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July 26–27, 2011

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC			METRIC TO ENGLISH		
LENGTH (APPROXIMATE)			**LENGTH** (APPROXIMATE)		
1 inch (in)	=	2.5 centimeters (cm)	1 millimeter (mm)	=	0.04 inch (in)
1 foot (ft)	=	30 centimeters (cm)	1 centimeter (cm)	=	0.4 inch (in)
1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
1 mile (mi)	=	1.6 kilometers (km)	1 meter (m)	=	1.1 yards (yd)
			1 kilometer (km)	=	0.6 mile (mi)
AREA (APPROXIMATE)			**AREA** (APPROXIMATE)		
1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)	1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)			
MASS - WEIGHT (APPROXIMATE)			**MASS - WEIGHT** (APPROXIMATE)		
1 ounce (oz)	=	28 grams (gm)	1 gram (gm)	=	0.036 ounce (oz)
1 pound (lb)	=	0.45 kilogram (kg)	1 kilogram (kg)	=	2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)	1 tonne (t)	=	1,000 kilograms (kg)
				=	1.1 short tons
VOLUME (APPROXIMATE)			**VOLUME** (APPROXIMATE)		
1 teaspoon (tsp)	=	5 milliliters (ml)	1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)			**TEMPERATURE** (EXACT)		
[(x-32)(5/9)] °F	=	y °C	[(9/5) y + 32] °C	=	x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches	0					1					2				3				4				5
Centimeters	0	1	2	3	4	5	6	7	8	9	10	11	12	13									

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Contents

Executive Summary 1

1 Introduction 3

1.1 Objectives 3
1.2 Overall Approach 4
1.3 Organization of the Report 4

2 Workshop Description 5

3 Opening Remarks/Workshop Objectives 7

4 Technical Presentations 8

5 Suppliers’ Panel Discussion 20

6 Moderators’ Key Points and Workshop Discussion 23

6.1 John Tunna 23
6.2 Semih Kalay 28

7 Conclusions 31

Appendix. Presentations 33

Abbreviations and Acronyms 211

Illustrations

Figure 1. Flowchart Showing Factors Contributing to RCF (Eric E. Magel — NRC Canada)..... 8

Tables

Table 1. Workshop Participants.. 6

Executive Summary

In July 2011, the Transportation Technology Center, Inc. (TTCI), coordinated the joint Federal Railroad Administration (FRA)/Association of American Railroads (AAR) Workshop on Rolling Contact Fatigue (RCF). The workshop was held at the Congress Plaza Hotel in Chicago, IL. The objective of the workshop was to establish an understanding of the root causes for RCF and the procedures to eliminate, control, or mitigate the effects of RCF under passenger, freight, and mixed passenger/freight operation. Of particular concern is the impact of RCF on rail safety into future rail operations in North America, particularly with the advent of high-speed passenger rail operations. The workshop was tasked to identify any gaps in the current knowledge base so that timely research may be focused on these gaps in the near future.

RCF on rails came to prominence when it was identified as the root cause for the Hatfield derailment in the United Kingdom (UK) in October 2000. Subsequently, much research has led to the introduction of rigorous maintenance standards on European railroads to ensure safety. In addition to safety concerns, RCF leads to wheel and rail degradation and reduced service life.

The workshop was conducted over 2 days. Because implications of RCF differ for passenger and freight operations, two moderators were chosen to represent each point of view: John Tunna from FRA represented the interests of passenger operations and Semih Kalay from TTCI addressed freight issues. A series of 13 technical presentations and a panel discussion reflected various points of view on RCF implications, the current state of knowledge, and what still needs to be understood. The workshop was concluded with a moderated discussion, summarizing workshop results and identifying research needs.

Results of the workshop clearly indicate that there is much to learn about the root causes and potential effects of RCF. One of the lessons from Hatfield is that those in charge of the railway did not see the problem coming. This highlights the need for research that will help the rail industry in North America be better prepared for the likely introduction of new equipment and traffic patterns over the next few years.

A great deal of work has been done already. For example, extensive laboratory and field testing by Deutsche Bahn, Voestalpine, and others have allowed the INNOTRACK project to compile recommendations for rail grade, based on curvature versus tonnage or the surface condition of the rail being removed. Sophisticated wheel/rail roller rigs have been developed. In other projects, the Whole Life Rail Model (WLRM), based on T-gamma ($T\gamma$) and developed in the UK, is used extensively; other models are currently in development.

A flowchart was provided (see Figure 1) that gives a good overview of the factors influencing RCF. It provides a useful way of breaking down the problem and of identifying blank spaces in our knowledge.

Many potential future research needs were identified. A few of the most important needs are summarized below. Nearly all apply to passenger, freight, and mixed traffic operations.

- Interest centered on industry sponsorship of shared vehicle track interaction models along with standardized input data.
- Calibration of damage functions to theoretical models is essential. Factors include wheel and rail material properties, traffic conditions, and climate.

- Measurement of RCF (crack size, depth, density) is essential to effective RCF management.
- Although it is not expected that squats will arise as a problem for shared traffic corridors, squats are a threat on dedicated high-speed lines.
- Tγ is probably the best available tool for rail RCF prediction. The AAR/TTCI is currently using Track-Ex to apply the Tγ approach.
- The National Research Council Canada (NRC) roller rig in Ottawa is a convenient resource for, particularly, wheel steel RCF calibration and a possible resource for rail RCF calibration.
- Traditional belief is that in heavy haul operations, cracks are unlikely to turn down. However, according to Australian experience on ultraheavy haul lines indicates that cracks do occasionally turn down potentially leading to broken rails.
- The costs and benefits of remedial procedures need to be accurately quantified.

All participants agreed about the need to follow up on the issues discussed. Information exchange regarding RCF is needed beyond this workshop to provide practitioners day-to-day management tools for RCF.

1. Introduction

In July 2011, TTCI coordinated a joint FRA/AAR Workshop on RCF. The workshop was held at the Congress Plaza Hotel in Chicago, IL. The objective of the workshop was to establish an understanding of the root causes for RCF and the procedures to eliminate, control, or mitigate its effects under passenger, freight, and mixed passenger/freight operation. Of particular concern is the impact of RCF on the future of rail safety in North America, particularly with the advent of new and expanded high-speed passenger rail services. The purpose of the workshop was to identify gaps in the current knowledge base and to focus timely research efforts on them in the future.

RCF on rails came to prominence when it was identified as the root cause for the Hatfield derailment in the UK in October 2000. Subsequently, much research has led to the introduction of rigorous maintenance standards on European railroads. In addition to safety concerns such as rail fracture or interference with internal rail flaw inspection, RCF leads to wheel and rail degradation and reduced life.

Wheel/rail RCF can be defined as one or a combination of crack formation, material flow, and wear of the running surface of the wheel or rail, leading to degradation of this surface, higher vertical forces, and premature failure of the wheel, the rail, or the accelerated degradation of the vehicle and track structure. Premature failure can lead to a reduction in safety performance; degradation can lead to unacceptably high maintenance costs.

North American freight railroads are currently investigating the root causes for RCF under heavy axle loads (HAL) (286,000-pound (lb) cars or 32.5-metric ton axle loads) to further improve current wheel and rail life. However, North America is likely to see new and or expanded high-speed passenger rail equipment and traffic patterns on both new, dedicated and mixed passenger/freight operations. The need is to more fully understand the impact of these operations on RCF and capital and operating costs.

1.1 Objectives

The workshop was intended to help determine RCF research needs for FRA and AAR to improve the safety of passenger, freight, and mixed passenger/freight operations and to identify RCF technical parameters critical to the safe and efficient operation in the evolving North American railroad environment. Specifically, the workshop was intended to:

- Establish the current worldwide knowledge base of the root causes for RCF and applicable technologies useful to improve safety, extend wheel/rail life, and reduce maintenance costs.
- Identify technologies and standards to support improved safety and reduction of operating costs and
- Identify gaps in those technologies and standards.
- Identify potential resources or solutions to fill these technology gaps.

1.2 Overall Approach

An organizing committee was established to develop the conference agenda, invitees, and venue. The committee members were Ali Tajaddini from FRA, Jeff Gordon from the Volpe National Transportation Systems Center (Volpe), as well as Richard Joy and Harry Tournay from TTCI.

The workshop included a series of 13 technical presentations, and a panel discussion reflecting various points of view on RCF implications, the current state of knowledge, and what still needs to be understood. The workshop was concluded with a moderated discussion, summarizing workshop results and identifying research needs.

1.3 Organization of the Report

Section 2 provides an overall description of the workshop; Section 3 summarizes the problem definition from the FRA and AAR points of view; Section 4 provides a brief summary of each technical presentation; Section 5 summarizes the wheel and rail suppliers' panel discussion; Section 6 describes results of the moderated discussion summarizing workshop results/identified research needs; and Section 7 summarizes and draws conclusions from the workshop results.

2. Workshop Description

There were 36 participants, 28 from North America and 8 from overseas. Workshop participants were chosen to represent a diverse range of wheel and rail RCF experience on freight and passenger rail systems. Table 1 lists the participants.

The workshop was led by two moderators, John Tunna and Semih Kalay. Kalay focused on issues surrounding heavy haul freight, and Tunna concentrated on passenger rail. Both moderators considered issues surrounding mixed traffic.

Each moderator provided opening remarks and a discussion of the workshop objectives and problem definition from his perspective. The introductions were followed by 13 formal presentations on topics chosen by the steering committee. This was followed by a panel discussion among the wheel and rail suppliers that was moderated by Gary Carr of FRA. Following the panel discussion, Kalay and Tunna presented a summary of key points raised, with emphasis on the research needs identified. This was followed by a discussion period during which a moderator’s comments were augmented and modified.

Table 1. Workshop Participants

Name	Company	Country
Peter Mutton	Monash University Institute of Railway Technology (Monash-IRT)	Australia
Richard Stock	Voestalpine	Austria
Eric Magel	National Research Council of Canada (NRC)	Canada
Katrin Mädler	Deutsche Bahn	Germany
Makoto Ishida	Railway Technical Research Institute (RTRI)	Japan
Anders Ekberg	Chalmers University of Technology	Sweden
Paul Molyneux-Berry	Manchester Metropolitan University	UK
Mark A. Dembosky	Network Rail	UK
Ken Timmis	Rail Safety and Standards Board (RSSB)	UK
Cameron Lonsdale	Amsted Rail	United States
Steve Chrismer	Amtrak	United States
Conrad Ruppert	Amtrak	United States
Joe Smak	Amtrak	United States
Robert Nester	ArcelorMittal	United States
Dennis Morgart	BNSF Railway	United States
Darrrel Iler	Canadian National Railway Company	United States
Wain Strickland	CSX	United States
Dan Daberkow	Evraz Rocky Mountain Steel	United States
Glenn Eavenson	Evraz Rocky Mountain Steel	United States
Gary Carr	FRA	United States
Carlo M. Patrick	FRA	United States
Ali Tajaddini	FRA	United States
John Tunna	FRA	United States
Dan Stone	Hunter Holiday Consulting	United States
Brad Kerchof	Norfolk Southern Railway	United States
Steven Dedmon	Standard Steel	United States
Scott Cummings	TTCI	United States
Richard Joy	TTCI	United States
Semih Kalay	TTCI	United States
Al Reinschmidt	TTCI	United States
Daniel Szablewski	TTCI	United States
Harry Tournay	TTCI	United States
Huimin Wu	TTCI	United States
Sam Atkinson	Union Pacific Railroad	United States
James M. Holder	Union Pacific Railroad	United States
Jeff Gordon	Volpe	United States

3. Opening Remarks/Workshop Objectives

Both moderators provided views on RCF-related problems facing the North American rail industry. As planned, Tunna's remarks were more focused on passenger rail, and Kalay's remarks were geared toward HAL freight.

Tunna's main exploratory objective was to better understand how to prevent RCF from causing safety problems in the United States in light of plans to increase the number and speed of passenger trains operating on freight corridors. Currently, regulations that give limits for RCF on rails or wheels do not exist.

John recalled the experience at British Rail research in the 1980s in which a great deal of knowledge about the mechanisms surrounding RCF existed. However, in the 1990s due to restructuring of the railroad, corporate understanding of the means to measure, control, and avoid the deleterious effects of RCF was lost.

Kalay noted that wheel tread and rail internal defects and surface damage are the primary causes of wheel/rail replacement in the North American freight rail environment. As of 2010, spending on rails grinding and replacement is $3 billion per year. Vehicle maintenance and replacement costs are approximately $2 billion per year, 56 percent of which is for wheelsets.

With the large increases in rail life between 1994 and 2008, attributable to harder steels and improved wheel/rail interaction resulting in reduced wear, RCF has become a major degradation mode. In light of the sometimes conflicting requirements for shared track operations, the need to enhance understanding of RCF is immediate.

4. Technical Presentations

RCF — A Comprehensive Review (Eric E. Magel — NRC Canada).

Summary

Magel presented a review of RCF based on a report sponsored by FRA. This report, *Rolling Contact Fatigue: A Comprehensive Review* (DOT/FRA/ORD-11/24), was posted online at http://www.fra.dot.gov/rpd/downloads/TR_Rolling_Contact_Fatigue_Comprehensive_Review_final.pdf. Topics covered included RCF consequences, crack initiation, crack propagation, role of materials, monitoring technologies, management of RCF, rail grinding opportunities/needs, and systems for assessing vehicle track interaction (VTI) characteristics.

Figure 1 shows a flowchart from the report that summarizes contributing factors to RCF.

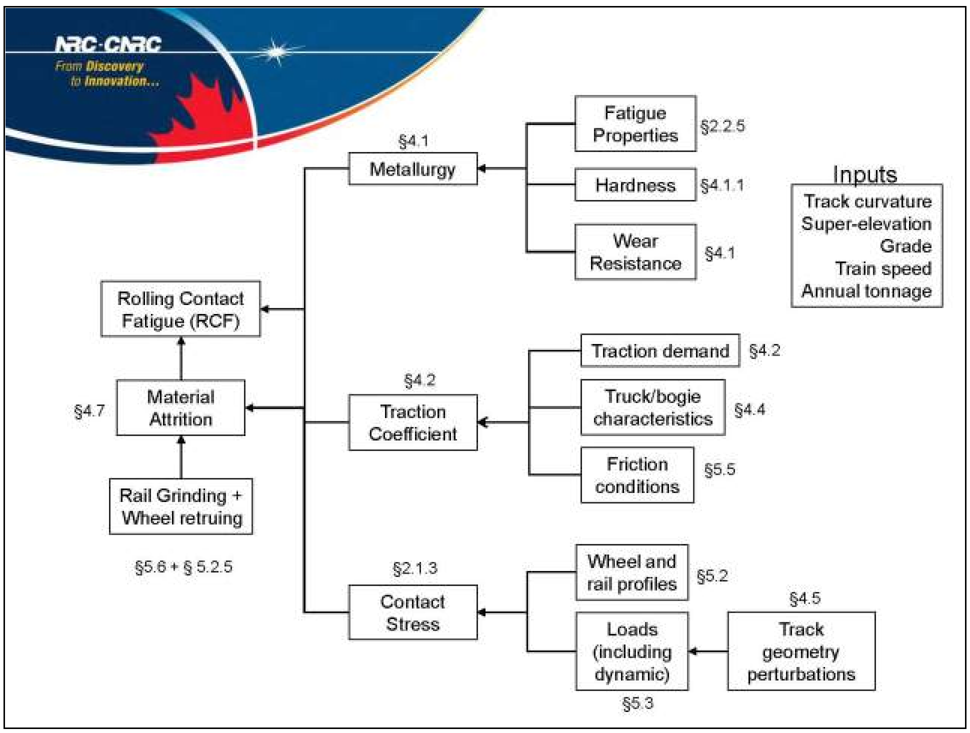


Figure 1. Flowchart Showing Factors Contributing to RCF (Eric E. Magel — NRC Canada)

RCF on Rails and Wheels in Amtrak Service (Steve Chrismer, Joe Smak, and Conrad Ruppert — Amtrak and Ali Tajaddini — FRA, United States)

Summary

Chrismer and Smak discussed Amtrak's experience with RCF, as well as results from an FRA-sponsored study to mitigate wheel/rail wear and damage on the Northeast Corridor (NEC). A key challenge is dealing with the wide range of wheel profiles, conditions, and loads on the NEC from mixed passenger and freight traffic. Evolution of Acela wheel profiles and NEC rail profiles was discussed along with rail grinding and friction management strategies.

The FRA-sponsored study provided guidance to extend the service life of Acela wheels and NEC rail. NRC-design wheel profile and grinding patterns for rail are limiting wear and RCF damage. Despite conditions that could lead to RCF, little to no limiting wear or RCF damage was observed on the rails. This is likely the result of improved profiles, monitoring, and maintenance practices.

Analysis to date suggests RCF remains under control because energy in the contact patch (Tγ) may be typically in the "Wear Only" regime.

Discussion

- The NEC accommodates up to 25 million gross tons (MGT) of freight annually on some parts of the lines.
- Amtrak is a relatively small player in the contract grinding business, so grinding schedules need to be driven by the availability of grinders.

UK RCF Models: Whole Life Rail Model and Wheel RCF Damage (Paul Molyneux-Berry — Manchester Metropolitan University Rail Technology Unit, Ken Timmis — RSSB, UK)

Summary

Molyneux-Berry began with an introduction to the Rail Technology Unit at Manchester Metropolitan University and a brief discussion of the Hatfield accident and how it affected rail safety research in the UK. This was followed by a description of the WLRM and a discussion on how it was developed as a result of renewed interest in RCF after Hatfield. The WLRM is based on Tγ, which is a measure of energy dissipation in the contact patch from tangential force and creepage.

Factors influencing Tγ and RCF include curve radius, cant deficiency or excess (with cant excess generally worse), wheel and rail profiles (contacts near gauge corner are bad) vehicle suspension yaw stiffness, traction and braking forces, load conditions, and track irregularities. Comparisons between the WLRM and shakedown predictions are generally good.

Although classic RCF is well predicted by the WLRM, other forms of damage exist for which other models are needed. Examples of damage include wear (for which several models exist), plastic flow, and low-cycle fatigue. A unique presentation tool is in use for which position and angle of forces and cracks are plotted using surface plots, the contact position and creep force angle is given as the position in a polar plot, and $T\gamma$-magnitude is indicated by color.

Discussion

- A 250-meter (m) curve with cracks/plastic flow on the low rail and wear on the high rail was changed to premium grade (400, Hardness Brinell, HB). This led to RCF on the high rail and no plastic flow on the low rail.
- The Hatfield rail was a 350-HB (not heat treated) rail.
- Tγ is an empirical parameter. Changes may need to be made to the WLRM so that changes in friction, rail grades, etc., are considered.

Molyneux-Berry indicated that new RCF patterns were emerging from mixed passenger and freight operation on parts of the network.

Wheel and Rail Fatigue Prediction (Anders Ekberg — Chalmers Railway Mechanics (CHARMEC) at Chalmers University of Technology)

Ekberg presented research from CHARMEC. Much of this research was conducted under the European Community's INNOTRACK project. Topics included the following:

- Effect of operating conditions on fatigue
- Mechanisms for surface initiated RCF and two RCF prediction models
- Thermal loading of wheels and rails
- Experience with RCF in Sweden
- Subsurface initiated RCF
- Prediction of RCF and wear in switches and crossings
- Miscellaneous issues/considerations

Surface-initiated RCF is related to ratcheting at the surface layer. Two RCF initiation models were discussed. The $T\gamma$ model uses a damage function that accounts for wear. The FI_{Surf} model is still under development, and it includes provisions for traction, contact patch size cyclic yield stress, normal load, and damage. Knowing the limitations of each parameter is important.

