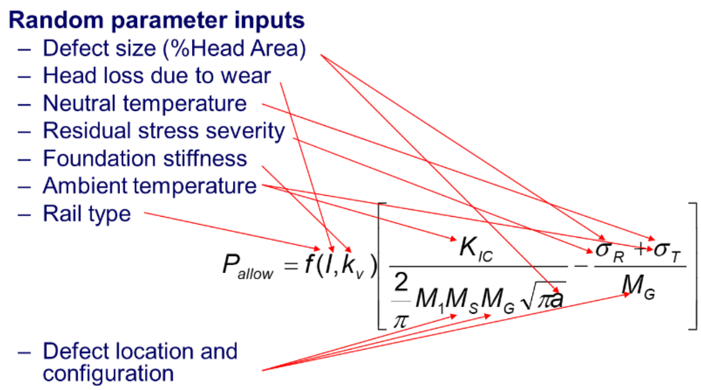


Figure 10: Strength model—statistical simulation approach

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 [9] shows that 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.

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

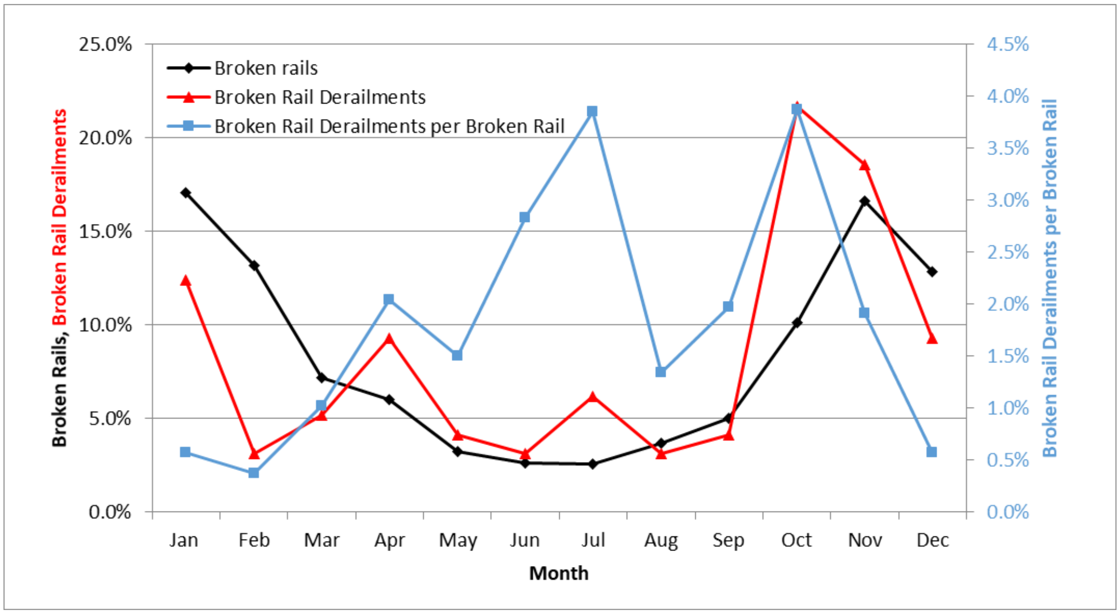


Figure 11: Seasonal BNSF broken rail derailment distribution

3.7.4 Broken Rails Modeling – Phase 2

Building off the phase 1 rail safety work and risk analysis that was completed in 2020-2021, 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.