Causes of wheel cracking range from (almost) purely thermal to (almost) purely mechanical. One problem surrounding thermal loading of wheels is that wheel heat induces compressive stresses that may cause tensile residual stresses. These can cause radial crack growth. In addition, cold temperature induces tensile stresses in all-welded rails that promote crack growth and fracture. The influence of cold on initiation is less clear.

RCF problems (both on wheels and rails) in Sweden are significantly related to winter weather conditions. Root causes include the following:

- Changes in steel properties (ductility, toughness, etc.)
- Thermal stresses in rails
- Frozen track bed (increased vertical loads in cases of wheel flats, hanging sleepers, etc.)
- Increased friction causing wear, RCF initiation
- Melting snow promoting RCF crack growth
- Ice accumulation on trains, on rails, in switches, etc.
- Decreased suspension capabilities/performance

Subsurface-initiated RCF is caused by a combination of poor contact geometry, high vertical loads, and material defects.

Further research is required to establish a more fundamental understanding and to develop current knowledge. Also, railroad and operator management initiatives need to deal with unbalanced incentives. For example, increased traction, while potentially damaging to the rail, will not give much cracking on the wheel. This leaves little incentive for operators to decrease traction (because it will increase travel times, etc.). It requires sufficient knowledge to quantify the costs and benefits of mitigation strategies.

RCF prediction using Track-Ex: root causes & remedies for RCF focusing on the relationship between track alignment errors & incidence of RCF (Mark A. Dembosky — Systems Engineering at Network Rail, UK)

Dembosky provided an introduction to Track-Ex, a tool developed by Network Rail to predict wheel/rail forces. Track-Ex sacrifices some of the accuracy of the more common packages such as Vampire® and NUCARS® for simplicity and speed. Advantages include:

- Quick and easily obtained estimates by relatively untrained staff
- In-house owned software running on typical PCs
- Uses new RCF findings from research sponsored by RSSB, the Vehicle Track System Interface Committee and others

The model's overall purpose is to help local staff identify and remediate damage and to become proactive, as well as to help central staff optimize standards, procedures, budgets, etc. At least 200 people in the UK have now been trained in its use. Training consists of 2 days including some theory and a 1-day top-up course.

The Tγ-model is included in Track-Ex. Work is under way for deriving a curve for head-hardened rails.

Under UK traffic conditions, most RCF on the high rail is induced by the leading axle. On the lower rail, the leading axle causes metal flow, and the trailing axle causes crack growth. Track-Ex approximates Tγ by using tables pregenerated by Vampire. The tables output Tγ is based on curvature and cant deficiency. Previous versions of Track-Ex simply interpolated the vehicle dynamic matrixes values by using curvature and cant. It often underestimated RCF, especially in shallow curves, because it took no account of track alignment variations. The Track-Ex Quasi-Dynamic prediction now used is a compromise: an 80/20 "cheat" based on Klingel motion.

The Route/Fleet Analysis function produces results from an entire fleet over the entire route for a specific method.

Track-Ex is a tool established in the UK and used for many applications. It is important to consider how much accuracy is actually needed and whether a simplified model such as Track-Ex may be sufficient for the applicable task.

Discussion

- Q. How sensitive is Tγ to lateral alignment and cant deficiency?
  - A. Very sensitive in some cases.
- Q. Is there any part in the UK with similar fleets where the RCF can be correlated with the model?
  - A. Yes, there are some spots where this has been done.
- Q. How much is the Klingel wavelength likely to be "smeared out" with a mixed fleet?

  - A. On high-speed lines the wavelengths are consistent. The wavelength on commuter lines varies from the high-speed lines by maybe 5 m.
- Note that Track-Ex is currently being used in the UK to evaluate vehicle performance during the procurement process.

Wheel and Rail Material Concepts to Control RCF and Wear (Katrin Mädler, Detlev Ullrich, Rene Heyder, Andreas Zoll, Marcel Brehmer, and Henri Bettac — Deutsche Bahn AG, DB Systemtechnik, Germany)

Summary

Deutsche Bahn has 67,440 kilometers (km) of track, 66, 875 switches and crossings. Passenger and freight operations include approximately 27,000 passenger trains and 5,000 freight trains per day. Maximum speed is 300 km/hour (h) for passenger and 120 km/h for freight, with a maximum axle load of 22.5 tonnes (t).

Head checks were first noticed in the 1980s, but there has been an enormous increase in the past 10 years. Rail problems include the following:

- Rail wear on sharp curves
- Rail wear and head checks on curves less than 3,000 m
- Head checks on curves between 3,000 and 5,000 m
- Corrugations, Belgrospis (RCF cracks associated with corrugations) and squats on tangent track

Rail material on Deutsche Bahn is mainly R260 and R350HT. Extensive long-term field tests were conducted between 1989 and 2009 with eight pearlitic and three bainitic rail grades. Bainitic steels did not show any RCF cracks. Two of them had relatively high wear, but 1400CrB showed also very low wear rates. These will now be adopted in curves $1500 < R < 3000$ m.

Three test stands are available in Kirchmöser, a heavy load wheelset test stand, a linear test stand for track components, and a wheel/rail system test stand. The wheel-rail system test stand started in1999 as a rolling test stand, yet in 2010, with modifications, it was used as a linear test stand to analyze track components including rails, frogs, and tongue rails In addition, frog testing is being conducted on a field test site near Hanover.

Also, wheel surface RCF has increased enormously in the past 10 years. Subsurface-initiated RCF also shows a slight increase. Europe often uses a softer wheel material than the rest of the world. Field tests results were very positive for harder wheel steels. Extended field tests starting in 2005 showed longer lifetimes for C64RMwheels. Wheel material grade has a strong influence on RCF damages of wheels.

Although harder rail and wheel materials offer many advantages, the risks associated with higher notch sensitivity must be considered.

Discussion

- Bainitic steels were used in the United States some years ago. They exhibited excellent RCF performance characteristics but more wear. Absence of a welding process was the main problem. Processes for both flash-butt and thermite welding have now been developed in Germany. The complication depends on the amount of alloying elements included.

RCF in Japan and application of twin disk machines: nature of wheel and rail RCF, root causes and remedial action in Japan (Makoto Ishida — RTRI, Railway Mechanics & Track Technology, Japan)

Summary

The main types of rail RCF seen in Japan are squats, gauge corner cracking, and head checks. The white etching layer is significant in the formation of squats. Wheel RCF consists of deep shells (also influenced by the white etching layer) and heat checks. The balance between RCF and wear is a key issue. Derivations of contact stresses under hertzian conditions and with rough surfaces were compared. Stresses are considerably higher when roughness is considered.

Testing has resulted in a diagram of needed grinding depth (millimeters per 50 MGT) as function of accumulated passing tonnage. Rail grinding was implemented on the Tokaido–Shinkansen line in 1993. This drastically reduced the number of defects. Examples of existing defects (basically on other lines than the Shinkansen) are closely spaced squats in connection to white etching layers. In addition, gauge corner cracking and flaking are seen. These cracks typically do not grow deeply into the rail. Field measurements of the occurrence of head check in relation to the wear rate confirm that the balance of wear and fatigue is significantly important.

RTRI has a rail/wheel high-speed contact fatigue testing machine. Laboratory results with various combinations of angle of attack, wheel profile, and lateral load are shown. The test rig is used for variation of wear with some experimental arrangements.

Discussion

- The gauge corner cracking usually occurs in curves approximately 600–1,200 m in radius. Also, “dark spots” are occurring on the gauge corner.
- Roughly half of the RCF defects occurring in Japan are squats. More problems with white etching layers occur for head hardened rail grades. However, these are mainly used in tighter curves.
- Flaking can be seen in sharp curves but also occasionally in shallow curves.

Understanding the Root Causes and Remedies for Wheel and Rail RCF in Freight Service in North America (Harry Tournay — TTCI, United States)

Summary

RCF can be defined as crack initiation and propagation, material flow, and wear.

In North American freight service, RCF research is driven by the high cost of rails and wheels. Wheelset replacement costs in North America are approximately $800 million per year. In 2009, capital and operating spending per year on rail replacement and grinding for U.S. railroads was approximately $3.2 billion in total. Head loss as the result of grinding low rail could be as high as 50 percent of total loss because of crack generation, wear, and material flow.

Thermal mechanical fatigue (TMS) accounts for approximately 50 percent of all high-impact wheels. Root causes include high steering tractions and high wheel temperatures (mainly because of stuck brakes). Solutions include controlled friction, controlled rail profiles, improved wheel steels, improved steering trucks, and reduced/controlled wheel temperatures. However, it is not yet clear how to quantify the relative benefits of each of these preventative measures.

Potential methods to establish the relative roles of causal mechanisms include twin disk and rolling load machines, in-service monitoring, and shakedown-based analytical tools. In-service monitoring is ongoing with different vehicle types. On the basis of shakedown analysis, improved steering trucks have led to an improvement up to 6.5 times. An improvement in RCF by using a modified bogie has resulted in increased wheel life. This improvement has been limited by an increase in asymmetric wheel wear, presumably as the result of asymmetric wear associated with the action of tread brakes bearing asymmetrically on the wheel treads; this is, in turn, the result of insufficient lateral guidance of the brake beams relative to the wheelsets.

Going forward, a shakedown-based model is in development, with the use of fatigue/Ekberg functions to incorporate temperature as well as friction limiting effects. An energy approach is in development as well. Rolling load testing is still an option, but cost/practicality is under exploration. TTCI will continue to obtain in-service performance data.

For rail, an energy approach has proven effective for predicting wear. In addition, material flow (lip growth) on the low rail can be quantified/predicted. Crack initiation remains difficult to quantify, in part, because of the variation found in the freight environment. Use of top of rail friction modifier has reduced wear, but cracks still occur on the top of the low rail. In very shallow curves, cracks that have a different pitch, depending on position, are a problem.

RCF is found in one 5-degree curve on the Facility for Accelerated Service Testing (FAST) test loop at the Transportation Technology Center (TTC) near Pueblo, CO. This proves to be an important test bed for model development and calibration, because vehicle and track parameters are very well defined, resulting in accurately quantified values for loads and creepages at specific rail locations.

Going forward, contact energy models will be used for determining wear, material flow, and crack formation. FAST is a good “rolling load machine.” Energy-based models are in development to simulate FAST conditions. In-service performance monitoring and simulation continues. Crack measurement methods continue to be assessed.

Discussion

- Q. How good are we in modeling the variation in operational parameters?
  - A. Not that good, particularly with respect to some bogie component characteristics (friction, stiffness, clearances, and tolerances); that is why we are interested in using instrumented wheelsets to qualify vehicles (and track parameters). We are also starting to trace several problems (e.g., asymmetric wear) back to their impact on the stress state of the system (stresses and loads on both vehicle and track).
- Q. Can we rely on top of rail lubrication for safety measures?

- A. It is always better to address the root causes (e.g., the truck steering).

- Q. Is the population of asymmetrically worn wheels related to cant deficiency?
  - A. No, it is a consequence of the action of the brakes; it then results in poor contact conditions: two-point contact, high lateral loads, wear, and rail rollover.
- Simulations for predicting lateral loads are very sensitive to initial conditions.
- Inclusion of temperature as a variable in predicting wheel RCF may be possible by reducing the value of *k* on the shakedown map and based on tested yield limits.

RCF in wheels and rails: Australian heavy haul operations (Peter Mutton — Monash-IRT and Ajay Kapoor — Swinburne University of Technology, Australia)

Summary

Australian heavy haul today consists of the following:

- The Pilbara in the northwest — iron ore service with 35- to 40-tonne axle loads, 1,435-millimeter gauge, 68-kilogram rail
- Queensland — metallurgical coal service with 28-tonne axle loads, narrow gauge (1,067 mm), 60-kilogram rail
- New South Wales — thermal coal service with 32-tonne axle loads, standard gauge, 60-kilogram rail

Current practices include use of wear adapted wheel and rail profiles, forged multiwear wheels, heat treated rails, and preventive rail grinding. On the iron ore systems, use of hypereutectoid rail steels increased. No lubrication occurs in 400- to 900-meter curves. On the coal systems, extensive lubrications are used.

On the iron ore systems, rim shelling (“shattered rim”) defects were a major problem. Since the mid-1990s, the problem has been eliminated through improved wheels, prequalification of wheel suppliers, and ultrasonic testing before reprofiling existing wheels. There is also surface-initiated RCF on wheels, which develops after ~200,000–250,000 km at 37-tonne axle load operations.

On the iron ore systems (37-tonne axle loads), wheel RCF develops in high-mileage wheels (>200,000–250,000 km). Defect initiation is the result of plastic deformation and ratcheting failure at the tread surface. Defects are addressed through implementation of microalloyed wheel grades and improved wheel maintenance (reprofiling at ~200,000–250,000 km, limiting tread hollowing to 3–4 mm, minimizing metal removal during machining).

For the rails, reduced rail wear rates and RCF have been obtained by profile optimization, preventive grinding, and monitoring of rail surface conditions. However, no robust monitoring system exists today. As rail hardness increases, there is a tendency to have finer spacing of head check cracks, which can make them hard to detect. Transverse defects originating from railhead RCF have an increased tendency to occur at higher rail head losses.

Localized RCF damage is associated with aluminothermic welds with increased cracking in softened zones as the result of reduced material strength. In addition, spalling is occurring in flash-butt welds on hypereutectic rails. This problem can be exacerbated by extending grinding intervals.

Monash-IRT and Rio Tinto Iron Ore are developing a revised rail grinding strategy pertaining to mainline heavy haul rail operations. This is a five-stage process: (1) data acquisition and assessment, (2) detailed simulation and analysis, (3) preliminary strategy development, (4) trial and monitoring, and (5) scheduling and implementation.

Monash-IRT and Swinburne University of Technology are working to improve prediction of RCF damage for premium rail grades and extend the WLRM to heavy haul conditions. Monash-IRT and Swinburne are collaborating on another effort to predict conditions under which transverse defect development occurs from RCF damage. There is also a proposed project on the behavior of rail welds in wheel/rail contact.

Key issues still to be addressed include the following:

- Understanding and managing the risks associated with RCF versus wear as the main damage mode
- More effective method of quantifying surface-initiated RCF damage during rail inspection; this is important because crack depth data is required for planning rail grinding
- Hypereutectoid rail grades
- Influence of material properties on RCF initiation
- Grinding requirements to offset reduced wear
- Development of transverse defects from RCF damage in rails
- Localized RCF damage associated with rail welds

Discussion

Q. [A] previous report states that transverse defects very rarely develop from head checks in Australia. Has that changed?

> A. It became apparent at railways where the minimum head dimensions are low. Also, these railways had standard carbon rail.

Strategies to extend freight wheel life and eliminate failures in North America (Scott Cummings — TTCI, United States)

Summary

Wheel shelling, as the result of fatigue (RCF and TMS) and spalls (because of martensite from sliding), is a major concern in North American freight rail operations. The overall wheel tread damage problem is split about evenly between shells and spalls. Broken rims are third in frequency of all equipment accident causes. Broken rim wheels frequently exhibit increased impact loads before failure.

There are three ways to reduce wheel shelling: (1) improve wheel resistance, (2) decrease thermal loading, or (3) decrease contact loads. This presentation focused on the first two.

Improved wheel resistance comes from high-performance wheel steels. AAR is currently testing eight types of high-performance wheel steels in the field. Laboratory testing was completed in

2009. Durability testing at FAST and in revenue service is under way. The laboratory tests showed some wheels have substantially higher yield strength than AAR Class C wheels. All of the wheel types are performing well at 100,000 miles.

To reduce Thermal Mechanical Shell (TMS), heat input should be controlled. The maximum acceptable operating tread temperature to minimize TMS is approximately 315°C (600°F). Wayside temperature detectors are being used to measure wheel temperature to attain a similar brake work load at all wheels in the train. A large variation currently exists between wheel temperatures in individual cars as the result of variation in brake shoe force and variation in brake shoe friction.

Less than 1 percent of the wheels measured at a particular location in a grade had temperatures above 315°C (600°F). However, if the braking efforts could be evenly spread over the car, this could be reduced by a factor of 8. Sources for uneven braking include uneven brake levers. This also relates to the asymmetric wear that Tournay discussed. It is also an effect of the brake shoe composition.

Going forward will require accurate quantification of the effects of TMS. This is difficult without a laboratory test. Wayside detectors do not provide continuous wheel temperature history. Furthermore, it is impractical to continuously measure wheel/rail tangential forces on a large sample size of wheels. The state of knowledge could be dramatically increased with a twin disc roller rig.

Discussion

Temperature is measured on the wheel tread using contacting thermocouples.

Vertical split rims occur both toward the field side and the flange side. The field side is more common.

Use of a rolling load machine to simulate and predict RCF (Richard Stock, Voestalpine Schienen GmbH, Austria)

The Voestalpine experience is that the predominant failure mode on sharp curves is wear, on medium curves head checks, and on wide curves and tangent track squats.

Voestalpine has a full-scale rail–wheel test rig with the capability of applying up to 40 t wheel load and 15 t lateral load. Both rail inclination and angle of attack can be varied. Simulation of bidirectional or unidirectional traffic is possible. The total loaded length for testing is approximately 1 m, and the machine is capable of approximately 25,000 test cycles per day.

Results are reported for R260, R350HT, R400HT and bainitic grade rail. The rail section used was 60EI (132 lb/yard). Contact conditions were chosen to ensure formation of RCF defects within 100,000 wheel passes. In general, all rails showed decreased wear and plastic depth with increasing hardness. Bainitic steels fall between R260 and R350HT in hardness but can vary depending on the bainitic steel grade. Generally, higher rail hardness decreases crack spacing, but no cracks were observed for the bainitic steels tested. Results indicate that rail hardness does not affect the rate of wheel wear. Application of the friction modifier resulted in reduced wear and cracking. The improvement factor with premium rail grades for the rig is less than for what is observed from field tests.

Squats are defined as shallow surface impressions with a crack network below. They are associated with low wear conditions, tractive conditions, stiffness of track and vehicles, and material transformation (white etching layers). Mechanisms are not yet fully understood. There seems to be a difference in current squats and in the squats of the 1980s.

Voestalpine is developing a new test rig that is expected to generate head checks in a shorter period of time, allow generation of squats, and allow automated rail inspection.

Discussion

- Q. With regard to crack spacing depending on the material properties. Does it stay constant with time?
  - A. Crack spacing evolve in time in the test rig over larger distances.
- The term "squat" is not much used in the United States. It seems that squats are not occurring in the United States today.
- The squats in the 1980s occurred as the result of hydrogen embrittlement. The defects today are different and have a different cause (surface defects).
- Q. Have you tried to apply a spectrum loading to see how differences between rail grades change as operational conditions change?
  - A. No, but we have thought about it and it should have an effect.
- Q. Can you simulate low rail contact?
  - A. Yes.
- Q. Has it been confirmed that the white etching layer is martensite?
  - A. For thicker layers it has been confirmed. For thinner layers it is difficult to know what it is.

Wear and RCF Prediction Algorithms for North American Railway Service (Huimin Wu — TTCI, United States)

TTCI has developed a wheel/rail interface management (WRIM) model and is adapting the model for mixed high-speed passenger and lower speed freight operations. WRIM has three modules: (1) precomputation of wheel contact parameters, (2) determination of $T\gamma$ values of all contact points, based on the simulation results, and (3) accumulation of the associated wear and RCF damage for all contact positions using the WLRM.

North American operational conditions include axle loads from 29.8 to 32.4 t, with some up to 35.7, three-piece bogies, and many small radius curves. There is much higher deviation in wheel and rail profiles as compared with the UK and, therefore, less feasible to do simulations with nominal profiles. Instead, WRIM precomputes wheel/rail contact parameters, using a representative group of wheel pairs and measured rail profiles.

Simulation results correlate well with reality, but based on results at FAST, the WLRM damage curve was revised with a start of RCF at 0.1 percent, peak RCF at 0.2 percent, and wear only above 2-percent slip. A question remains on how RCF damage values should be spatially distributed and accumulated in the contact patch to predict the initiation of RCF. Another issue is how to account for the material characteristics.

TTCI has also developed a Wheel/Rail Contact Inspection (WRCI) System, which combines output from an automated wheel profile measurement system with precollected wheel profiles to output wheel/rail interaction parameters and maintenance recommendations.

Additional work includes further field verification of prediction algorithms, more elaborate simulations, and laboratory tests to determine material characteristics.

Discussion

- FAST tests were bidirectional, whereas the operational data was a division of approximately 80/20 in two directions. It is also believed that outliers (e.g., the asymmetric wheel profiles) are responsible for much of the scatter in the data.
- The software is not commercially available, but it can probably be arranged so that it can be used by others.

5. Suppliers' Panel Discussion

Participants in the Suppliers' Panel Discussion included the following:

- Dan Daberkow — Evraz Rocky Mountain Steel, United States
- Steven Dedmon — Standard Steel, United States
- Glenn Eavenson — Evraz Rocky Mountain Steel, United States
- Cameron Lonsdale — Amsted Rail, United States
- Robert Nester — ArcelorMittal, United States
- Richard Stock — voestalpine, Austria

Gary Carr of FRA's Office of Railroad Policy and Development, Track Research Division, moderated the discussion.

The discussion was initiated with a summary of each supplier's perspective on the current state of RCF ongoing developments.

Amsted Rail and Standard Steel

Lonsdale of Amsted Rail and Dedmon of Standard Steel presented perspectives on wheel RCF. A summary of the presentation follows. The presentation materials are included in the appendix.

Known factors related to wheel RCF include the following:

- Elastic limit must be exceeded for RCF to occur
- Thermal mechanical shelling is more common in unit train service than mixed freight service
- Initial material strength and work hardening are important
- Lateral and longitudinal creepage plays a role, but we do not know how important this is in North American freight service

Multiple unknown factors related to wheel RCF include the following:

- The effect of impact loads – related to vertical shelled rims
- High strain rate dynamics
- The role of anisotropy
- How properties change in service
- Brake heating effects
- Role of residual stresses
- Rail grinding's effect on wheels
- Environment: dust, humidity, temperature, etc.

Development of a Class D wheel is described. Pearlitic wheel steels are microalloyed with chromium, molybdenum, vanadium, niobium, boron, or tungsten or some combination of these alloying elements. Increased strength is accomplished by ferrite strengthening and grain refinement and by increasing hardenability. Bainitic wheel steels, with different microstructure, are alloyed primarily with manganese, nickel, chromium, molybdenum, vanadium, niobium, or boron or some combination of these elements. Increasing strength is accomplished by increasing hardenability. However, at comparable hardness levels, bainitic steels wear worse than pearlitic steels. Improved wheels do not only relate to harder steels because this normally decreases the ductility. Furthermore, elevated surface temperature properties may decrease.

An example of Class D steel improvements, based on field tests, shows a 72-percent improvement in wheel life with average mileage to first reprofile increasing from 213,600 for a Class C wheel to 368,150 for a microalloy wheel.

Axial residual stresses have been measured in radial slices removed from various wheels. Results were presented at the American Society of Mechanical Engineers Fall Rail Transportation Division Conference in September 2011. Measurements suggest that new wheels have little residual stress compared with the residual stress development during the wheel life. Future residual stress measurements should include hoop and radial stress measurements.

ArcelorMittal

Nester noted that ArcelorMittal has an advanced head hardened rail development program. Although no specific RCF-related research is being conducted, he noted that improvements in mechanical properties generally result in a reduction in RCF.

Voestalpine

Richard Stock described voestalpine's systems approach and stressed the importance of mechanical properties in RCF initiation. Much of the research reported was funded through INNOTRACK and is available on the INNOTRACK Web site. Developments at Voestalpine include:

- Improvement of pearlitic rails (wear resistance, defect resistance)
- Bainitic rail development (for mixed and passenger traffic in Europe)
- Long rail production (120-meter rail lengths, issues with manufacture and transport of this rail length, working closely with welding companies toward that end)

Evraz Rocky Mountain Steel

Daberkow and Eavenson reported that Evraz Rocky Mountain Steel research includes head hardened and hypereutectoid rail development programs as well as work to characterize RCF and wear development with twin disk tests. Several head hardened and hypereutectoid grades are being tested to see whether crack initiation is reduced in-service applications. There is currently no bainitic rail research.

Discussion

Key discussion points are included below as follows:

- What is the influence of lateral forces? If lateral forces are important, how can we quantify this? Note that the $T\gamma$ and the FI_{sub} parameters do quantify this.

- Wheel/rail profile management is very important.
- The life of wheels is increasing with the new steels. Also, there is a shift to more coherent failure modes, which means that both the longest and the shortest lives increase.
- Are there test existing rig systems that can be used, or does one have to be developed for North America? Can we rent time on other dynamometers or do we need to build our own?
    - The Korean test rig is used for RCF testing for high-speed rails. The system is available for purchase (approximate cost is $1–2 million). It can handle 1,400-millimeter diameter wheels (up to 38-inch wheels) with large contact forces. It would likely provide good replication of North American HAL traffic conditions.
    - The two others investigated are voestalpine’s rig and the Deutsche Bahn rig, but they are being constantly used.
    - The brake shoe wear seems to be significant. Thus, a dynamometer should also include braking.
    - NRC has had a wheelset test rig for about 20 years, which can apply brakes. It was previously used to calibrate instrumented wheelsets. Tournay will follow up on its capabilities.
- Do savings from improved wheel and rail steels justify their extra expense?
    - Yes. North American railroads are buying them.
    - Yes. Life-cycle costs were evaluated as part of the INNOTRACK project with positive results. See their Web page.
    - Yes. ArcelorMittal and Evraz Rocky Mountain Steel consider life-cycle costs when developing new products.
- It would be useful to look at INNOTRACK program test results and how they compare to what AAR research is trying to accomplish with regard to wheel/rail contact patch measurements.

6. Moderators' Key Points and Workshop Discussion

6.1 John Tunna

Tunna posed a number of questions to generate discussion. The questions below are in **boldface** and are followed by many of the discussion points raised. Some of the discussion points were received via email.

North America is likely to see new equipment and new traffic patterns. Similarly, in the UK after privatization, stiffer European vehicles were introduced. What do we need to do to prepare for the changes?

- One of the lessons from Hatfield is that those in charge of the railway did not see the problem coming. This highlights the need for research to assure that we understand both root causes and potential effects of RCF under mixed traffic.

There was much discussion about a theoretical versus practical approach. Magel's flowchart (see Figure 1) gives a good overview and is a useful way of breaking down the problem. It is also a useful way to identify blank spaces in our knowledge, and it is applicable to either approach.

Freight railroads are dealing with RCF by grinding and reprofiling. Amtrak is managing RCF with optimized contact conditions. What more do we need to do?

- Optimization of wheel and rail profiles is necessary with changes in traffic mix.
- Optimization of curve superelevation should be considered.
- The Dang Van criterion is a high-cycle fatigue criterion—better for subsurface fatigue, not as good for surface fatigue. More information can be obtained from Ekberg.

Is this issue a safety issue or a maintenance issue?

The UK attempts to manage the problem by track access charges tied to how much damage a vehicle may cause. How are track access charges handled in the United States?

- A Class 1 freight railroad has the policy that passenger traffic will be allowed as long as it does not encroach on capacity or affect business.
- Another Class 1 freight railroad requires passenger operators to fund any updates required to accommodate passenger traffic.
- Another Class 1 railroad has considered charging private car owners different rates depending on equipment condition.
- Another Class 1 freight railroad reported using wayside detectors to identify poorly performing vehicles but cannot remove equipment unless the car violates an AAR rule.

We have NUCARS, Simpack, Vampire, SAMS/Rail, etc., for vehicle-track modeling. Do we really want more than one package for wheel/rail contact modeling? Should FRA sponsor

development of shared models? Wheel Rail Tolerance (WRTOL) and pummeling are also well developed wheel/rail interaction tools. Should the FRA be developing a model that combines the two?

- Potential uses for standardized vehicle models include Railroad Safety Advisory Committee work, validations of the safety and economics of new trucks, etc.
- Similar to what the RSSB has done with the WLRM in the UK, some agency would need to take charge of such a tool to ensure that it is capable, widely available, and maintained for the foreseeable future.
- Would it be possible to develop a shared tool and assure that adequate, consistent data is available? UK has developed a "virtual test track" that incorporates a standard modeling environment for vehicle acceptance.
    - The idea of the virtual track is one that makes sense, especially as new (high speed) vehicles are expected to land on U.S. freight railroads. Presumably these new vehicles will be subject to VTI criteria that include stability (lateral accelerations), forces in curves, derailment criteria (L/V, wheel lift), and wear rates ($T\gamma$). A virtual track representative of planned shared use rail corridors should be created. Perhaps California, the Midwest, and Florida lines would have sufficiently different characteristics that would warrant two or three models? For VTI purposes, the virtual track would include typical geometry, perturbations, friction conditions, and rail profiles.
    - If there is a concern about whether analysts with computer models are comparing apples to apples, and especially when we start talking about regulations applied to freight, it would be very helpful (necessary?) to have available standard libraries of rail profiles for use in such modeling.
    - It is well understood that friction plays a huge role in any dynamic, $T\gamma$ or wheel/rail contact analyses. Libraries with typical tribometer measurements should be included, and a standard approach for their implementation derived. This includes distinguishing between gage face and top of rail contacts (there is no standard to dictate which coefficient applies when) as well as the Kalker slope of the friction characteristic.

Would development of appropriate measurement methods be more effective than modeling which may become overly complex (requiring extensive calibration to specific conditions)?

- Vision, eddy current, or ultrasonic approaches to either qualifying or quantifying surface RCF do not currently exist in North America. These are expected to
    - Be crucial as research tools for developing a confident understanding the relationship between operating conditions and the rates of crack initiation and propagation. With such a tool, it will be possible to develop correlations between surface crack characteristics (e.g., length, shape, spacing, orientation) and the depth of damage that needs to be treated. For this purpose, even a hand-held unit would be sufficient.

  - Enable dramatic improvements in monitoring of rail for purposes of improved safety and optimized (preventive or just-in-time) maintenance. Higher speed units would be required for this purpose.

- Although suppliers continue to work on and apply these with some success in Europe, it is time for North America to begin familiarizing itself with this technology and directing their development efforts. Ensuring that suppliers become familiar with the North American operating environment, steels, and expectations will facilitate their application and dissemination into the North American rail industry.

Should we be concerned about squats in the United States?

- Squats appear to be the result of traction effect in light traffic conditions.

- Ballast crushing under the wheels might be a contributing factor.

- Microscopic martensite on the surface (caused by maximum tractive effort) has been observed on some Amtrak lines in the past; however, squats have NOT been observed. The wear rate is probably too high on mixed passenger/freight lines in North America. Freight traffic probably wipes out these martensite layers.

- Designated high-speed lines may be another issue.

- Japan has squats in service. Their solution is to grind every 50 MGT of traffic.

- Although it is not expected that squats will arise as a problem for shared traffic corridors (vigilance of course is required nonetheless), one must certainly be conscious that they are a threat on dedicated high-speed lines. Accordingly, maintenance plans for such lines need to be vetted against experience gathered elsewhere and then subsequently monitored and reviewed.

How do we get around the problem of testing for defects in rail when there is rail surface damage?

- Work is progressing within the main detection companies to develop new probes that look across the rail.

- A freight railroad representative noted that automated ultrasonic inspections have improved dramatically in recent years, with many more detail fractures being identified prior to failure.

Should we develop a U.S. version of Track-Ex that uses a Tγ model calibrated for U.S. operating conditions? Should Track-Ex be used to look at optimized operation on the Northeast Corridor?

- TTCI has agreement with Network Rail to use Track-Ex and is working on calibrating it at FAST and later in revenue service.

- Models such as Track-Ex are tuned to existing conditions, whereas many models are invoked considering “normal” conditions.

- One way to assure that RCF is considered is to require economic analyses with a tool such as Track-Ex that includes financial implication outputs.

Should we set up a shared track service test site to study RCF?

- Would RCF monitoring be practical?

- How long would we expect it to take to get results?

- If installed early enough, a base case will be available.

- Besides initial design and the procurement and installation of monitoring equipment, it is important to ensure sufficient and appropriate monitoring and reporting.

Do we know why subsurface cracks sometimes break out to the surface and sometimes turn down into the rail?

- Shear initiates these cracks, whereas vertical force drives them down. Explore effect of residual stress: anisotropy, contact stresses, environmental factors (weather, lubrication, etc.), and combinations of the above.

- Cracks may turn down because of residual stresses. Residual stress testing may be useful.

- Traditional belief is that in heavy haul operations cracks are unlikely to turn down. However, experience on ultraheavy haul lines in the Pilbara iron ore region of Australia indicates that cracks do occasionally turn down. The problem is worse in rails with extreme head loss. This has been managed to date by tightening rail wear limits.

- Factors include shear stress at the surface, contact stress deeper, then bending stress, which drives crack growth.

- Although the influencing parameters can be anticipated, the theories remain to be validated and applied to North America's wide range of conditions and predictive and treatment algorithms derived.

Should we review the U.S. track geometry standards in the light of RCF? FRA sets minimum track safety limits but expects railroads to maintain to higher, sustainable standards. Should FRA consider a similar approach for RCF?

- Geometry standards generally based on mid-chord offsets—how should appropriate chord lengths be determined?

- In the UK, 20-meter mid-chord offsets do a good job of highlighting track geometry problems that will cause RCF. The 20-meter chord tends to correspond to Klingel wavelengths.

- With so many input variables, we should be cautious about implementing track geometry standards. Should FRA just be sure that railroads have a system in place to manage the RCF problem?

- Panel expressed concerns about how varying conditions such as wet and dry climates might be included in a FRA standard.

- Management of Tγ may be a way to account for variables (such as the effects of moisture and friction coefficient, which are not well understood).

- Limits may be difficult to apply evenly. Should the same standard apply to a railroad that has a well developed preventive grinding program to a railroad that does not grind regularly?

- FRA should help with the research but continue to allow the railroads to manage the problem.

- It would need to be a performance-based standard.

Deutsche Bahn's 10-year service test provides information on wheel and rail life. The INNOTRACK project has combined results into a decision table that makes recommendations for choosing rail grade based on traffic and rail condition. The methodology also includes a life-cycle cost element. Should FRA fund testing to develop a similar decision matrix for selection of rail grade?

Observations indicate that spacing of RCF cracks is related to material hardness—this is currently unexplained. Is this an opportunity to advance the knowledge of root causes of RCF? Are there other similar opportunities?

Test rigs are a great way of producing results. But why are results from service testing in some cases better than test rigs? What is [the] balance between laboratory testing and service testing?

- With FRA and industry support, it may be possible to refurbish the NRC roller rig to serve the industry's wide range of expressed needs.

Track and vehicle concerns are typically dealt with separately by engineering and mechanical groups. However, vehicle track interaction is a system. Should a group be set up in the United States similar to the UK Wheel Rail Interface System Authority to address cross-interface issues?

There has been much discussion of a "magic wear rate" that is just enough to wear RCF away as it is formed. Should we look for a "magic traffic pattern" in which wear-prevalent traffic would remove RCF formed by fatigue-producing traffic?

Should a Tγ specification be used as a criterion for ordering new vehicles?

- This is practiced in the UK.

- Industry needs to understand why premium equipment is worthwhile.

The UK uses crack length as a standard to determine required maintenance actions for existing RCF. Do we need similar limits?

- May apply differently, depending on particular railroads standards.
- Crack length-to-depth relationships are different, depending on environment.
- The UK now monitors depth with ultrasonic acoustically because a good depth versus length relationship does not exist.
- Passenger traffic implies a higher consequence for broken rails.

Are there additional gaps that need to be bridged?

- Friction is a governing parameter in numerous wheel/rail phenomenon including hunting, curving forces, derailment, wear, and fatigue. But for modeling purposes, it is often trivialized as having a dry (theoretical Kalker characteristic) with a nominal value. There is very little understanding of what the real friction levels are, how they change through the day, through the seasons, and from region to region.
  - Can the instrumented wheelset (IWS) be used as a tribometer? NRC experience suggests that the top of low rail friction can readily be analyzed from IWS data, and this information may be useful on its own. It is unknown whether it would be possible, even with further refinement, for the IWS to be able to measure high rail friction (especially for two-point contacts).
  - Preliminary inquiries suggest that it "should be possible" to extract traction-creepage information from locomotives for assessment of friction conditions. This is an obvious avenue to explore.
  - FRA has already provided significant sponsorship for an NRC research (push) tribometer designed to measure the complete friction characteristic using lateral creepage. Although functioning in principle, further work remains.

6.2 Semih Kalay

Kalay identified the following research needs from the AAR's perspective.

There is a need for more fundamental understanding of root causes of RCF:

- Modeling — effects and causes. How important is it to realistically model the performance of the actual vehicle? How good are we at doing this? Outliers are those which produce the most RCF damage. High-precision models are sensitive to slight perturbations, which may affect their ability to reflect reality.

- Increasing state of knowledge with a TMS machine (i.e., twin disc roller rig). What is the effect of wheel temperature on contact patch energy? A roller rig should include the capability to apply brakes.

- Using full-scale laboratory tests (quicker) and field evaluations (more realistic).

- Addressing root cause(s) more appropriate than "quick-fix" solutions.

We need to validate existing models for all axle loads, wheel/rail steels, and mixed freight/passenger operations by:

- Conducting laboratory tests to determine shear yield strength and other material parameters used in prediction models.
- Improving prediction of RCF damage for premium rail grades.
- Determining whether rail wear limits are appropriate for RCF-affected rails?

Extend WLRM to heavy haul conditions by the following:

- Validating WRIM, Track-Ex, and other models.

RCF measurement systems for heavy haul conditions are needed urgently:

- Obtaining crack depth data required for optimized rail grinding.
- Adjusting inspection/maintenance frequencies, based on presence of RCF and size of cracks?
- What is not measured and quantified is not managed—another possible cause for missing the problems at Hatfield.

Management of RCF is needed in light of different stakeholder incentives (i.e., operators and infrastructure owners). What are industry incentives to invest in improvements?

We need to quantify the costs and benefits of remedial procedures such as friction control, improved wheel/rail steels, controlled wheel/rail profiles, improved steering trucks, and controlled wheel temperatures.

The following are open questions regarding performance of high-strength, high-carbon rail steels:

- What is the influence of material properties on RCF initiation? Will improved/more realistic data for material properties (nonstatic) make a substantial difference from the point of view of modeling?
- How should grinding requirements be established to offset reduced wear?
- Understanding and managing the risks associated with RCF versus wear. Design profiles such that wear prevents RCF accumulation?
- Limits on rail weldability must be understood (i.e., a process has been developed for welding certain types of bainitic rail to pearlitic rail).

What is the risk of developing transverse defects from RCF damage in rails?

RCF damage associated with rail welds is becoming an important consideration:

- Need improved flash-butt welding process(es).

- Need improved methodology to predict behavior of welds under dynamic loading conditions.

Further development of cost-effective maintenance methods is needed:

- Track geometry and rail flaw inspection
- Wheel/rail profile management and grinding
- Wheel/rail interface treatment
- Training and education

Further development of cost-effective prevention methods is needed:

- Improved truck characteristics.
- Improved wheel/rail materials. Should new materials be adopted without demonstrated economic benefit?
- Use models/empirical data to evaluate “track friendliness” of fleet types prior to acquisition or introduction into service.