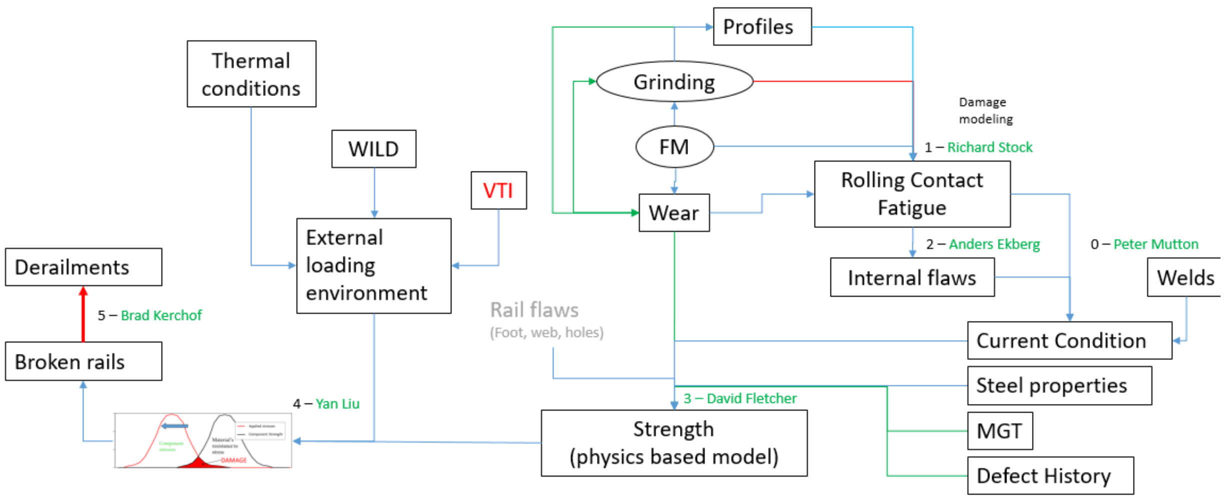


Figure 12: Stress-strength approach to modeling broken rails

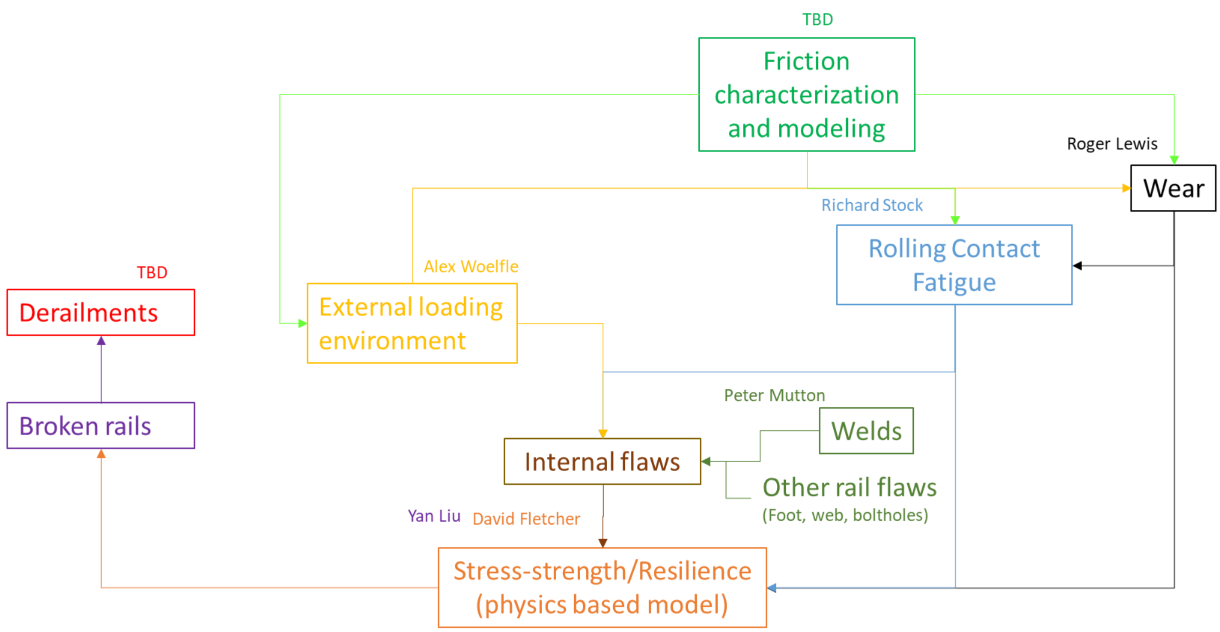


Figure 13: Outline of broken rails to derailment model

3.7.4.1 Broken Rails Module Framework Development

Leaders and teams of interested individuals have been or are being created to develop each module shown in Figure 13. Each team plans 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 will also identify current methods/understanding and research gaps or new technology needs. Currently, 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 later.

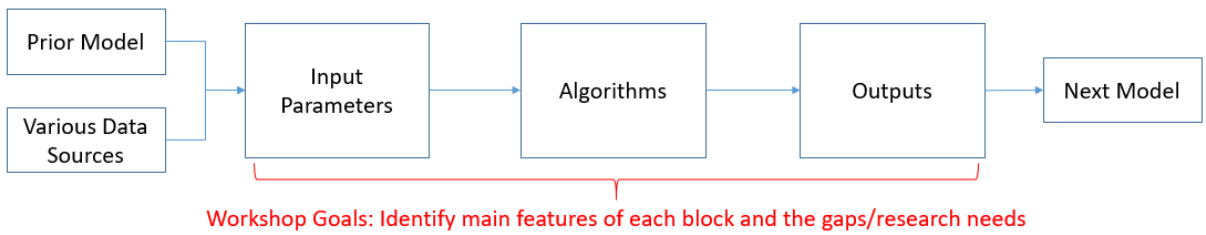


Figure 14: Generic approach to the broken rails modules workshops

Table 11 shows a summary of the broken rails modeling modules and the status of each. Workshops are expected to be held for each module by the end of April 2022.

Table 11: 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	Apr 14, 2022
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. Strength/Resilience Model	David Fletcher (Sheffield University)	15	Feb 16, 2022
8. Stress-Strength Model	Yan Liu and Chris Ladubec (NRC)	8	Feb 17, 2022
9. Broken Rail Derailments	TBD	TBD	Presentation at ICRI Ottawa Workshop week of April 25th

3.7.4.1.1 External Loading Environment

Multibody dynamics models are 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. Figure 15 shows a draft outline of the loading environment module the team will be initially considering.

This workshop is expected to be held the week of March 21st. The workshop results and discussions; including the input and output parameters, algorithms, research gaps or new technology needs will be recorded and included in the final Broken Rails Modeling Framework report.

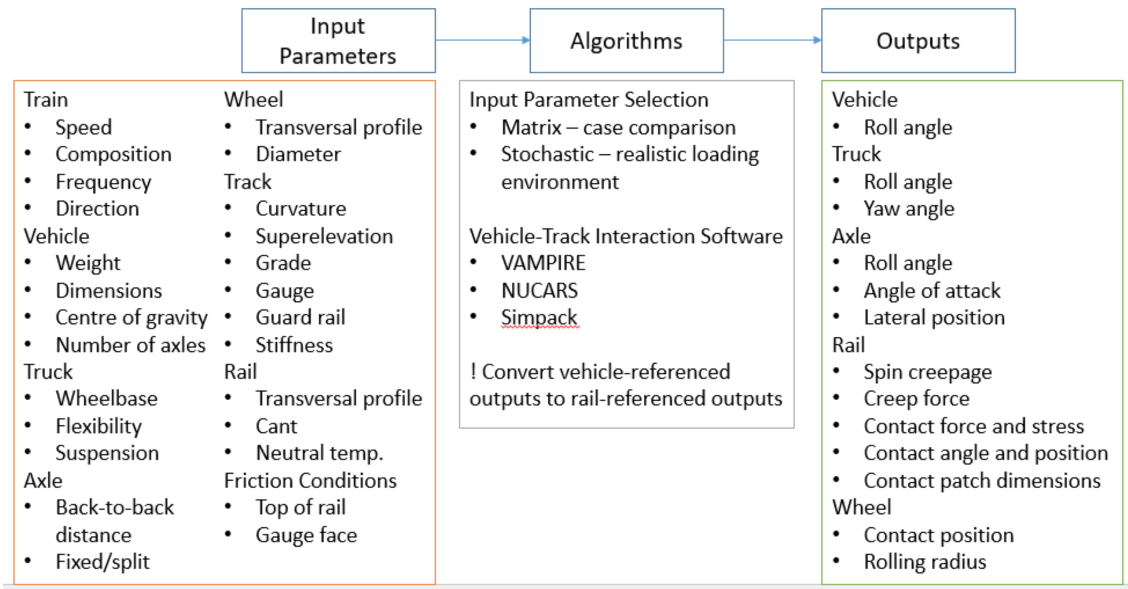


Figure 15: Draft outline of the loading environment module (pre-workshop)