All participants agreed followup was needed on the issues discussed. Information exchange regarding RCF is needed beyond this workshop to provide practitioners day-to-day management tools for addressing RCF. The Biannual Contact Mechanics Conference may provide an opportunity; the Brisbane conference in 2006 had large industry participation.

7. Conclusions

Results of the joint workshop on RCF clearly indicate that there is still much to learn about the root causes and potential effects of RCF. One of the lessons from Hatfield is that those in charge of the railway did not see the problem coming. This highlights the need for research that will help the rail industry in North America be better prepared for the expected introduction of new equipment and traffic patterns over the next few years.

A great deal of work has been done already. For example, extensive laboratory and field testing by Deutsche Bahn, Voestalpine, and others have allowed the INNOTRACK project to compile recommendations for rail grade, based on curvature versus tonnage or the surface condition of the rail being removed. Sophisticated wheel/rail roller rigs have been developed. In other projects, the WLRM (based on Tγ) developed in the UK is being used extensively; other models are currently in development. A flowchart was provided (see Figure 1) that gives a good overview of the factors influencing RCF. It provides a useful way of breaking down the problem. It is also a useful way to identify blank spaces in our knowledge.

Many potential research needs were identified. A few of the most important ones are summarized below. Nearly all apply to passenger freight and mixed traffic operations.

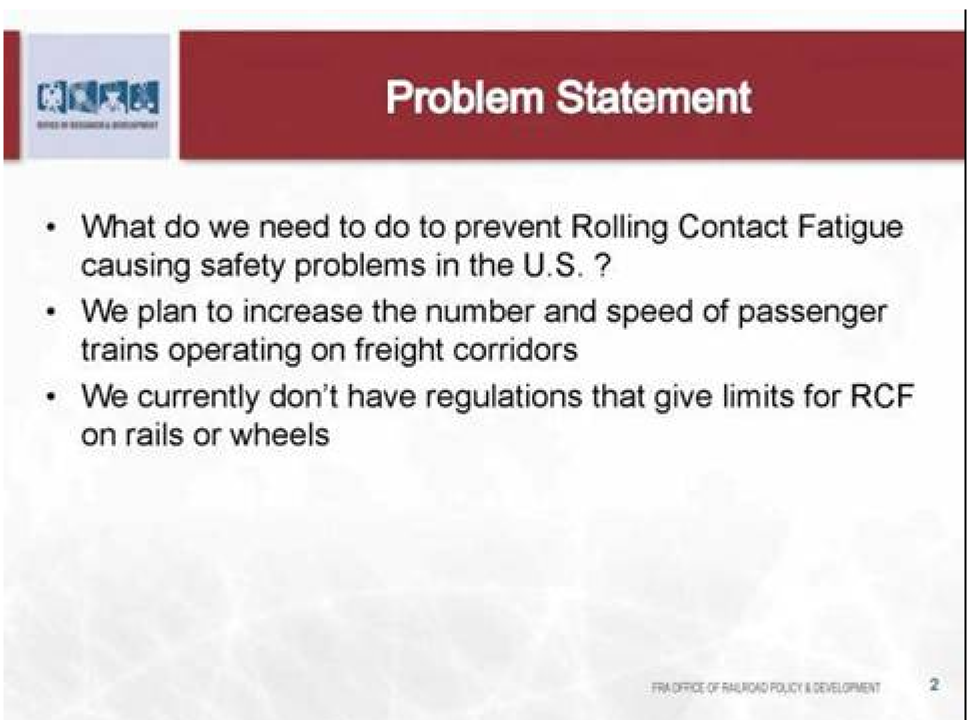
- Interest centered on industry and FRA sponsorship of shared vehicle track interaction models along with standardized input data. A "virtual test track" representative of planned shared use rail corridors would allow side-by-side comparison of vehicle performance. Some agency would need to take charge of such a tool to ensure that it is viable, widely available, and maintained for the foreseeable future.

- Calibration of damage functions to theoretical models is essential. Factors include wheel and rail material properties, traffic conditions, and climate.
- Measurement of RCF (crack size, depth, density) is essential to RCF management. Vision, eddy current, or ultrasonic approaches to either qualifying or quantifying surface RCF do not currently exist in North America.
- Although it is not expected that squats will arise as a problem for shared traffic corridors (vigilance of course is required), nonetheless, squats are a threat on dedicated high-speed lines. Accordingly, maintenance plans for such lines need to be vetted against experience gathered elsewhere and then subsequently monitored and reviewed.
- Tγ is probably the best available tool for rail RCF prediction. The AAR/TTCI is currently using Track-Ex to apply the Tγ approach. Wheel RCF remains a challenge. The AAR/TTCI is currently using shakedown theory and is exploring using Tγ.
- The NRC roller rig in Ottawa is a convenient resource, particularly for wheel steel RCF calibration and a possible resource for rail RCF calibration.
- Traditional belief is that in heavy haul operations cracks are unlikely to turn down. However, experience on ultraheavy haul lines in the Pilbara iron ore region of Australia indicates that cracks do occasionally turn down potentially leading to broken rails. The problem is worse in rails with extreme head loss. This has been managed to date by tightening rail wear limits.

- The costs and benefits of remedial procedures such as friction control, improved wheel/rail steels, controlled wheel/rail profiles, improved steering trucks, and controlled wheel temperatures need to be quantified.

All participants agreed there was a need to follow up on the issues discussed. Information exchange regarding RCF is needed beyond this workshop to provide practitioners day-to-day management tools for addressing RCF.

Appendix.
Presentations



High Speed & Intercity Passenger Rail

	Emerging/Feeder	Regional	Core Express
Speed (mph)	Up to 90	91 to 125	126 +
FRA Track Class	5	6 and 7	8 and 9
Track	Shared	Shared or dedicated	Dedicated
Grade Crossings	Standard	Enhanced	None
Route Length (miles)	~100	100 to 500	200 to 600

- Source: National Rail Plan – Moving Forward, D.O.T. September 2010

FRA OFFICE OF RAILROAD POLICY & DEVELOPMENT 3

Rail Defect Regulations

- 49 CFR 213.113 Defective rails
  - Transverse or compound fissure, detail fracture, engine burn, defective weld, split head or web, etc.
- 49 CFR 213.237 Inspection of rail
  - At least every 40 MGT or annually
  - Not counted if surface condition prevents defect detection
- Rail defect Rail Safety Advisory Committee working group

FRA OFFICE OF RAILROAD POLICY & DEVELOPMENT 4

Wheel Defect Regulations

- 49 CFR 238.107 Inspection, testing and maintenance plan
  - Describes procedures, intervals, criteria and equipment
- Engineering Task Force of the Rail Safety Advisory Committee

FRA OFFICE OF RAILROAD POLICY & DEVELOPMENT 5

Meeting Objectives

- Determine current industry and government understanding of RCF's issues
- Identify gaps in current research and technologies
- Indentify and prioritize research and development needs aimed at maintaining and improving safety

FRA OFFICE OF RAILROAD POLICY & DEVELOPMENT 6

What do we need?

- **More knowledge, understanding and better models**
  - ❖ Improve fundamental understanding of RCF development
    - Wheel profile
    - Tran geometry
    - Lubrication
    - Vehicle characteristics
    - Tracking and creeping
    - Friction
  - ❖ Risk associated with RCF crack parameters
  - ❖ Develop methods to characterize RCF and associate indices
  - ❖ Effects of track geometry and strengths to prevent RCF

FRA OFFICE OF RAILROAD POLICY & DEVELOPMENT 7

What do we need? Cont.

- **Regulations or best practice guidelines**
  - ❖ Crack length and depth limits
  - ❖ Wheel-rail contact condition limits
  - ❖ Suspension design constraints
  - ❖ Rail grinding surfacing guidelines

FRA OFFICE OF RAILROAD POLICY & DEVELOPMENT 8

What do we need? Cont.

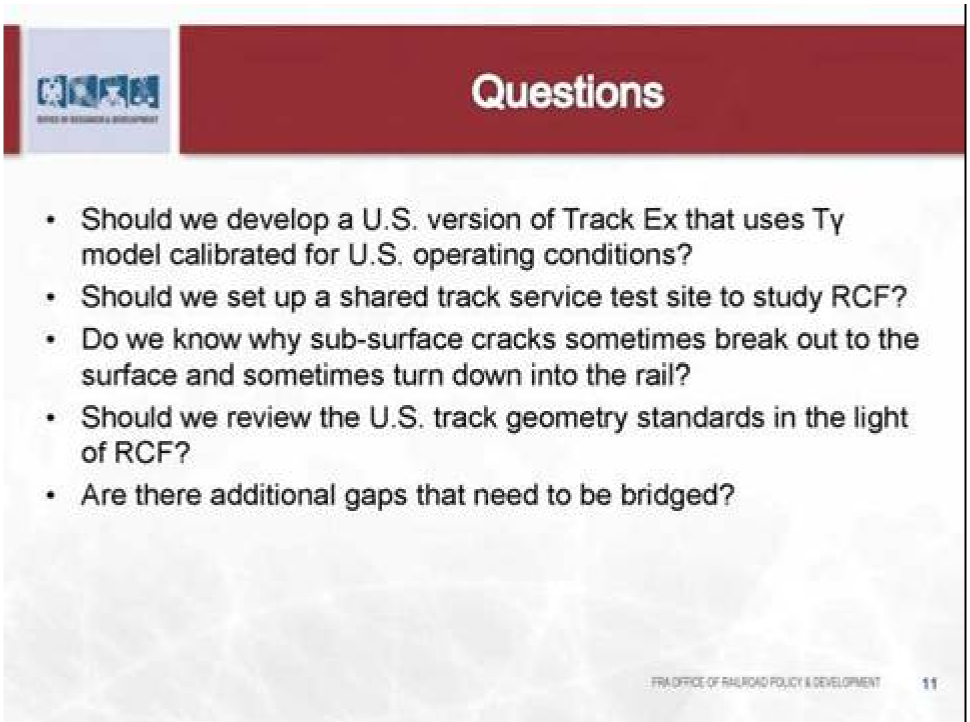
- **Inspection technology**
  - ❖ Automated methods to measure RCF parameters
    - Crack length, depth and width
    - Normalization/comparison methods

FRA OFFICE OF RAILROAD POLICY & DEVELOPMENT 9

Questions

- Freight Railroads are dealing with RCF by grinding and re-profiling. Amtrak is managing RCF with optimized contact conditions. What more do we need to do?
- Is this issue a safety issue or a maintenance issue?
- We have NUCARS, Simpack, Vampire, SAMSRail, etc. for vehicle-track modeling. Do we really want more than one package for wheel-rail contact modeling?
- Should we be concerned about squats in the U.S.?
- How do we get around the problem of testing for defects in rail when there is rail surface damage?

FRA OFFICE OF RAILROAD POLICY & DEVELOPMENT 10


Questions
Should we develop a U.S. version of Track Ex that uses Tγ model calibrated for U.S. operating conditions?
Should we set up a shared track service test site to study RCF?
Do we know why sub-surface cracks sometimes break out to the surface and sometimes turn down into the rail?
Should we review the U.S. track geometry standards in the light of RCF?
Are there additional gaps that need to be bridged?
FRA OFFICE OF RAILROAD POLICY & DEVELOPMENT
11

Background and Problem Definition

- Wheel tread and rail internal defects and surface damage are the primary cause of wheel/rail replacement in North America
- Even though significant increases in wheel/rail lives have been achieved, more research is needed to reduce costs
- RCF is a prominent degradation mode in new rail steels
- Conflicting requirements for shared track operations
- RCF Definition
  - Fatigue based process – Many cycles of high stress produced at the wheel/rail interface result in
    - Crack Initiation & Propagation
    - Material Flow
    - Wear

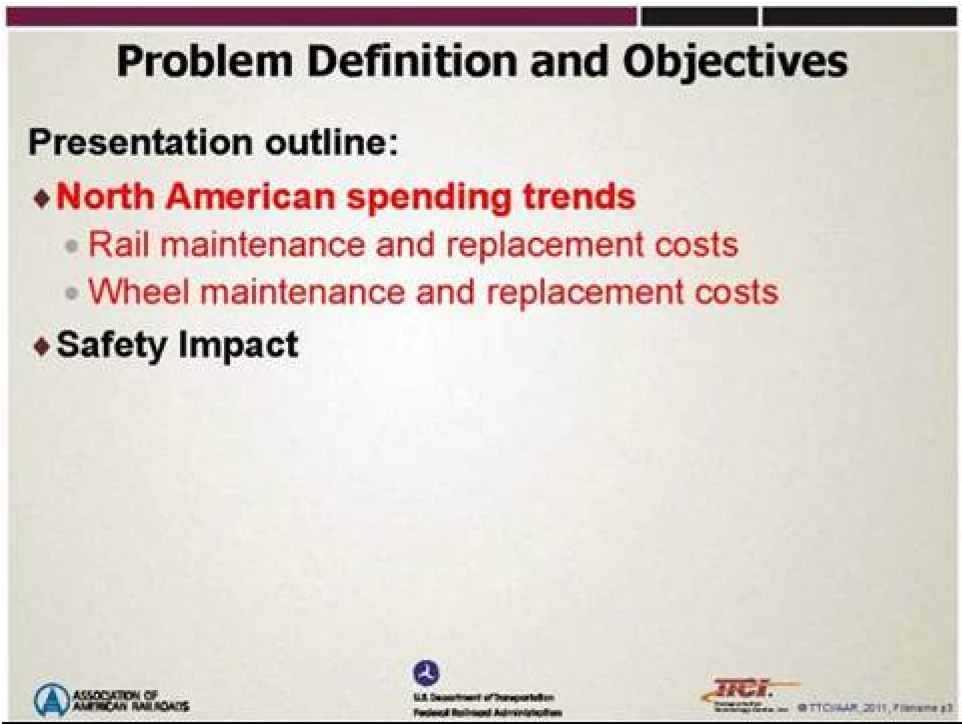
Association of American Railroads — U.S. Department of Transportation Federal Railroad Administration — TTCI

Problem Definition and Objectives

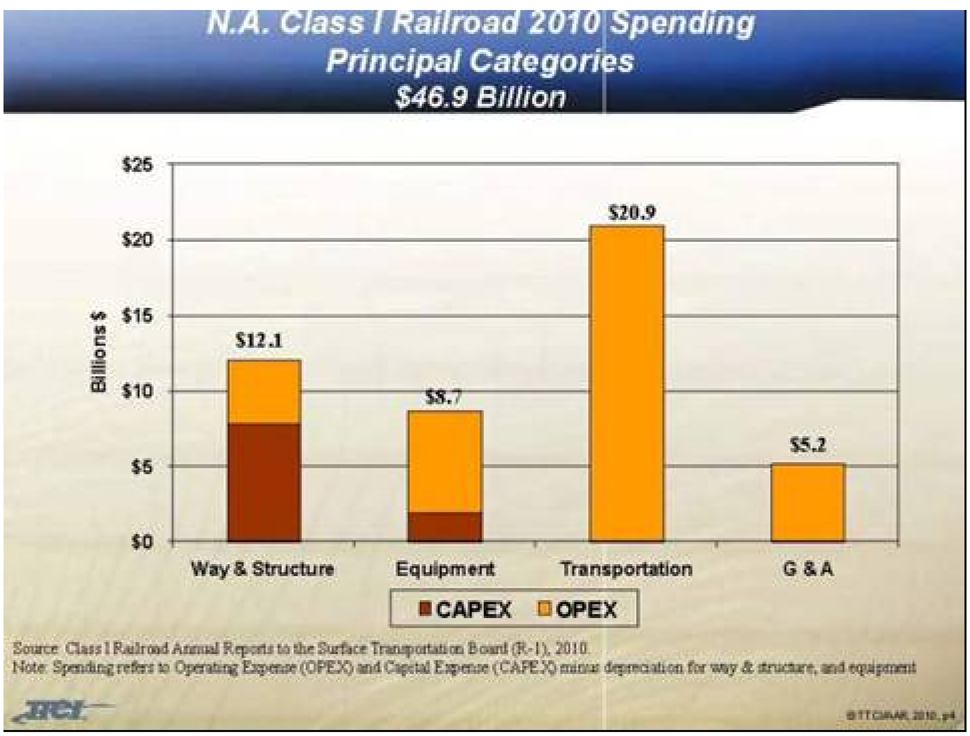
Workshop Objectives:

- **TTCI/AAR and FRA teamed up to bring experts from NA and oversees to:**
  - Share information to enhance the understanding of the root causes of RCF and prevention and remedial procedures
  - Learn from experiences of infrastructure owners, maintainers, researchers and suppliers
  - Accelerate efforts worldwide to advance the knowledge base and implement counter measures to significantly reduce and/or prevent occurrence of wheel/rail RCF
  - Develop cooperative research projects
- **North American railroad asset utilization**
  - Need to wear our assets not fatigue them

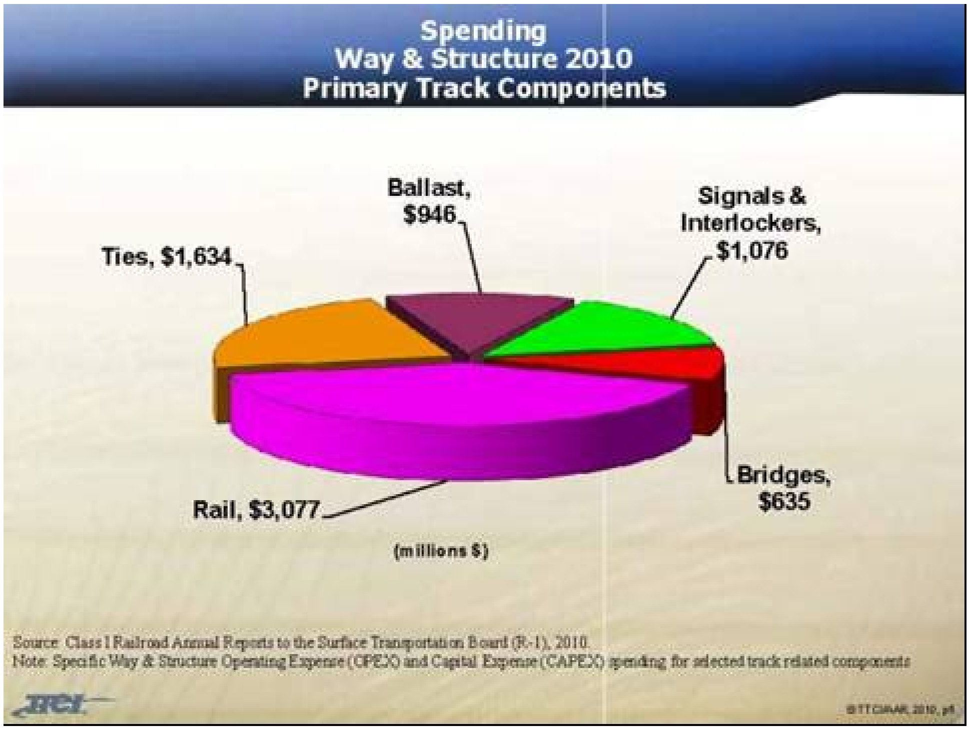
Association of American Railroads — U.S. Department of Transportation Federal Railroad Administration — TTCI

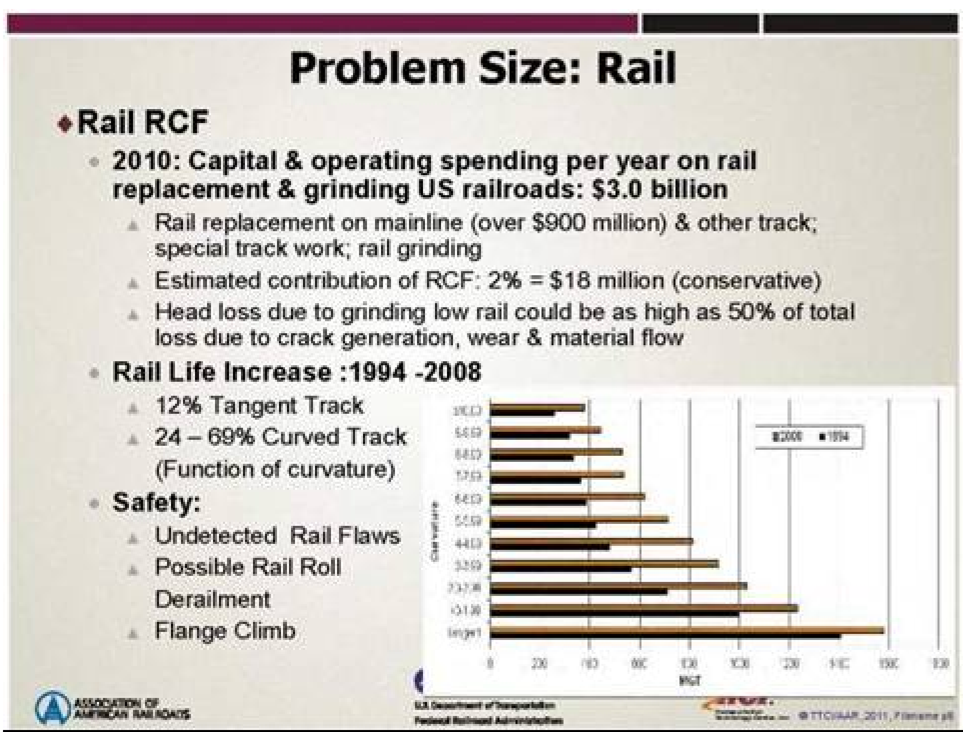


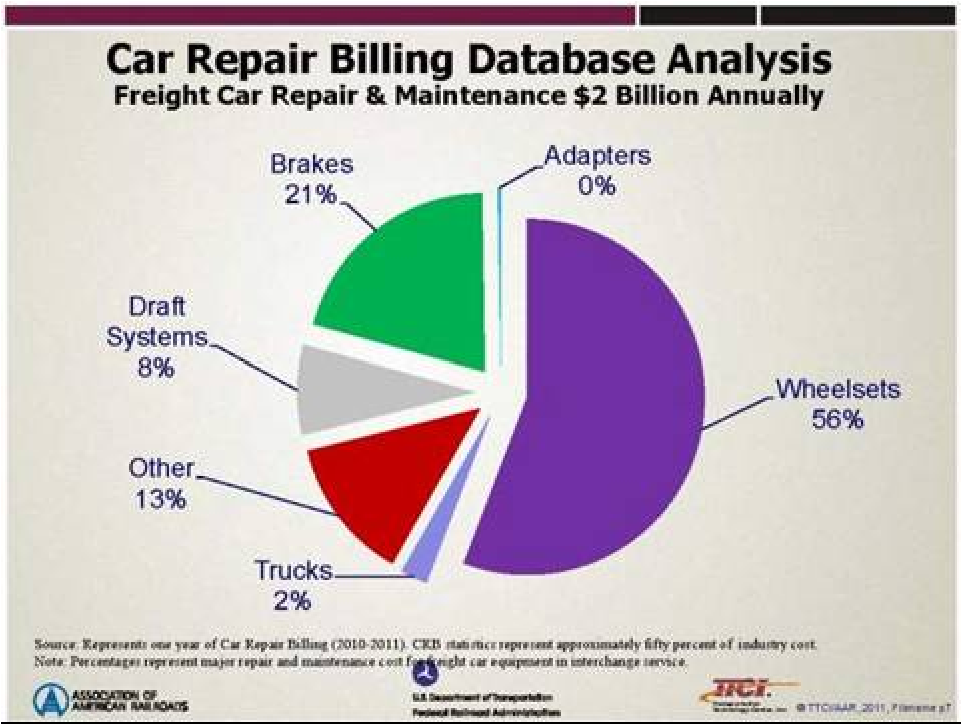
Problem Definition and Objectives
Presentation outline:
North American spending trends
Rail maintenance and replacement costs
Wheel maintenance and replacement costs
Safety Impact
ASSOCIATION OF AMERICAN RAILROADS



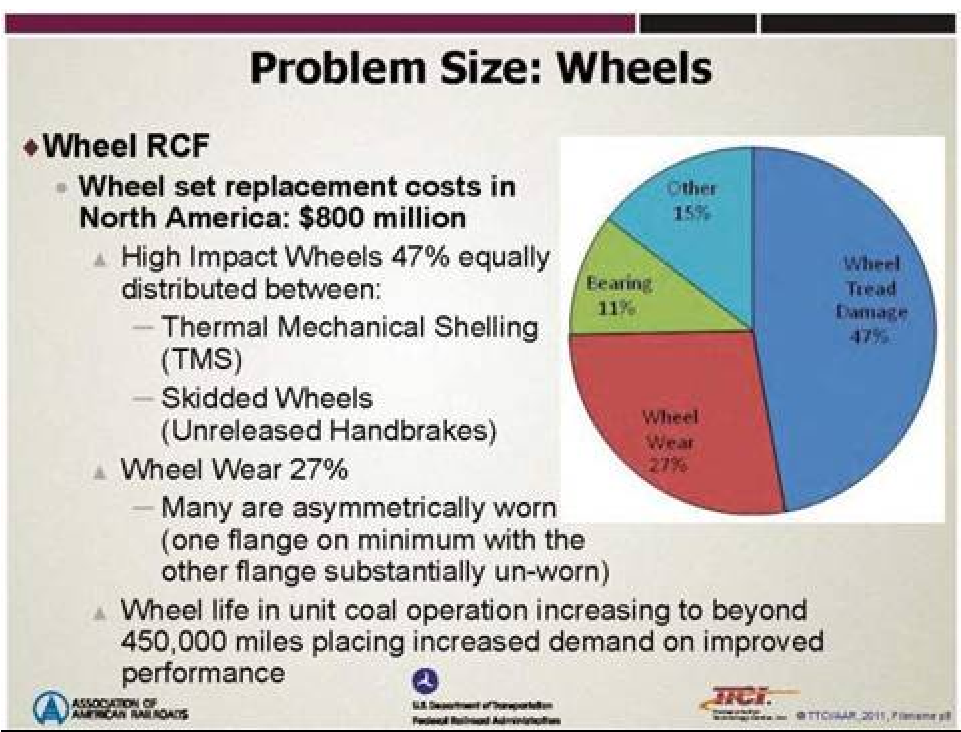
N.A. Class I Railroad 2010 Spending
Principal Categories
$46.9 Billion
Billions $
$25
$20
$15
$10
$5
$0
$12.1
$8.7
$20.9
$5.2
Way & Structure
Equipment
Transportation
G & A
CAPEX
OPEX
Source: Class I Railroad Annual Reports to the Surface Transportation Board (R-1), 2010.
Note: Spending refers to Operating Expense (OPEX) and Capital Expense (CAPEX) minus depreciation for way & structure, and equipment


Spending
Way & Structure 2010
Primary Track Components
Ballast, $946
Signals & Interlockers, $1,076
Ties, $1,634
Bridges, $635
Rail, $3,077
(millions $)
Source: Class I Railroad Annual Reports to the Surface Transportation Board (R-1), 2010.
Note: Specific Way & Structure Operating Expense (OPEX) and Capital Expense (CAPEX) spending for selected track related components

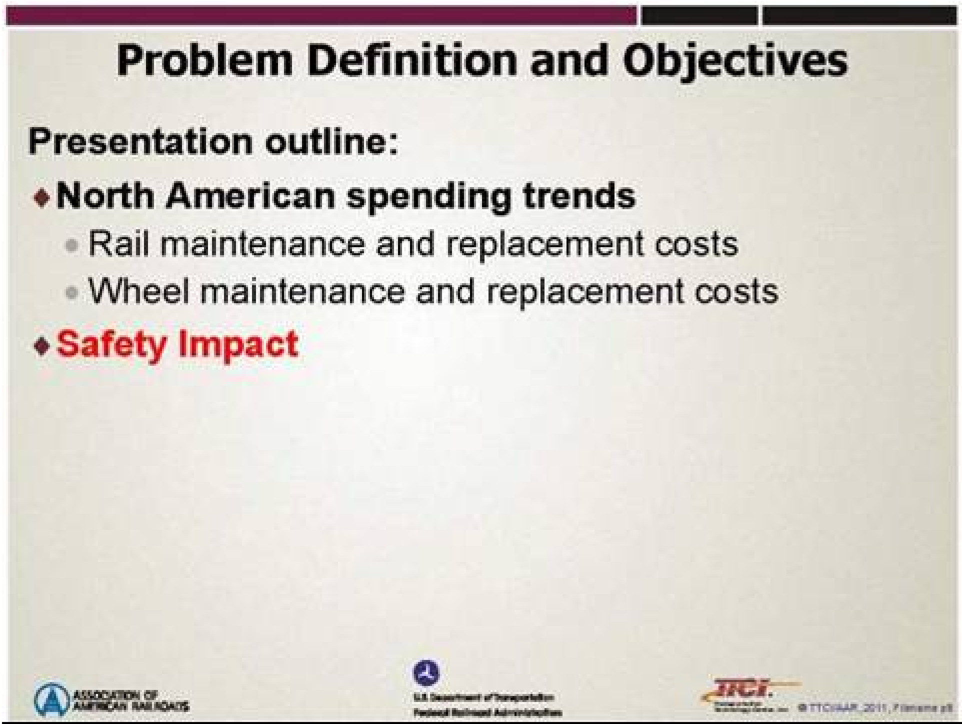

Problem Size: Rail
Rail RCF
2010: Capital & operating spending per year on rail replacement & grinding US railroads: $3.0 billion
Rail replacement on mainline (over $900 million) & other track; special track work; rail grinding
Estimated contribution of RCF: 2% = $18 million (conservative)
Head loss due to grinding low rail could be as high as 50% of total loss due to crack generation, wear & material flow
Rail Life Increase :1994 -2008
12% Tangent Track
24 – 69% Curved Track
(Function of curvature)
Safety:
Undetected Rail Flaws
Possible Rail Roll
Derailment
Flange Climb
Curvature
MGT
ASSOCIATION OF AMERICAN RAILROADS
U.S. Department of Transportation
Federal Railroad Administration



Car Repair Billing Database Analysis
Freight Car Repair & Maintenance $2 Billion Annually
Brakes 21%
Adapters 0%
Draft Systems 8%
Wheelsets 56%
Other 13%
Trucks 2%
Source: Represents one year of Car Repair Billing (2010-2011). CRB statistics represent approximately fifty percent of industry cost.
Note: Percentages represent major repair and maintenance cost for freight car equipment in interchange service.
ASSOCIATION OF AMERICAN RAILROADS



Problem Size: Wheels
Wheel RCF
Wheel set replacement costs in North America: $800 million
High Impact Wheels 47% equally distributed between:
Thermal Mechanical Shelling (TMS)
Skidded Wheels (Unreleased Handbrakes)
Wheel Wear 27%
Many are asymmetrically worn (one flange on minimum with the other flange substantially un-worn)
Wheel life in unit coal operation increasing to beyond 450,000 miles placing increased demand on improved performance
Other 15%
Bearing 11%
Wheel Tread Damage 47%
Wheel Wear 27%
ASSOCIATION OF AMERICAN RAILROADS


Problem Definition and Objectives
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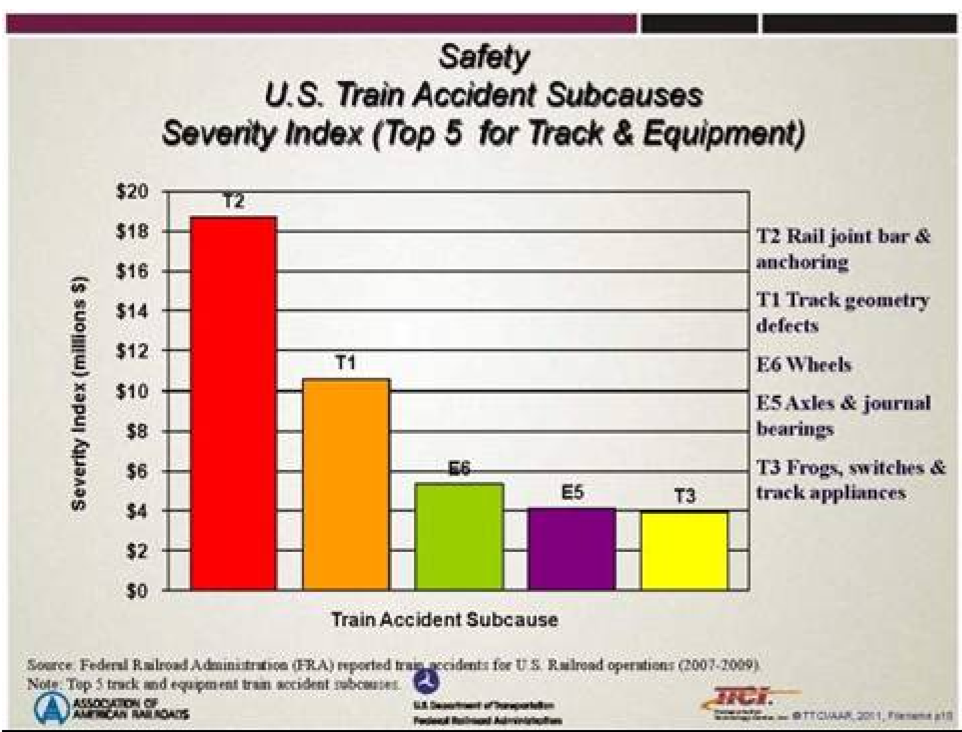
Safety
U.S. Train Accident Subcauses
Severity Index (Top 5 for Track & Equipment)
Severity Index (millions $)
$20
$18
$16
$14
$12
$10
$8
$6
$4
$2
$0
T2
T1
E6
E5
T3
Train Accident Subcause
T2 Rail joint bar & anchoring
T1 Track geometry defects
E6 Wheels
E5 Axles & journal bearings
T3 Frogs, switches & track appliances
Source: Federal Railroad Administration (FRA) reported train accidents for U.S. Railroad operations (2007-2009).
Note: Top 5 track and equipment train accident subcauses.
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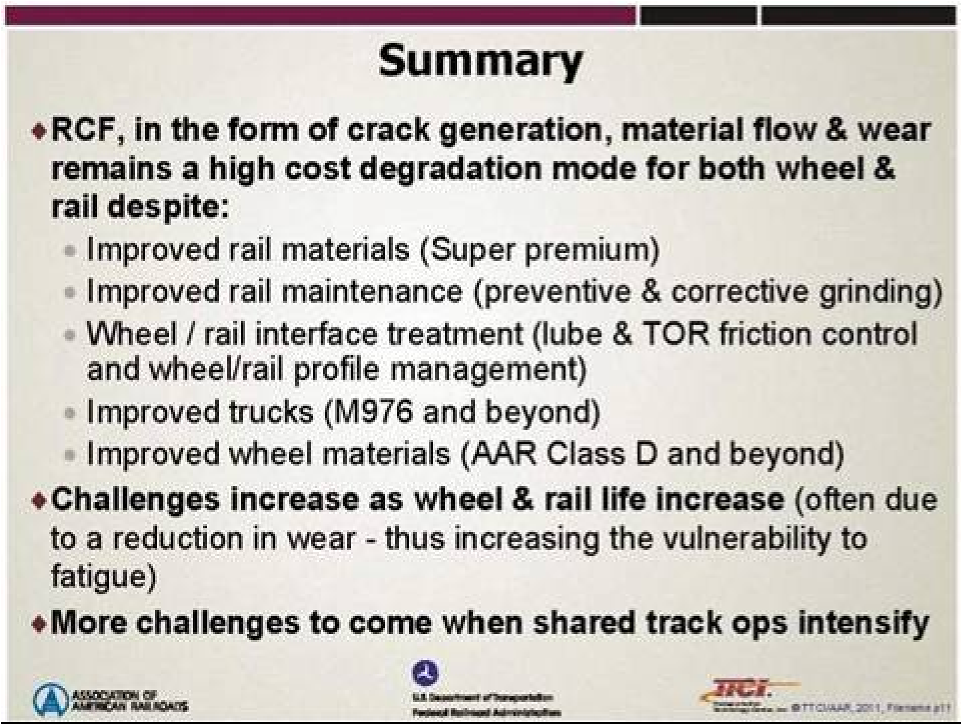

Summary
RCF, in the form of crack generation, material flow & wear remains a high cost degradation mode for both wheel & rail despite:
Improved rail materials (Super premium)
Improved rail maintenance (preventive & corrective grinding)
Wheel / rail interface treatment (lube & TOR friction control and wheel/rail profile management)
Improved trucks (M976 and beyond)
Improved wheel materials (AAR Class D and beyond)
Challenges increase as wheel & rail life increase (often due to a reduction in wear - thus increasing the vulnerability to fatigue)
More challenges to come when shared track ops intensify
ASSOCIATION OF AMERICAN RAILROADS
U.S. Department of Transportation
Federal Railroad Administration

NRC·CNRC

From Discovery to Innovation...

Rolling contact fatigue – A comprehensive review

Eric E. Magel
National Research Council Canada

July 25, 2011

National Research Council Canada

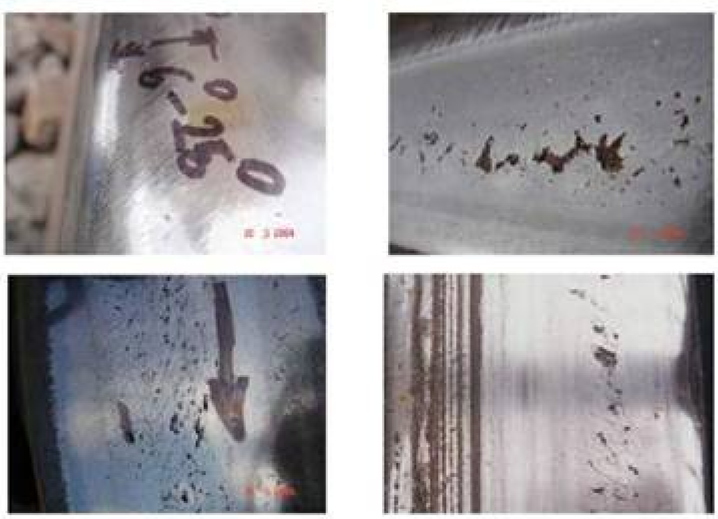
Conseil national de recherches Canada

Canada

NRC·CNRC

From Discovery to Innovation...