Lead: Alex Woelfle (NRC)

Participants: Georg Schnalzger (MCL), Werner Daves mailto:werner.daves@mcl.at (MCL), Adam Bevan (Huddersfield), Gerald Trummer (Virtual Vehicle

3.7.4.1.2 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 3.1.10): 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 3.1.2): 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:
        - Jan 17, 2022: Kick off meeting.
        - Next meeting expected to occur in April 2022.
3. Tribometer continuity plan (see Section 3.1.3): Ben White of Sheffield University leads this project to continue the development and help troubleshoot the OnTrak railhead tribometer, whilst also providing a platform to collaborate and share friction data.
    - Past Meetings:
        - Jan 5, 2022: Kick off meeting.
        - Jan 19, 2022: Development of project framework
        - Feb 3, 2022: Continue development of project framework
        - Feb 24, 2022: Meet with modeling community to determine their needs
        - Mar 24, 2022: Incorporate modeling community input into project framework

A team is being developed to host a workshop on this topic.

3.7.4.1.3 Rolling Contact Fatigue (RCF) Model

Mandate: For a given loading environment consisting of many passing wheel contacts, we need to model 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, which will be discussed during a workshop planned for April 14, 2022:

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.)?

The workshop results and discussions, including the input and output parameters, algorithms, research gaps or new technology needs will be recorded and included in the final Broken Rails Modeling Framework report.

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)

3.7.4.1.4 Surface Fatigue to Internal Defects Model

Mandate: Amongst billions of cracks, only some develop into transverse flaws that cause a broken rail. 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.

3.7.4.1.5 Wear Model

Mandate: For a given loading environment, current surface condition, third-body layers and metallurgical properties, apply appropriate algorithms to model the metal removal associated with wear.

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

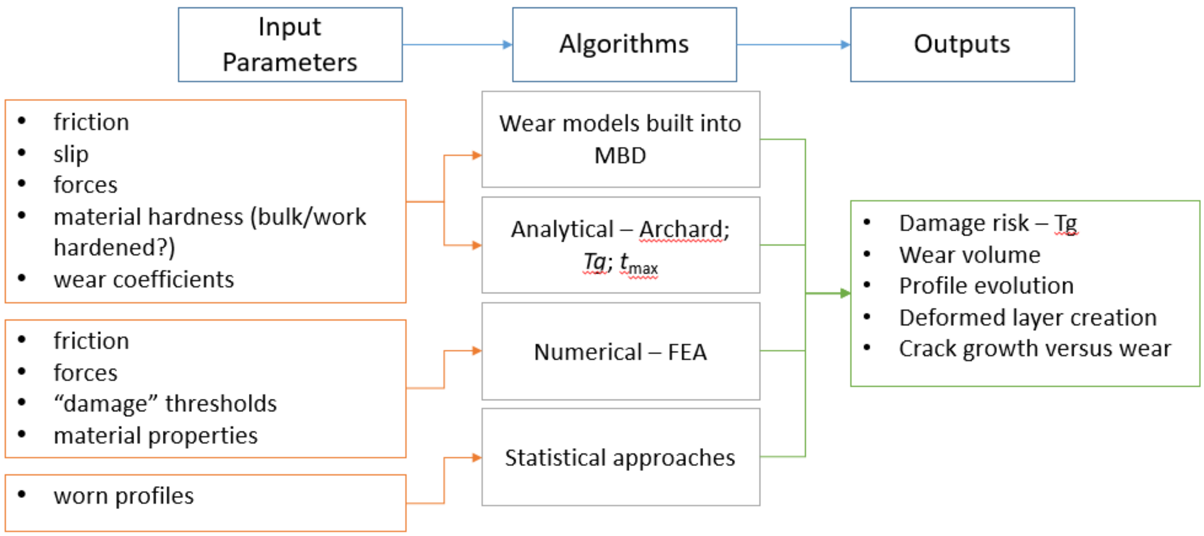


Figure 16: Wear module input, algorithms, and outputs

Inputs

Table 12 lists the inputs discussed by stakeholder category.

Table 12: Inputs listed 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/Tγ).
Research – Damage Modelling	• New more physically based modelling approaches.

Gaps:

- Friction data needed – instrumented wheelsets?
- 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 offered in recent call;
- 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 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 13 lists the algorithms discussed during the workshop.

Table 13: Algorithms discussed during 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.

Algorithms	Discussion
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; bi-directional 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 – 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, that could help);
- A good starting point would be to model small-scale tests initially to overcome full-scale modelling and validation complexities.

Outputs

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)

3.7.4.1.6 Welds and Internal Defects Model

Mandate: Welds are the source of 30-50% of FRA reported rail breaks. What conditions cause these to initiate cracks that develop 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 for 2014-2016 summer/winter periods)
    - 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 fatigue 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 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 to reduce 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:
    - 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 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 Labudec, NRC):
    - In regards 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 between 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

3.7.4.1.7 6.

3.7.4.1.8 Strength/Resilience Model

Mandate: 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, 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 16th, 2022. The results package is still being compiled but 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.