Rolling Contact Fatigue - RCF



2

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RCF consequences

- §1.2 Safety implications:
  - 100 (10% of all) FRA derailments annually in North America from RCF
  - Hatfield (UK): 4 deaths, 39 injuries, economic fallout >1B pounds
  - §1.3:
- §1.4: Economic implications:
  - NA class 1 RRs > $200M for rail replacement
  - + inspection, derailments, damage to track and rolling stock
  - > $100M for rail grinding
  - + lubrication, friction management

3

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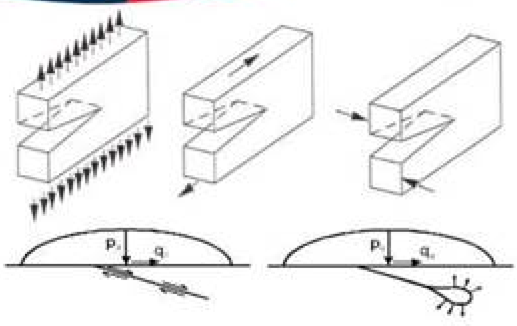
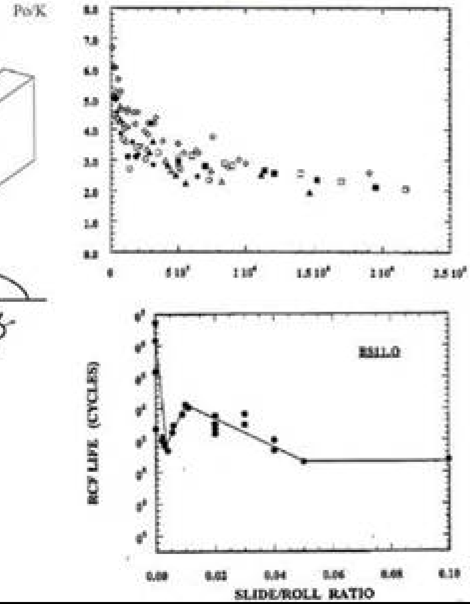
Crack initiation

- §2.1 Crack Initiation
  - Shakedown (primarily surface) and Dang Van (primarily subsurface)
  - Opportunities:
    - A) repeatable test methodologies that mimic
      - the true state of stress
      - the short loading duration (0.5 ms) and high strain rates (1.0)
    - B) proper characterization of model inputs
      - Metallurgical properties
      - Traction creepage relationship
      - Distribution of wheel, rail, vehicle and track properties.

4

Crack propagation





Crack propagation - opportunities

- Crack face friction, high cycle versus low cycle fatigue approaches?
- Role of Materials:
  - high strength materials better resist crack propagation.
  - Hardness + toughness (inclusions, residual stresses, alloying)

6

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Monitoring technologies

NDT technique	Systems available	Defects detected	Performance
Ultrasonics	Manual and high-speed systems (up to 70 km/h)	Surface defects, rail head internal defects, rail web and foot defects	Reliable manual inspection but can miss rail foot defects. At high speed can miss surface defects smaller <4 mm as well as internal defects particularly at the rail foot
Magnetic flux leakage	High-speed systems (up to 35 km/h)	Surface defects and near surface internal rail head defects	Reliable in detecting surface defects and shallow internal rail head defects although cannot detect cracks smaller than ~4 mm. MFL performance deteriorates at higher speeds
PEC (including FGI)	Manual and high-speed systems (up to 70 km/h)	Surface and near-surface internal defects	Reliable in detecting surface breaking defects. Adversely affected by grinding marks and lift-off variations
Automated visual inspection	Manual and high speed systems (up to 320 km/h)	Surface breaking defects, rail head profile, corrugation, missing parts, defective ballast	Reliable in detecting corrugation, rail head profile missing parts and defective ballast at high speeds. Cannot reliably detect surface breaking defects at speeds >4 km/h. Cannot assess the rail for internal defects
Radiography	Manual systems for static tests	Welds and known defects	Reliable in detecting internal defects in welds difficult to inspect by other means. Can miss certain transverse defects
EMAT	Low speed hi-rail vehicle (<10 km/h)	Surface defects, rail head, web and foot internal defects	Reliable for surface and internal defects. Can miss rail foot defects. Adversely affected by lift-off variations
Long range ultrasonics	Manual systems and low-speed hi-rail vehicle systems (<10 km/h)	Surface defects, rail head internal defects, rail web and foot defects	Reliable in detecting large transverse defects (>5 per cent of the overall cross-section)
Laser ultrasonics	Manual and low-speed hi-rail vehicle systems (<15 km/h)	Rail head, web and foot defects	Reliable in detecting internal defects. Can be affected by lift-off variations of the sensors, difficult to deploy at high speeds
ACFM	Manual systems (hi-speed system under development)	Surface breaking defects	Reliable in detecting and quantifying surface breaking defects. Cannot detect sub-surface defects. Very good tolerance to lift-off variations
AE	Experimental manual and high-speed systems	Rail breaks, wheel burns, squats, wet spots, worn rail profiles	Limited experiments. Cannot detect any internal defects
ACP	Experimental static tests	Surface defects, rail head internal defects, rail web and foot defects	Limited experiments. Can only be applied at predefined areas. Can miss non-transverse defects or small transverse defects
MAD	Experimental static tests	Broken rails, rail gaps	Limited experiments. Possibly capable of detecting large internal or surface-breaking defects (i.e. >50 per cent of the cross sectional area)

Papaelias M, Roberts C and Davis CL (2008), "A review of non-destructive evaluation of rails: state-of-the-art and future development", Journal of Rail and Rapid Transit, 22, 4, pp 367-384.

7

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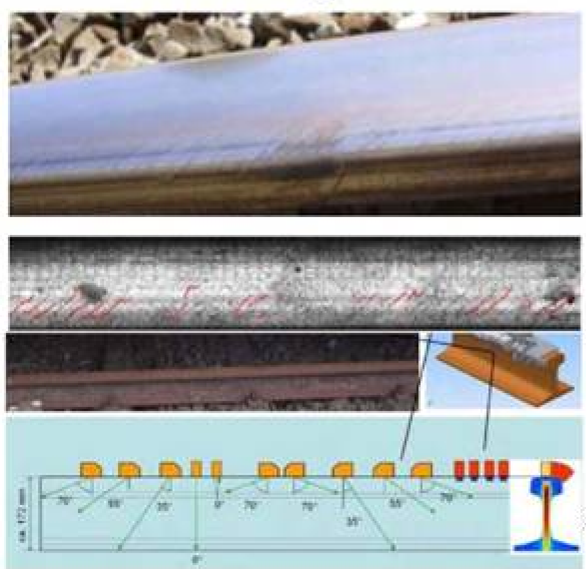
Monitoring Technologies

- Ultrasonics
- Vision systems (e.g. THIS)
- Eddy Current
- Accelerations (e.g. axle box, truck mounted)
- Wheel Inspection: need technologies to detect <1mm



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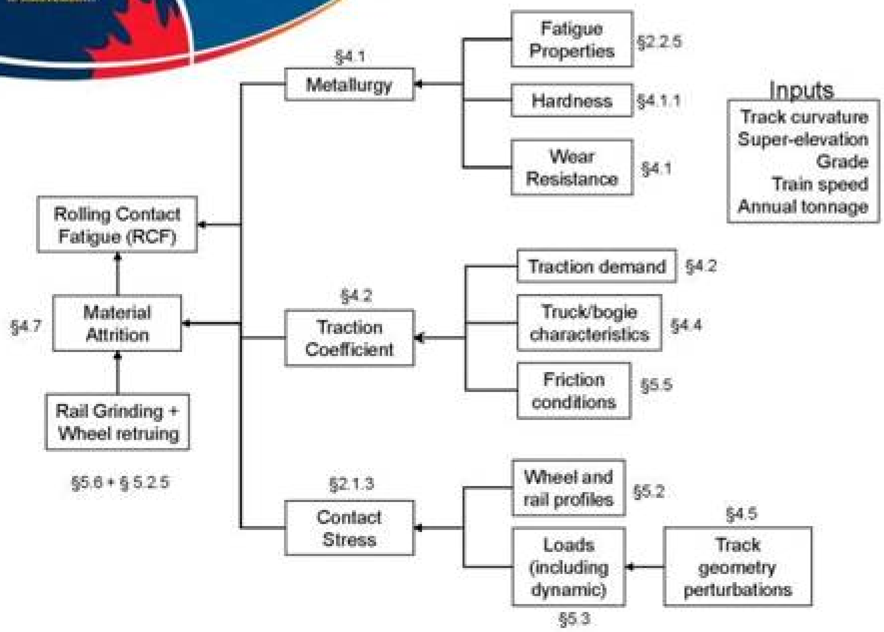
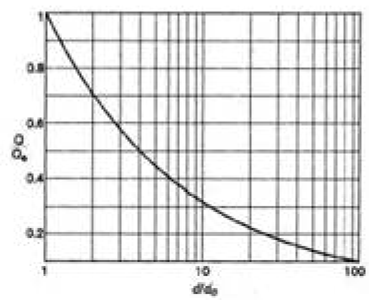


Management of RCF: Improved steels

- Opportunities
  - Composition (manganese, pearlitic, bainitic)
  - Hardness
  - Cleanliness
  - Layered steels?
  - Modeling and performance testing



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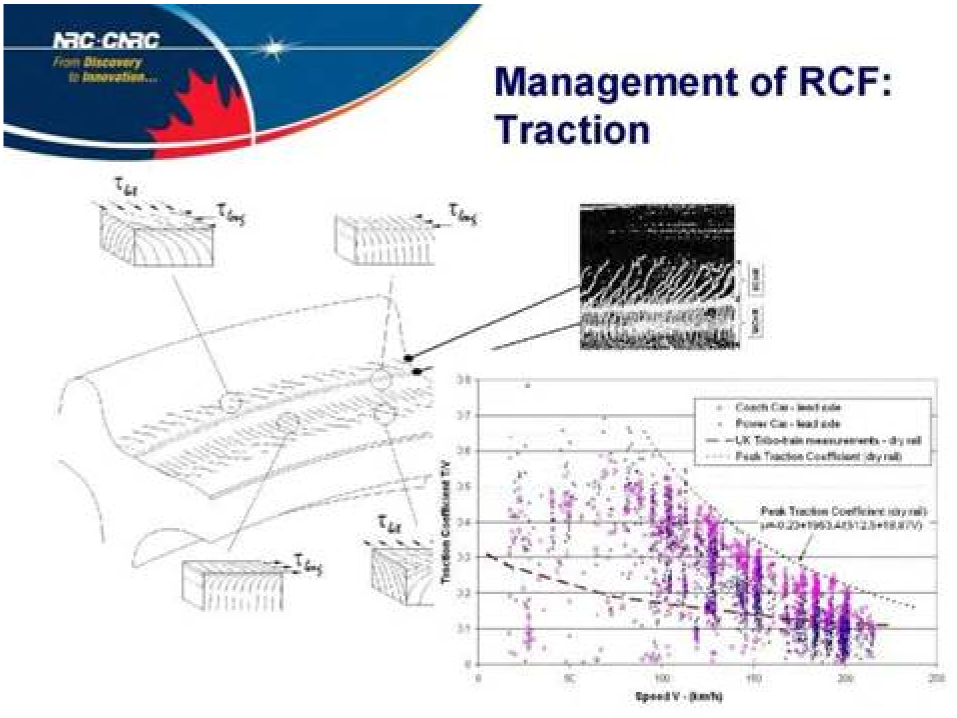
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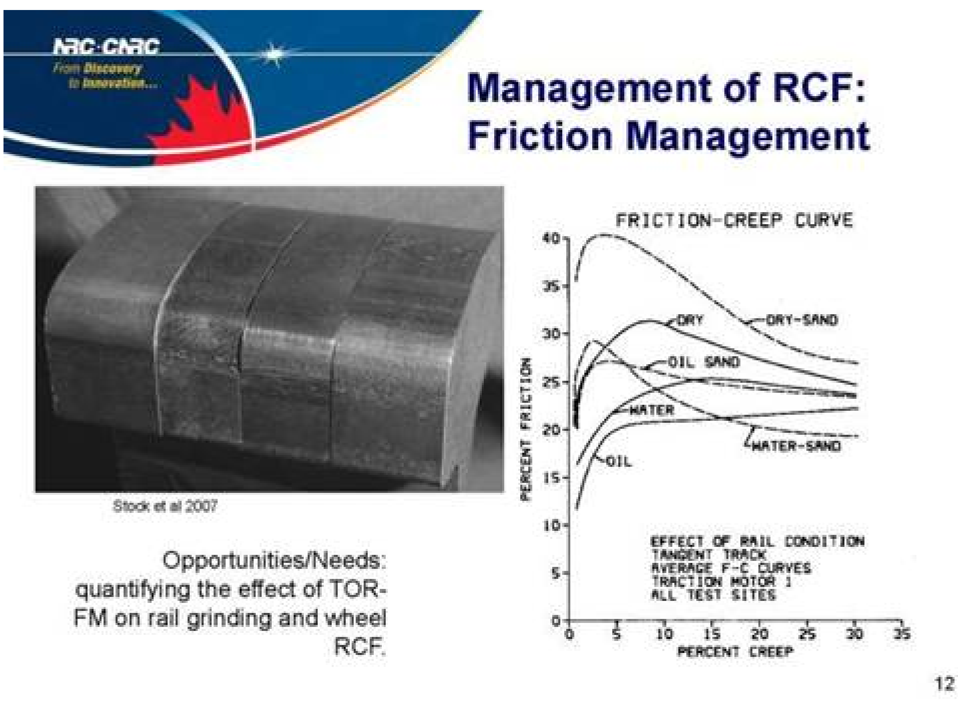
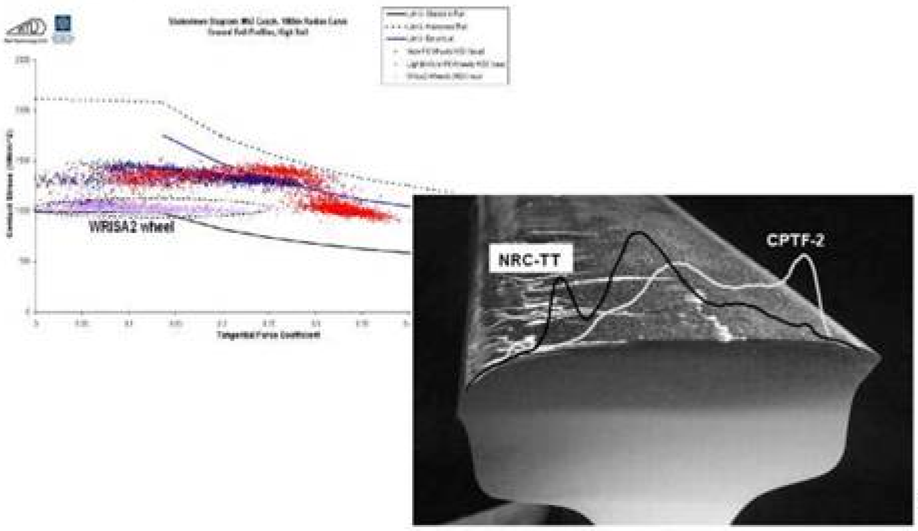
Management of RCF:
Traction
Coach Car - lead side
Power Car - lead side
UK Tribo-train measurements - dry rail
Peak Traction Coefficient (dry rail)
Peak Traction Coefficient (dry rail)
Traction Coefficient T/V
Speed V - (km/h)


NRC·CNRC
From Discovery to Innovation...
Management of RCF:
Friction Management
Stock et al 2007
Opportunities/Needs: quantifying the effect of TOR-FM on rail grinding and wheel RCF.
FRICTION-CREEP CURVE
DRY
DRY-SAND
OIL SAND
WATER
WATER-SAND
OIL
PERCENT FRICTION
PERCENT CREEP
EFFECT OF RAIL CONDITION
TANGENT TRACK
AVERAGE F-C CURVES
TRACTION MOTOR 1
ALL TEST SITES
12

Management of RCF: Profiles



13

Management of RCF

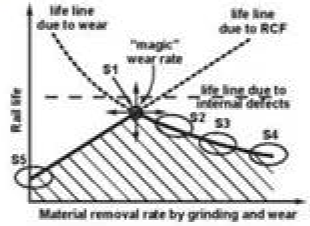
- Profile management, tolerances
- Friction management
- Wheel loads
- Track geometry defects
- Vehicle suspension
  - Reduce PYS (as per Network Rail)
  - Frame bracing (Brazil 400%, CPR 36% re shelling)
- Rail grinding

14

NRC·CNRC
From Discovery to Innovation...

Rail Grinding

- Opportunities/needs
  - Optimization of metal removal process, includes mechatronic rail grinder
  - Intervention frequency (logistics, philosophy, environment, rail steel, track profile, available machine)
  - Management tools, quality assurance



5

NRC·CNRC
From Discovery to Innovation...

Systems for assessing VTI characteristics

- WILD
- Skewed Truck Detector
- Truck Performance Detector
- Instrumented wheelsets
- Acceleration measurements
- Simulation
- Wheel rail contact inspection system

16

Organization	# of pubs.	Country / Headquarters
Chalmers Tekniska Högskola (27)	27	Sweden
University of Sheffield (16)	16	UK
RTRI, Railway Technical Research Institute (7) + Vehicle Strength (1) + Track Dynamics Laboratory (1) + Frictional Materials Laboratory (1) + Vehicle and Bogie Parts Strength (1)	11	Japan
Transportation Technology Center Inc (9) + TTCI UK Ltd (1)	10	USA / UK
University of Birmingham (9)	9	UK
Voest-Alpine AG (7) + Voest-Alpine Schienen GmbH (2)	9	International
AEA Technology Rail bv (4) + AEA Technology (4)	8	Netherlands / UK
Newcastle University United Kingdom (7) + Newcastle University (1)	8	UK
Semcon AB (6) (CARAN)	6	Sweden
Southwest Jiaotong University (6)	6	China
Imperial College London (5)	5	UK
Politecnico di Milano (5)	5	Italy
Kanazawa University (4)	4	Japan
Politechnika Warszawska (4)	4	Poland
Sumitomo Kinzoku Kogyo Kabushiki-gaisha (3) (Sumitomo Metal Industries Ltd.) + Amagasaki (1)	4	Japan
Centre for Surface Transportation Technology NRCC (3)	3	Canada
Corus Rail Technologies (3)	3	UK
Deutsche Bahn (3)	3	Germany
KRRI (2) + Korea Railroad Research Institute (1)	3	South Korea
RVD Consulting Inc. (2) + RVD Consulting (1)	3	USA
Spoornet (2) + Spoornet, Materials Engineering (Rollstock) (1)	3	South Africa
Swinburne University of Technology (3)	3	Australia
TSC Inspection Systems (3)	3	UK
Università degli Studi di Brescia (3)	3	Italy
Vanderbilt University (3)	3	USA
Manchester Metropolitan University (3)	3	UK
All-Russ. Railway Research Institute (2)	2	Russia
Banverket (1) + Banverket (1)	2	Sweden

Scopus search 1999-2010 Rolling contact fatigue in railways

17

Conclusions / Opportunities

- Monitoring Tools
- Friction management
- Profile management
- Improved steels
- Rail grinding
- Improved trucks

18

Rolling Contact Fatigue on Rails and Wheels in Amtrak Service

AMTRAK
Engineering

Safe Reliable Economical Smart

Managing wheel/rail interface on NEC

AMTRAK
Engineering

- Wide range of wheel profiles, conditions and loads on NEC from mixed passenger and freight traffic
- With introduction of HSR on corridor, FRA sponsored study to mitigate wheel/rail wear & damage
- Results provide guidance to wheel/rail management on shared-use corridor

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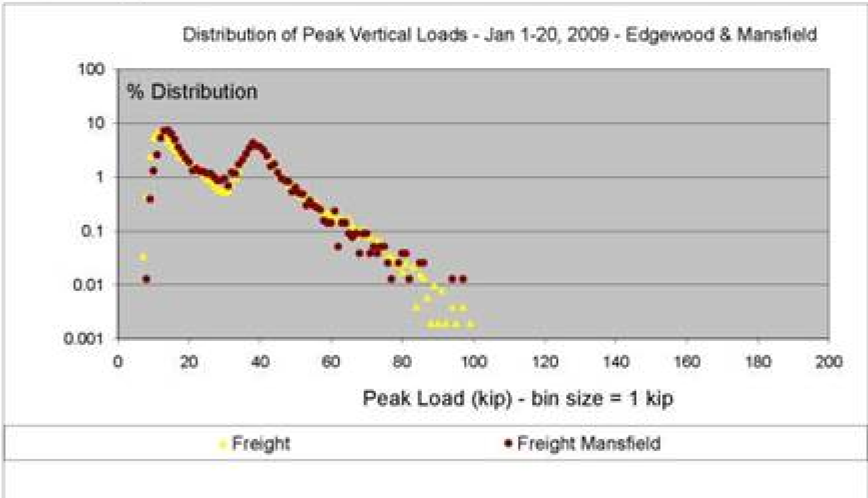
Measured wheel load distribution on NEC shows the challenge