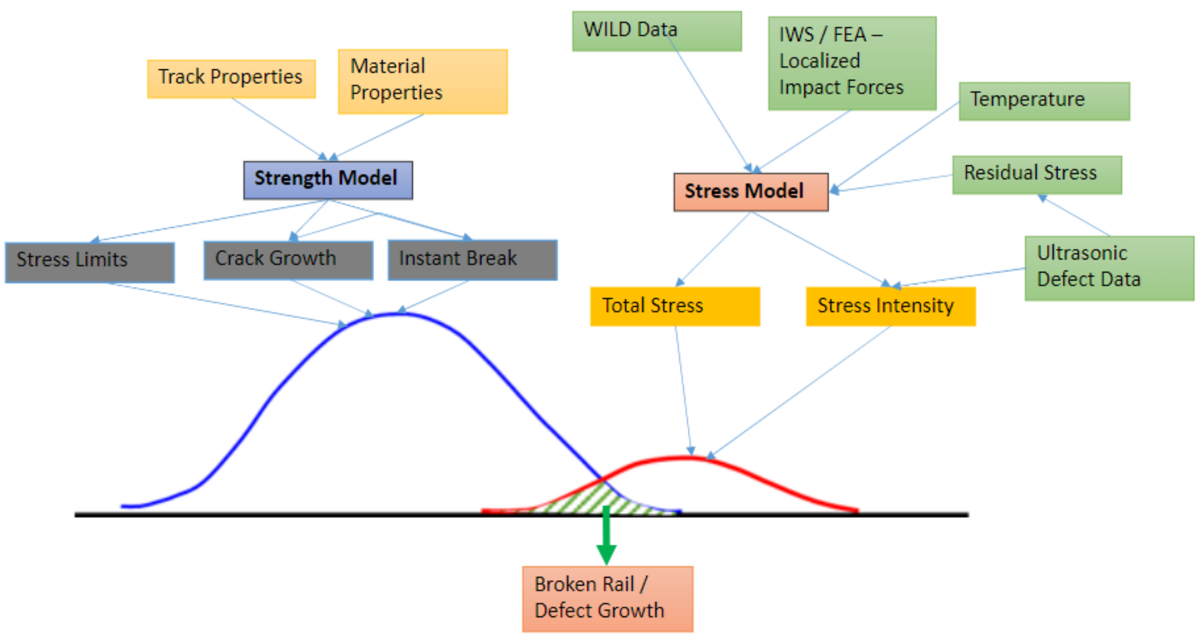


Figure 17: Initial concept of the interaction between the separate strength and stress models.

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)

3.7.4.1.9 Stress vs Strength

Mandate: 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.

This workshop was held February 17th, 2022. The results package is still being compiled but a follow-up meeting with theICRI coordinators and the System Strength module leader suggested that the System Strength and Stress vs Strength modules should be combined into one. A draft framework is shown in Figure 18.

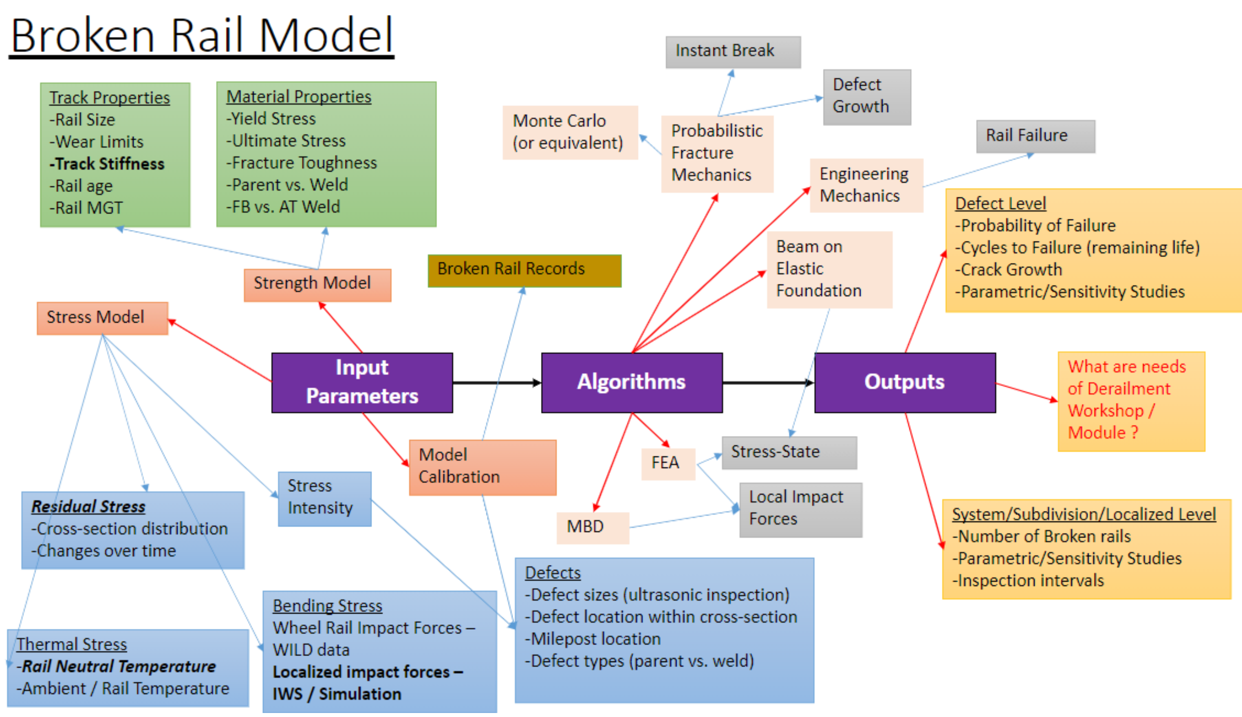


Figure 18: Draft Framework of the Combined Strength and Stress Modules

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)

3.7.4.1.10 Broken Rail Derailments

Mandate: Amongst thousands of broken rails that occur, only a handful result in a broken rail derailment. Understand and model those factors (e.g. type of failure and local track geometry).

A team has yet to be developed for this topic. A summary presentation for the Broken Rails model will be given at the ICRI Ottawa Workshop in the week of April 25th and at the ICRI Workshop during the WRI Transit Principles Course on June 21st. The leader and team for this topic is expected to emerge at these events.

3.7.4.2 Broken Rails Model Framework

The results from the workshops of Section 3.7.4 will be combined into a single document/framework that shows how the inputs and outputs of each module link to other modules. The path to a final report will include:

1. Reasoning through any differences/disagreements,
2. Highlighting all research gaps or new technology needs,
3. Reporting back to stakeholders, and
4. Developing an action plan.

3.7.5 Rail Defect Simulation Using Agent Based Modelling (ABM)

Agent-based models are a class of computational models for simulating the actions and interactions of autonomous agents (both individual and collective entities such as organizations or groups) with a view to assessing their effects on the system as a whole. It combines elements of complex systems, emergence, multi-agent systems, and evolutionary programming [15].

Agent-based models are microscale models that simulate the simultaneous operations and interactions of multiple agents in an attempt to re-create and predict the appearance of complex phenomena. The process is one of emergence, which some express as "the whole is greater than the sum of its parts".

Most agent-based models are composed of: (1) numerous agents specified at various scales (typically referred to as agent-granularity); (2) decision-making heuristics; (3) learning rules or adaptive processes; (4) an interaction topology; and (5) an environment.

Using ABM is especially beneficial when:

- A large number of entities of different fidelity and properties are involved;
- Entities will dynamically change during simulation; and
- An extremely large number of simulation scenarios are needed.

3.7.5.1 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 [16]. The expected broken rails per mile per year is expressed as follows:

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

$$U = Z^{*} + C_1S + C_2R + C_3A + C_4T + C_5L + C_6I + C_7G + C_8B \quad (2)$$

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)

$C_1, C_2, C_3, \ldots, C_8$ = coefficients

In the original model, the values for the adjusted model constant Z^{*} and coefficients $C_1, C_2, C_3, \ldots, C_8$ were based on data from the BNSF railway in the US. 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 [17] [18].

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.

3.7.5.2 Rail Defect Simulation Using Agent Based Modelling

The factors considered in this ABM study for rail defect simulation include:

- unit train and mixed train,
- weather condition (temperature, rain, snow),
- curvature, superelevation, train speed, rail hardness, rail age, rail weight, rail type, car weight, friction, etc.,
- annual traffic (MGT),
- rail inspection and maintenance to remove defects from the field,
- special trackwork and bridges, where defects can tend to cluster.

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 generic track profile (curvature, grade, gauge, speed, superelevation) was developed to represent typical Canadian mountain railway systems.

The initial NRC ABM model is shown in Figure 19. In this first instance the team has focused on predicting the emergence of rail defects, and will eventually extend this to derailments that occur as a result of broken rails. The right half of the window is the model world showing:

- track segments in different colors based on curvatures, white is tangent, light grey is mild curves, dark grey sharper curves,
- bridges are shown in red, and
- a map of rail defects, where black will represent recently initiated defects (<15% of the head area in size), orange are intermediate in size (15-30) and red represents “large” defects. At this stage, defect size is not correlated to head size but is a placeholder for a detailed defect growth model yet to be implemented.

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 existing number of defects.

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.

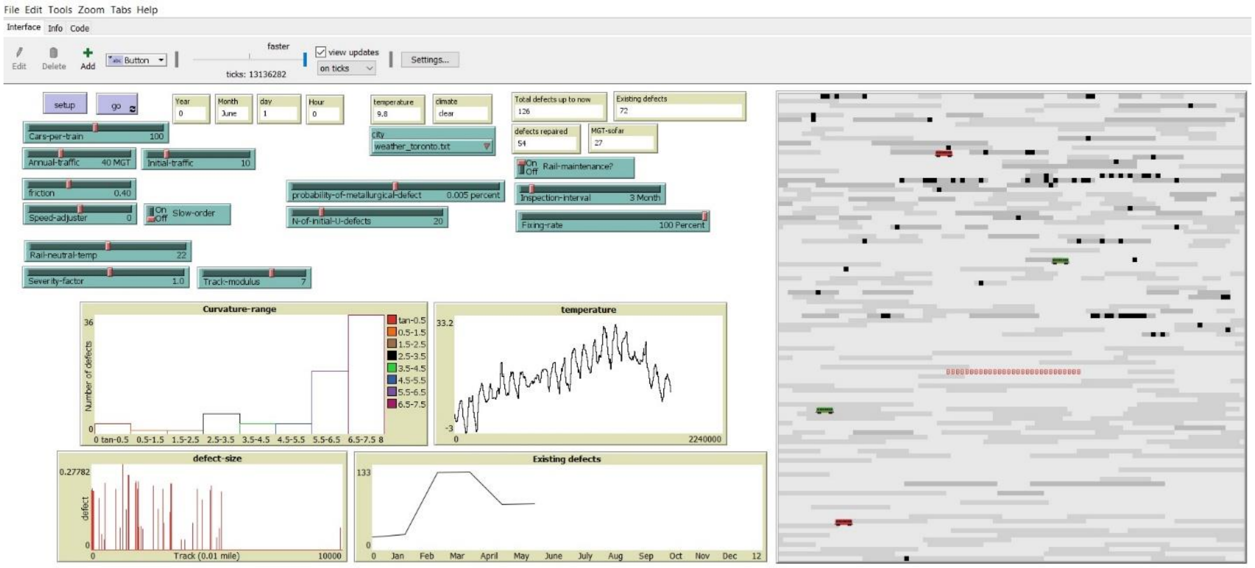


Figure 19: NRC ABM Model in progress

While still in the early stages, NRC plans to incorporate engineering models to account for:

- a distribution of axle loads and impact loading based on readings taken from WILD detectors,
- friction coefficients and their seasonal variation based on measurements and field experience on Canadian railroads,
- defect initiation as a result of localized loading and rail strength (metallurgy, rail wear, etc.) conditions,
- defect growth to include thermal stresses, rail strength and local load conditions.