Engineering



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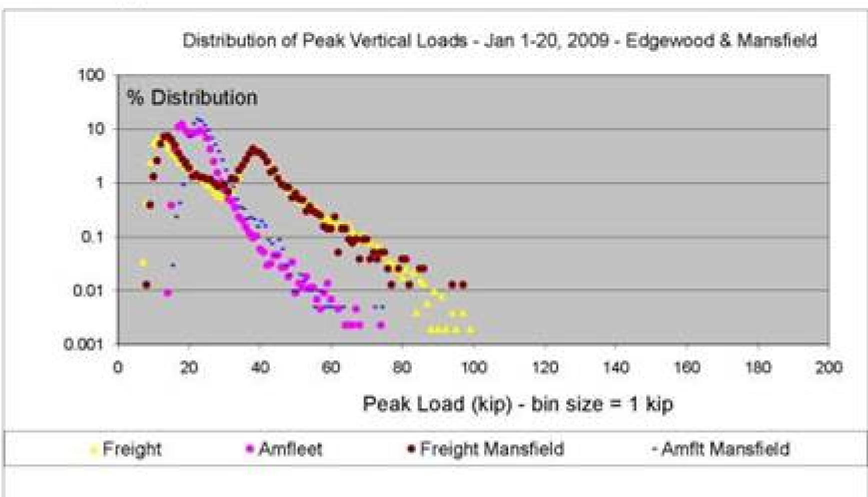
Measured wheel load distribution on NEC shows the challenge

Engineering



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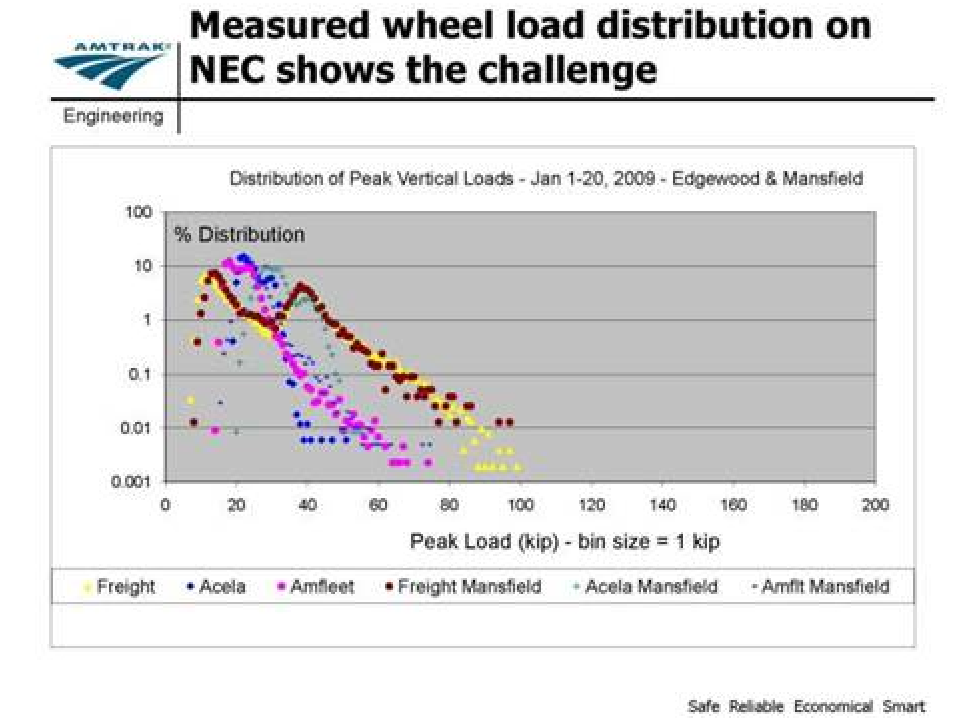
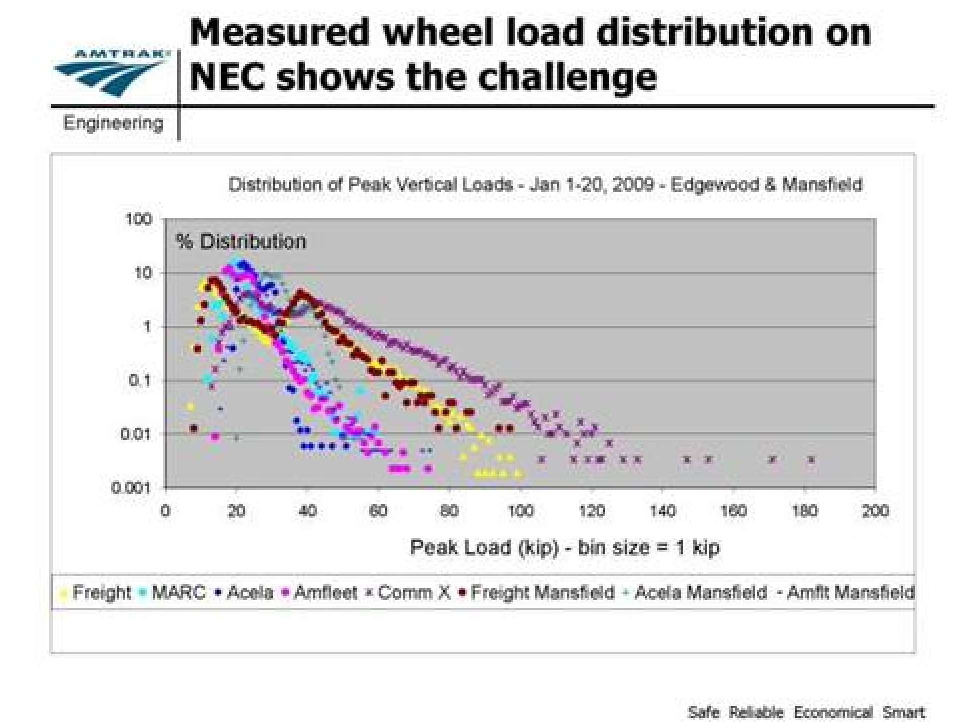

Measured wheel load distribution on NEC shows the challenge
AMTRAK
Engineering
Distribution of Peak Vertical Loads - Jan 1-20, 2009 - Edgewood & Mansfield
% Distribution
100
10
1
0.1
0.01
0.001
0 20 40 60 80 100 120 140 160 180 200
Peak Load (kip) - bin size = 1 kip
Freight
Acela
Amfleet
Freight Mansfield
Acela Mansfield
Amflt Mansfield
Safe Reliable Economical Smart


Measured wheel load distribution on NEC shows the challenge
AMTRAK
Engineering
Distribution of Peak Vertical Loads - Jan 1-20, 2009 - Edgewood & Mansfield
% Distribution
100
10
1
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0.01
0.001
0 20 40 60 80 100 120 140 160 180 200
Peak Load (kip) - bin size = 1 kip
Freight
MARC
Acela
Amfleet
Comm X
Freight Mansfield
Acela Mansfield
Amflt Mansfield
Safe Reliable Economical Smart

Evolution of Acela wheel profiles

Engineering

- Initial "VIL-15" profile conicity unstable at speed
- Lower conicity Amtrak std. profile was stable but heavy 2-pt contact gave high flange wear rate
- More conformal NRC-designed profile adopted: low wear and no RCF to date
- Wheel profile wear is being monitored for QC

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Evolution of Amtrak rail profiles

Engineering

- Rail RCF found along corridor in 2000 survey
- High rail profiles poorly matched to worn wheels
- NRC-designed better matching high rail profiles
- Two high rail profiles: for $<1°$ and $>1°$ curves
- Two tangent profiles: central contact, field biased
- Only minor RCF exists today

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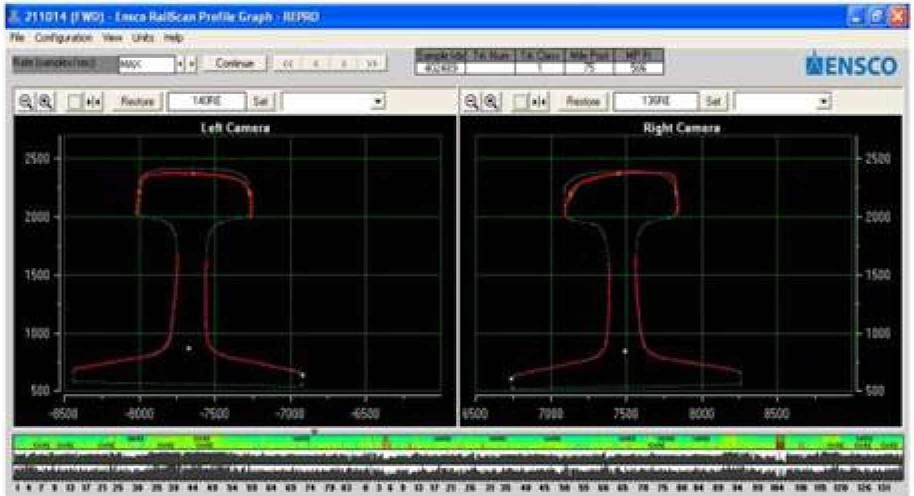
Continuous monitoring of rail condition and profiles

Engineering



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Rail grinding strategy

Engineering

- Preventative grinding on a 2 to 3 year schedule in general
- Grinding patterns continue to evolve but are based upon FRA/NRC findings
- In 2009 Amtrak utilized S & C grinder
- In 2011 Amtrak utilized 44 stone production grinder, mainly to correct weld conditions on new rail

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AMTRAK

Engineering

Friction Management (FM) strategy

- No on-board FM systems, only wayside lubricators
- Over 200 lubricators in service along corridor
- Harsh Winter 2009/2010 froze lubricators, ran dry for a time giving increased wear

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AMTRAK

Engineering

Rail Defects 2010 – 2011 YTD

TYPE	2010		2011	
BH	16	8%	13	8%
BRO	3	1%	0	0%
DWE	0	0%	2	1%
DWF	29	14%	23	14%
DWP	7	3%	4	2%
EBF	36	18%	51	30%
HSH	18	9%	22	13%
HW	26	13%	16	9%
SW	12	6%	9	5%
TDD	32	16%	25	15%
TDT	2	1%	1	1%
VSH	23	11%	3	2%
TOTAL	204		169	

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Rail Service Failures 2010 – 2011 YTD

TYPE	2010	2011
BB	8	3
BHB	1	0
DR	0	2
DWF	7	10
DWP	1	2
HW	1	1
TDD	2	2
TDC	1	1
VSH	2	0
TOTAL	23	21

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Findings from RCF Studies Related to Amtrak

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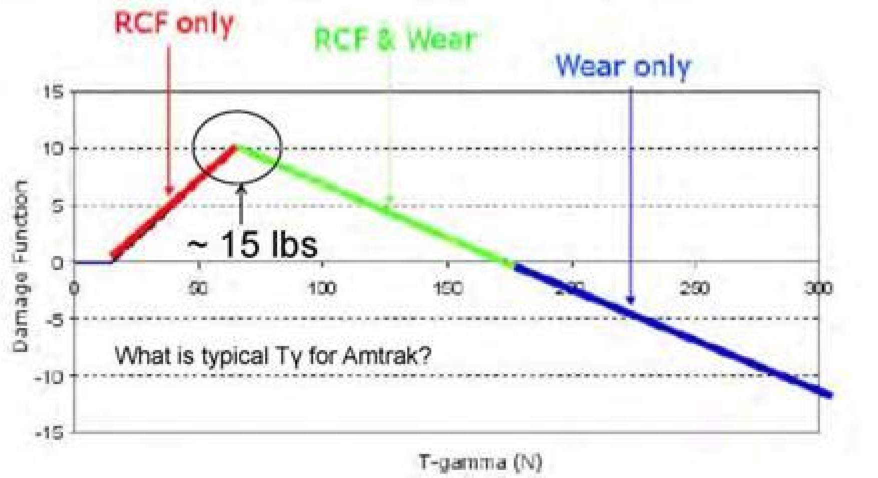
AMTRAK Engineering

Most potential for RCF when Tγ~15 lbs

Tγ (T gamma) is the creep force in contact patch that can produce RCF and/or wear



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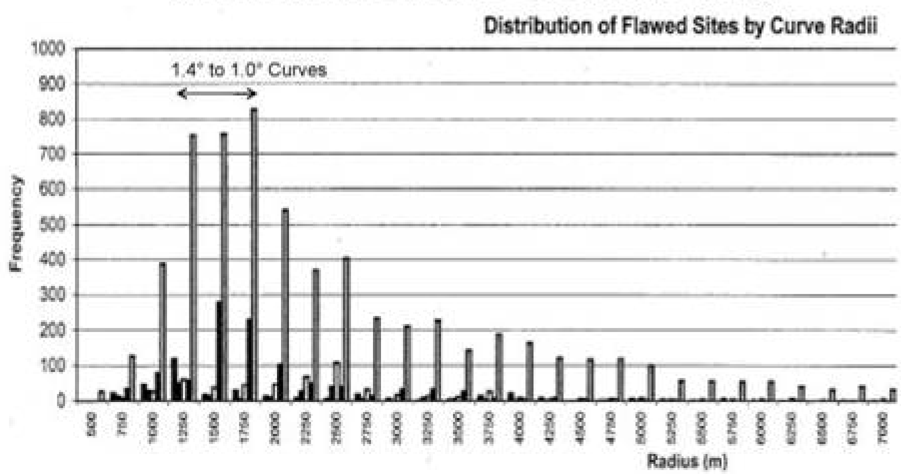
Arup/TTCI post Hatfield study: RCF most common in curves of 1.0° to 1.4°

Most curves on NEC are in this range



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Engineering

But we know RCF can also occur in turnouts...

Figure 1. GCC and contact band shift due to canted and uncanted rail and joint misalignment.

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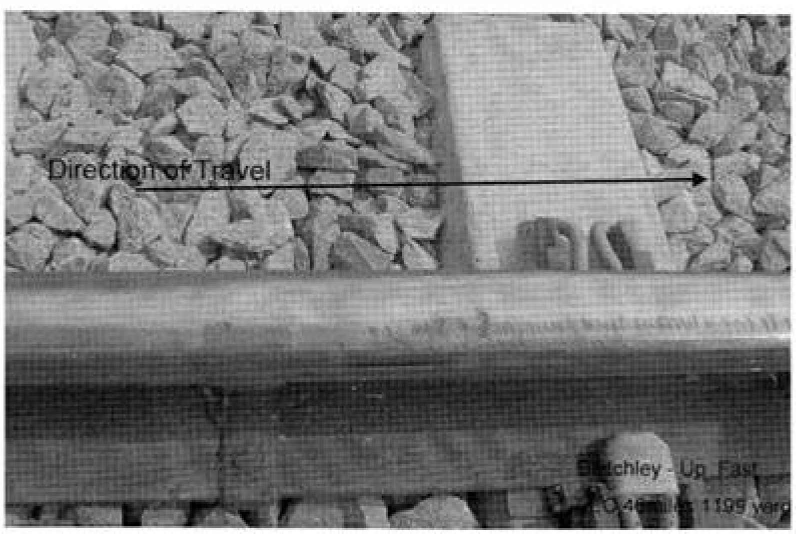
Engineering

...and anywhere rail profile suddenly changes



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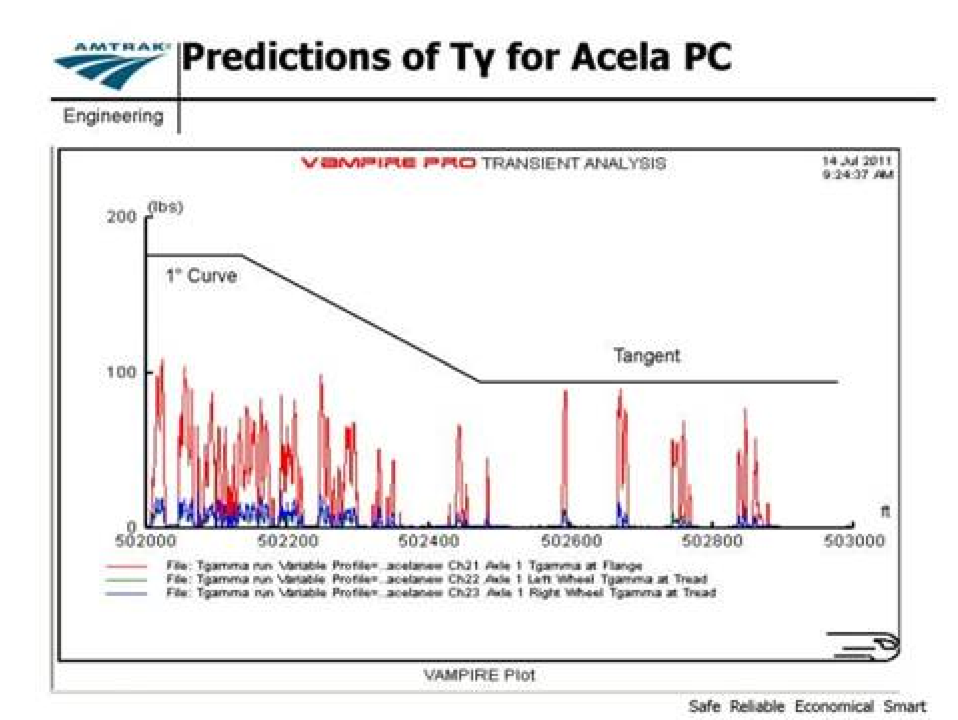
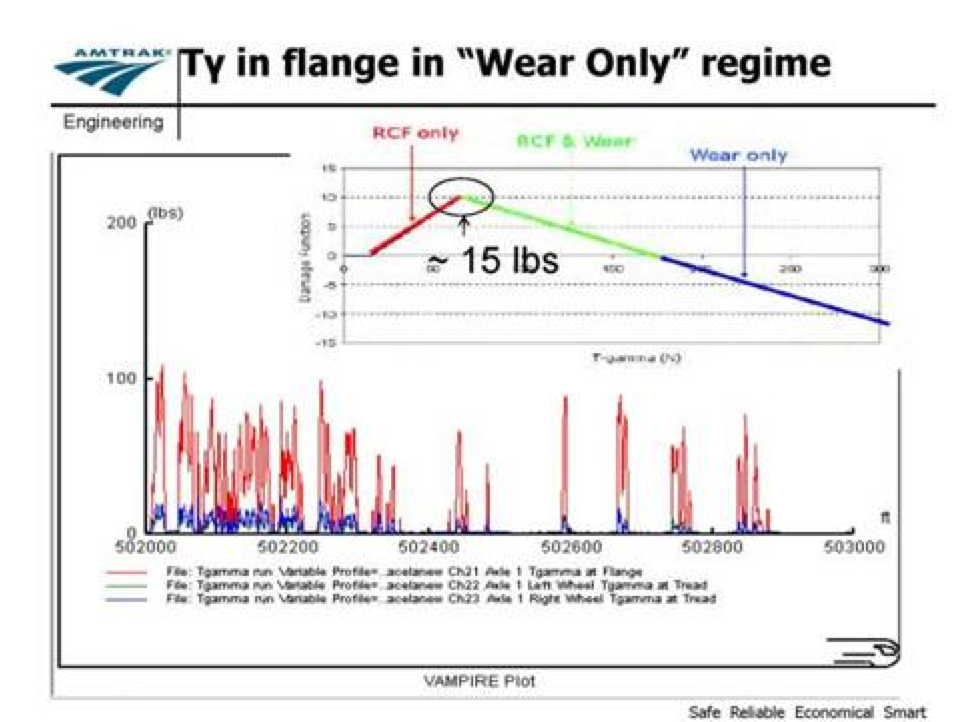