4 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. Progress in each of these projects has been briefly reviewed. The rail safety topic has seen by far the most activity, with a framework and several modules being developed for broken rail modeling that will be presented in the first half of 2022. It is hoped that field testing on the NS and/or CP Railway will open up greater opportunities for participation and progress in all the ICRI projects.

A major function of the ICRI is to bring together researchers to discuss and formulate collaborative research opportunities. This is usually accomplished through the annual ICRI workshop. Unfortunately, the 2020 event planned for Istanbul was cancelled due to the COVID-19 pandemic, and no workshops were planned in 2021. Planning for three in-person conferences/workshops is underway for 2022: one three-day workshop to be held in Ottawa, April 26-28; a half day workshop in Vancouver on June 21st during the WRI Transit Principles Course at the WRI 2022 Conference; and a one day workshop in Melbourne Australia, September 4th in advance of the CM 2022 Conference.

The web meetings and presentations have fulfilled the goal of bringing the ICRI community together and facilitate knowledge transfer between the members. In the most recent (2021-22) year of effort, 11 web presentations were held on topics ranging from defect modeling to the effects of track stiffness and friction modifiers on wheel/rail performance. Six workshops related to an ICRI-Safety initiative to model broken rails have been held; the results of which will feed into the broken rails modelling program.

The ICRI continues to grow, having added 52 members, 1 country and 11 new organizations to its membership list in 2020-21, a total gain of 130 new members, 57 organizations and 10 countries in the last three year period. It now numbers over 330 individuals from 160 organizations in 29 countries.

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Abbreviations and Acronyms

3BL	Third-Body Layer
ABM	agent-based modelling
ARM	Advanced Rail Management
AREMA	American Railway Engineering and Maintenance-of-Way Association
BART	Bay Area Rapid Transit
BNSF	BNSF Railway
CM 2022	12th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems
COF	coefficient of friction
CP	Canadian Pacific Railway
CQU	Central Queensland University
DEM	discrete element method
EC	eddy current
EGI	equivalent grinding index
FEA	finite element analysis
FRA	Federal Railroad Administration (United States)
GQI	grinding quality index
ICRI	International Collaborative Research Initiative
IE	International Engineering
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)
NS	Norfolk Southern Railway
NTSB	National Transportation Safety Board
RCF	rolling contact fatigue
RIV	Rail Inspection Vehicle

RSAC	Railroad Safety Advisory Committee (United States)
RSSB	Rail Safety and Standards Board
TC	Transport Canada
TSB	Transportation Safety Board of Canada
TTCI	Transportation Technology Center, Inc.
VTI	vehicle-track interaction
WPD	wheel profile detector
WILD	wheel impact load detector
WRI	wheel-rail interaction
WRI 2022	27th annual Wheel Rail Interaction Conference

Appendix A - Project Proposal for ICRI RCF & Wear Field Studies on Norfolk Southern Railway (NS)

Background

The International Collaborative Research Initiative (ICRI) on Rolling Contact Fatigue (RCF) and Wear of Rails and Wheels is an informal collection of academics, consultants, researchers, and engineers working in, or having significant involvement with, the international railway industry. The ICRI, formed in 2013, brings together roughly 325 people from over 160 organizations in 29 countries to collaborate on topics of mutual interest by leveraging current or future, already funded work.

At the July 2019 ICRI workshop the NS director of research revealed that NS had recently begun regular, eddy current measurements of rail surface condition. These frequent inspections are believed to be very useful for classifying and trending surface damage, key goals of more than one existing ICRI project. In fact, this had been the basis for a previous ICRI program on the CSX railroad, but which had never been realized because of technical difficulties with the eddy current measurement equipment. Those difficulties have evidently been overcome by the supplier and now the modified system is being deployed on the NS. NS stated a willingness to support an ICRI research project that would utilize data already being collected by its existing suppliers (e.g. Sperry and Loram).

Norfolk Southern Railway (NS) Opportunity

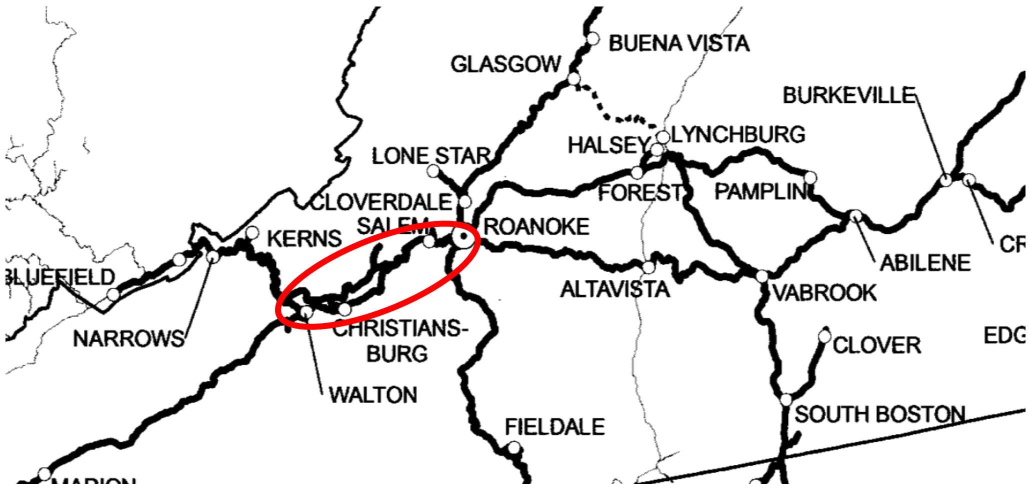
Norfolk Southern Railway is one of North America's larger Class I railroads and operates 20,000 route miles in 22 states and the District of Columbia, serves every major container port in the eastern United States and connects with other rail carriers. NS has a length of track in the Eastern US that is regularly scanned by Sperry using a high rail mounted eddy current system. Preliminary discussions determined that the most appropriate location for field studies would be in Virginia.

Proposed Location

Christiansburg District, MP between N270 and N297 (Salem to Walton). This is shown in the red oval in the figure below.

- Lots of curves and grade, and RCF of all levels
  - Grinding takes place twice annually – NS employs a “joint grinding” approach – teaming a large production grinder with a smaller switch and crossing grinder;
- Approximately 30 MGT of traffic annually;
- Good historical eddy current (EC) data and ongoing runs several times annually;
- Collect track geometry and rail profiles twice per year using NS’s track geometry cars or Loram’s Rail Inspection Vehicle (RIV);
  - RIV: profiles every 5 feet, images of the surface are scored by the operator to give visual defect severity ratings
- Gage face and top of rail (TOR) lubrication is applied. TOR units are spaced every 2 to 3 miles
- Majority of steel is from the 90’s, some curves with newer rail

The Christiansburg District does not have a wheel impact load detector (WILD) or a wheel profile detector (WPD). There is a WILD at Forest, MP N215 (40 miles east of Roanoke). The majority of trains that operate via the Christiansburg District run over this WILD. There is a WPD at Ironto, on the Whitethorne District, which runs parallel to Christiansburg. Ironto could be used to characterize the wheel profiles that run through Roanoke.



<u>The following ICRI Technical Goals are addressed in this proposal:</u>

1. Developing relationships between visible surface damage and depth of damage
2. Developing relationships between surface damage and risk, particularly with respect to service failures and defects detected by ultrasonic testing
3. Developing methods to incorporate new inspection technologies into regular maintenance practices (in particular grinding and milling)
4. Establish a best practice for grinding of new rail
5. Characterizing friction conditions in freight railway operations
6. Understanding the rate of crack initiation and growth rates as a function of:
   - Type of steel
   - Track curvature
   - Grade, tractive effort
   - Rail (and wheel) profiles
   - Cant deficiency
   - Track geometry errors/roughness
   - Proximity to special trackwork (crossings, switches, bridges)
   - Friction conditions
7. Developing and validating models of wear and surface fatigue
8. Quantifying “the magic Wear Rate”
9. Quantify economic benefits of improved maintenance practices

Scope of Work (SOW)

<u>T1: Selection of Field Test Sites</u>

The criteria for selection of the field test sites must include the following:

- Range of curvatures
- Must be safely and (ideally) easily accessible. Roadside access preferred.
- All sites can be measured up within 1.5-2 days of field work

- Various stages of RCF formation (low, moderate, heavy)
- Some new rail
- Ideally both friction treated and untreated
- Ideally various cant deficiencies, track grades, steel types
- Target a couple of locations where we know that rail is already planned for removal

Responsibility: Loram to propose several locations for consideration, decision to be made in concert with NS.

<u>T2: Initial Trending of Eddy Current Data</u>

Review existing and upcoming EC data runs from Sperry and trend the growth rate of RCF for various curvatures and tangent tracks. Chase outliers to understand the physical reasons for locally good or poor behaviour. Initial work will simply be to understand the consistency and reliability of the data and determine the accuracy with which the data can be aligned spatially.

Identify the system change as a result of rail grinding by comparing the pre-grind EC run with a post-grind one.

Responsibilities: To be assigned

<u>T3: Field Data Collection</u>

This project will require a minimum of four sets of measurements taken at the selected test locations. The following items will be collected by the ICRI team for each pre/post grind activity:

3.1. Friction characterized at a wide range of locations;
3.2. Pre- and post-grind rail profiles
- ICRI will collect MiniProf measurements of the rail;
- Rail profile measurements will be collected by the rail grinder;

3.3. Eddy current walking stick;
3.4. Photo documentation;
3.5. Machine vision images provided by Loram's RIV.

This collection will then be repeated at least once to meet the minimum-of-four-sets-of-measurements requirement.

Responsibilities: To be assigned

<u>T4: Data Analytics</u>

4.1 Wear rates: natural (post1-pre2) and grinding (preN-postN);
4.2 Profile shape change: conformality, head radius, grinding quality index (GQI);
4.3 RCF removal by grinding, RCF growth rates;
4.4 Friction map, and assessment of carry down etc. as possible;
4.5 Correlations: wear and RCF as functions of:
- Type of steel;
- Friction conditions;
- Track curvature;
- Grade, tractive effort;
- Rail shape;
- Cant deficiency;
- Track geometry errors/roughness;
- Proximity to special trackwork (crossings, switches, bridges);

4.6 Comparison of Sperry and walking stick eddy current measurements;
4.7 Comparison of electro-magnetic to machine vision and photographs;
4.8 Relate service failures and detected defects to surface condition, rail profile etc.;

4.9 Extract the magic wear rate curves for sharp curves, mild curves and tangent rails.

Responsibilities: To be assigned

T5: Reporting

5.1. RCF growth and wear rate curves
- Different curvatures, steels, friction, etc.;
- Identify and quantify most significant factors.

5.2. Economic analysis
- Lubrication practices;
- Different rail grinding approaches;

5.3. Criteria for achieving the magic wear rate on the participating railroad;
5.4. Revision to existing “Atlas of Rail Surface Defects” to add new photographs and RCF severity indices;
5.5. Review of relationship (or lack thereof) between service failures and surface condition (if enough data is available);
5.6. Discussion of suitability (accuracy etc.) for use of new inspection technologies to guide rail grinding program;
5.7. Present guideline for grinding of new rail (if data supports this);
5.8. Provide NS with a map of measured friction;
5.9. Future Activities
- May include dynamic modeling of rail load conditions and the application of wear and RCF models.

Responsibilities: To be assigned

Data Requested from NS:

Task	Data
T1: Selection of Field Test Sites	Data to determine selection of field test sites • Track profile (curvatures, grade, crossings) • Location of lube/TOR units and type • Locations of new rail • Train speeds and/or cant deficiency
T2: Initial Trending of Eddy Current Data	Existing EC data runs and notes of if/when there has been a grinding cycle between data runs (with Sperry)
T3: Field Data Collection	Pre-/post-grind activity • Eddy current measurements (with Sperry) • Rail/track/train info: – Type of steel – Train speed info – Tractive effort info – Axle loads (from nearby WILD) – Rail profiles (e.g. from track geometry car) – Track chart including position of friction units – Track geometry (with space curve) – Track geometry errors/roughness – Rail breaks occurring during test period – Possibly wheel profiles from nearby WPD
T4: Data Analytics	• Rail defects detected and service failures

Loram will be asked to provide:
- Profiles and machine vision images from the RIV;

- Rail profiles as collected by the rail grinder(s).

Proposed Schedule

The schedule is based around the rail grinding plan since pre and post-grinding measurements will be required for most of the scope items.

Task	Proposed Date
First Measurement Cycle: Pre-Grind	Mid-end of April 2022
First Measurement Cycle: Post-Grind	End of May 2022
Second Measurement Cycle: Pre-Grind	End of October 2022
Second Measurement Cycle: Post-Grind	End of November

Deliverables

Regular web meetings will be held to discuss the status of the project including data, findings, and next steps.

Assumptions / conditions

1. NS will ensure that its suppliers make the appropriate NS data available to the ICRI project team.
2. All data collected is for research purposes only and may not be utilized or applied outside the research team for any other project without the express permission of NS.
3. NS will provide on track protection safety and requested data sets for additional field inspections conducted by the ICRI team members along with the suppliers. At least three trips are expected and each field trip is likely to require two days on track.
4. While NS will cannot promise an ongoing commitment of resources, it has committed to the best of its ability to support the program for at least one continuous year. Equivalently – the ICRI cannot promise concrete outcomes from the effort, but commits through this proposal to execute the program plan to the best of its ability based on the informal commitments of the participants.
5. ICRI members will supply any data (e.g. measurements, photographs, etc.) collected over the course of this project to NS at its request.
6. Participants will be required to meet regularly, at a mutually agreed frequency, to share data and analysis results. When possible and practical, face-to-face meetings will be arranged.
7. Roadblocks or schedule slippage by one member will be communicated as soon as practical to the project team.

Budget Considerations

ICRI participants are “self-funded” and participation in this study will be at no cost to the ICRI or NS. All participants must plan for and be aware of potential travel costs, equipment supply, labour, etc.

Publications

There is an expectation of several publications or presentations arising from the work. NS is encouraged to co-author and co-present. NS has final editorial rights and only in extreme cases would veto the development of a publication. NS will work in good faith with the team to overcome any arising concerns (e.g. anonymizing data).

Responsibilities

In addition to the responsibilities described in the SOW section, each member is expected to participate in bi-weekly conference calls, share data in a central data repository and work together on publications. There is no expectation of IP being generated by participation in this project.

Project Risks and Dependencies

- This project will require time and expense commitments from each participant. The success of this project will be a direct result of participants remaining fully committed to the research project.
- While the project can function without one or two of the collaborative partners, it will not succeed if NS withdraws its support of field work and supply of data. All partners must accept that the situation may arise whereby NS or its personnel nominated at the outset of the program may change and that further direct support may be terminated.

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Appendix B - Leveraging the CP Thompson Friction Management Test Zone

Background

Dean Pietch, a track engineer with Canadian Pacific Railway (CP) and reporting to John Furlong, attended the July-2019 ICRI workshop in Vancouver. He advised workshop participants of a 7 mile "test zone" that was being established by CP in the Thompson near Kamloops. This length of track was being outfitted with brand new rail, effective friction management and an L/V measuring station. It apparently included 54 curves of various radii. At the workshop it was agreed that such a test location would be perfect for studies on things like the rate of wear and RCF development as a function of curvature, impact of cant deficiency, crack growth monitoring via eddy current, migration of friction products, effectiveness of grinding, need for initial rail grinding to remove mill scale, role of rail profiles, etc.

At the ICRI workshop, a tentative team of CP, NRC, LB Foster, Loram, Advanced Rail Management and potentially Athena Technologies was proposed for supporting ICRI led research activities on the Thompson.

Mr. Pietsch reported on 11SEP19 that "the request is being vetted through CP". The program that follows attempts to summarize opportunities and to lay out a specific request for CP support of ICRI initiatives.

Based on previous experience at CSX, we can envision field trips of two days each, probably on a quarterly basis. Short additional trips might be required if, for example, there is a need to capture both the pre- and post-grind data.

Table B-1 lists the expected project contributors and their main roles.

Table B-1: Expected role of collaboration participants.

Organization	Role
CP	On-track safety support for field trips; Wheel profile data (from automated systems); L/V records (including train speed).
Loram	Rail profile data; Surface condition information (RIV images, MRX RSCM); Rail grinding information (dates, number of passes, etc.)
Advanced Rail Management	Surface condition quantification using the Rohmann Draisine eddy current system; Data management (?) and analytics.
LB Foster	Friction measurements; Trials of friction management products; Data analytics.
NRC Canada	Program coordination; Data analytics; Wheel-rail and pummel modeling; Reporting.
Athena Technologies	Surface condition quantification; Data analytics.

It is also possible that universities in Canada and the USA will be interested to support the activity.

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