AMTRAK
Predictions of Tγ for Acela PC
Engineering
VAMPIRE PRO TRANSIENT ANALYSIS
14 Jul 2011
9:24:37 AM
(lbs)
200
100
0
1° Curve
Tangent
ft
502000
502200
502400
502600
502800
503000
File: Tgamma run Variable Profile=..acelanew Ch21 Axle 1 Tgamma at Flange
File: Tgamma run Variable Profile=..acelanew Ch22 Axle 1 Left Wheel Tgamma at Tread
File: Tgamma run Variable Profile=..acelanew Ch23 Axle 1 Right Wheel Tgamma at Tread
VAMPIRE Plot
Safe Reliable Economical Smart


AMTRAK
Tγ in flange in "Wear Only" regime
Engineering
RCF only
RCF & Wear
Wear only
Damage function
~ 15 lbs
T-gamma (N)
(lbs)
200
100
0
ft
502000
502200
502400
502600
502800
503000
File: Tgamma run Variable Profile=..acelanew Ch21 Axle 1 Tgamma at Flange
File: Tgamma run Variable Profile=..acelanew Ch22 Axle 1 Left Wheel Tgamma at Tread
File: Tgamma run Variable Profile=..acelanew Ch23 Axle 1 Right Wheel Tgamma at Tread
VAMPIRE Plot
Safe Reliable Economical Smart

AMTRAK Engineering

Current status of RCF on Amtrak

- FRA-sponsored study provided guidance to extend life of Acela wheels and NEC rail
- NRC-design wheel profile and grinding patterns for rail limits wear and RCF damage
- Despite conditions that could lead to RCF, there is little to none due to improved profiles, monitoring and maintenance practices
- Analysis indicates that energy in contact patch ($T\gamma$) may be typically in the “Wear Only” regime

Safe Reliable Economical Smart

UK Rolling Contact Fatigue Models: Whole Life Rail Model & Wheel RCF Damage

Paul Molyneux-Berry (MMU RTU)
Ken Timmis (RSSB)
July 2011

Contents

- Introduction and Background
- The Whole Life Rail Model
- Other Rail Surface Damage Modes and Models
- Rail RCF: Conclusions
- Wheel RCF: Observations and Trends
- Wheel RCF: Conclusions

Research Funded By:

Rail Research UK
Rail Safety & Standards Board
Network Rail

Myself and the RTU

- Rail Technology Unit
  - Based at Manchester Metropolitan University
  - Formed in February 1998, now grown to 12 staff
  - Undertakes consultancy and research work
  - Main focus is on wheel/rail interaction
  - Many recent projects on RCF in both wheels and rails
  - Hosting IAVSD conference next month
- Paul Molyneux-Berry MEng CEng MIMechE
  - 11 years in the Rail Industry, with:
  - ADtranz / Bombardier
  - AEA Technology / DeltaRail (former BR Research)
  - Rail Technology Unit
  - Mostly in vehicle dynamics and wheel/rail interaction
  - Working on PhD in rolling contact fatigue of wheels

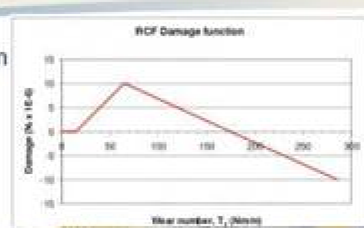
railtechnologyunit

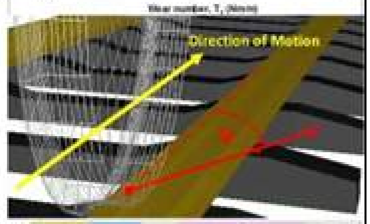
Where it all began: Hatfield

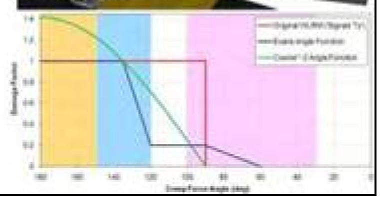
- Crash at Hatfield on 17/10/2000
- Express train running at 120mph
- Four passengers killed, many injured
- Severe RCF cracks - rails shattered under train into hundreds of pieces
- Major disruption to UK rail network from inspections, speed restrictions and emergency renewals nationwide
- Infrastructure Owner Railtrack went bankrupt

The Whole Life Rail Model

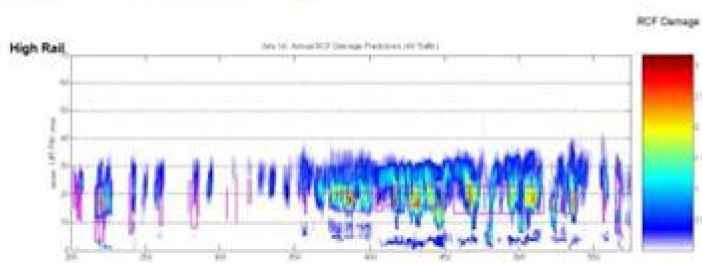
- Developed by a collaboration of engineers from across the industry
- Key parameter is Tγ:
  - Energy dissipated in the contact patch
  - Considers tangential forces and creepages
  - Angle of creep force also considered
- RCF and Wear damage depend on Tγ:
  - No damage for Tγ < 15
  - Peak RCF damage at Tγ = 65
    - Cracks visible after 100,000 axle passes
    - Rail life-expired after 2,000,000 axle passes
  - Wear removes RCF for Tγ > 175
  - Calibrated for normal UK rail steel (R260)
- Validated for tread contacts:
  - Classic high rail RCF (leading wheelset)
  - Low rail RCF (trailing wheelset)
  - Mostly passenger traffic

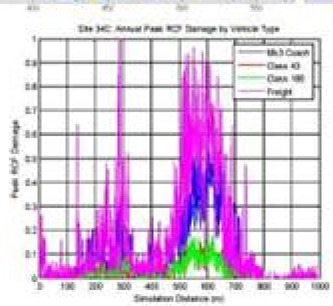




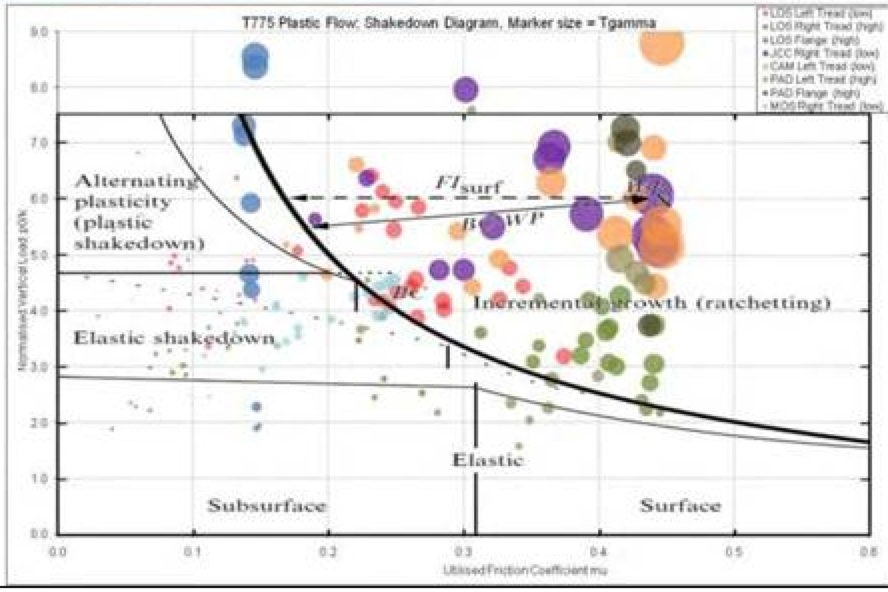


WLRM RCF Validation



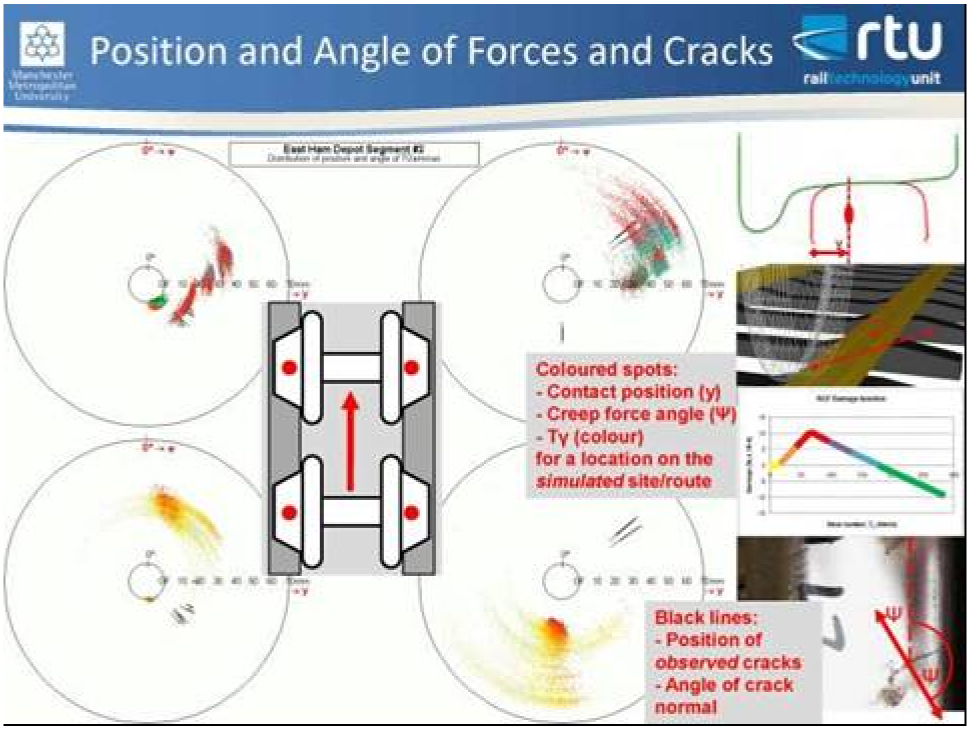


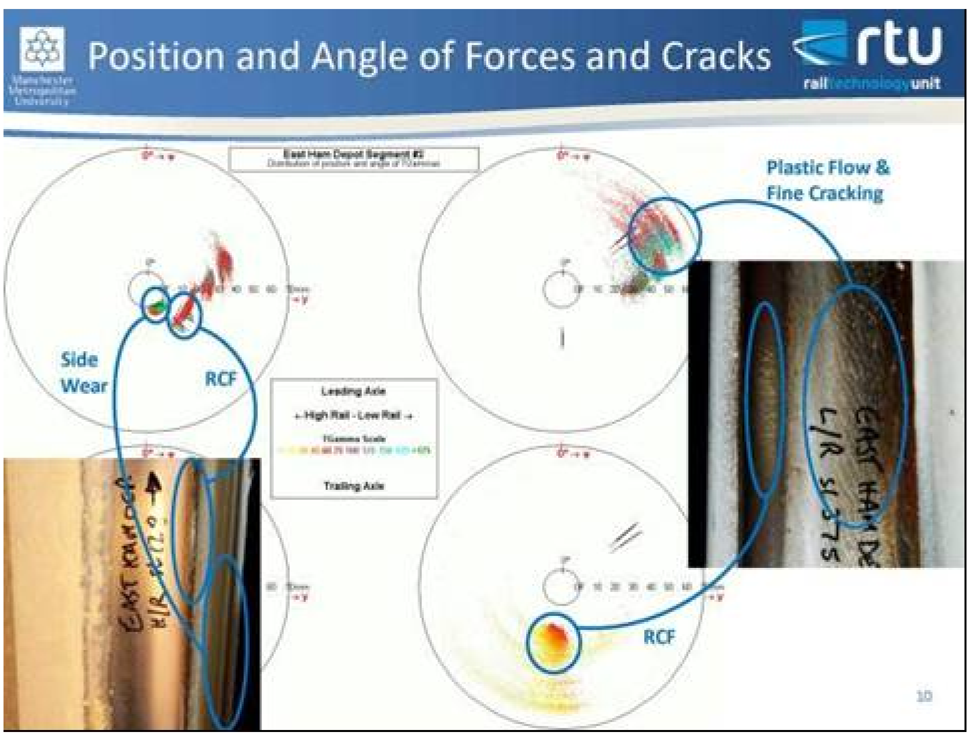
Shakedown and Tγ



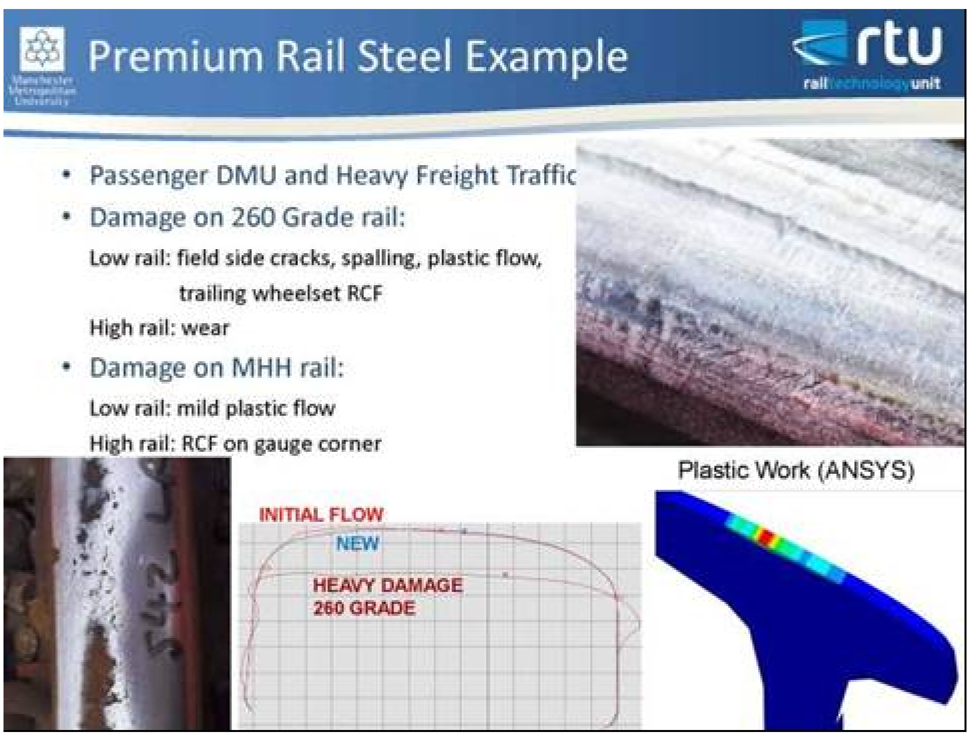
What Influences Rail RCF?

- Tγ and RCF are influenced by:
  - Curve Radius
    - high rail RCF typically 500m – 1500m
    - low rail RCF typically < 500m
  - Cant Deficiency / Excess
    - Cant excess normally worse
  - Wheel and rail profiles
    - Contacts near gauge corner are bad
  - Vehicle suspension yaw stiffness
    - Higher stiffness normally worse
  - Traction & Braking forces
    - Traction forces contribute to rail RCF
  - Load conditions
    - Higher contact stresses increase RCF (implicit in Tγ)
  - Track Irregularities
- WLRM has been used to identify remediation measures for RCF sites


Position and Angle of Forces and Cracks
rtu
railtechnologyunit
Manchester Metropolitan University
East Ham Depot Segment #2
Coloured spots:
- Contact position (y)
- Creep force angle (Ψ)
- Tγ (colour)
for a location on the *simulated* site/route
Black lines:
- Position of *observed* cracks
- Angle of crack normal

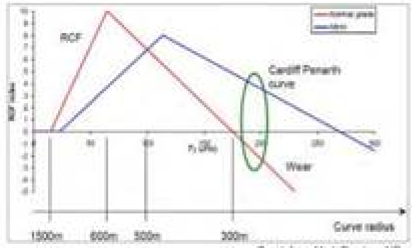

Position and Angle of Forces and Cracks
rtu
railtechnologyunit
Manchester Metropolitan University
East Ham Depot Segment #2
Plastic Flow & Fine Cracking
Side Wear
RCF
Leading Axle
← High Rail - Low Rail →
Trailing Axle
RCF
10


Other Rail Surface Damage
rtu
railtechnologyunit
• 'Classic RCF' is well predicted by the WLRM
• Other forms of damage exist, and models are being developed for these:
▪ Wear
○ Several models available
○ Reasonably accurate in un-lubricated condition
○ Wear in lubricated condition less well understood
▪ Plastic Flow
○ Often on low rail of sharp curves
○ Simulated using Vampire and ANSYS
○ New model developed based on contact stress, contact patch shape & material properties
○ Will be incorporated in WLRM
▪ Low Cycle Fatigue
○ Often on low rail of sharp curves
○ Severe damage after <100,000 axles (heavy freight)
○ Combination of plastic flow, trailing wheelset RCF and contact stress?
S177


Premium Rail Steel Example
rtu
railtechnologyunit
• Passenger DMU and Heavy Freight Traffic
• Damage on 260 Grade rail:
Low rail: field side cracks, spalling, plastic flow, trailing wheelset RCF
High rail: wear
• Damage on MHH rail:
Low rail: mild plastic flow
High rail: RCF on gauge corner
Plastic Work (ANSYS)
INITIAL FLOW
NEW
HEAVY DAMAGE
260 GRADE

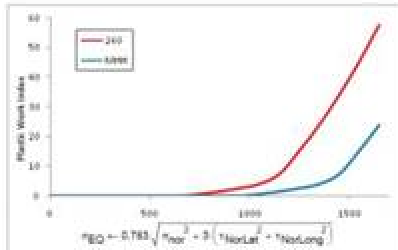
Effect of MHH Premium Steel

- High Rail:
  - Normal steel – wear regime
  - MHH steel – RCF regime



Graph from Mark Burstow, NR

- Low Rail:
  - Normal steel – Equivalent stress significantly exceeds yield stress
  - MHH steel – Higher Yield stress => Less plastic flow



Rail RCF Conclusions

- Rail RCF can be a significant problem
  - Safety issues
  - Monitoring and management costs
  - Maintenance/repair/renewal costs
- Modelling and simulation has helped us understand the conditions causing RCF damage
  - Predictions of damage rates
  - Improved management techniques
  - Optimised maintenance
  - Lower costs
- More research ongoing, funded by:

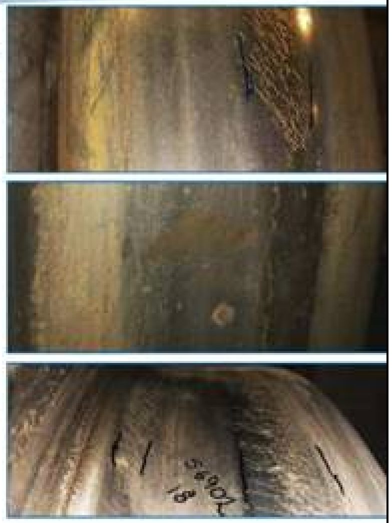
Rail Research UK

Rail Safety & Standards Board

Network Rail

Wheel RCF: Observations

- Wheel RCF is usually toward the field side of the wheel tread
  - usually uniform around the wheel
- Cracks are typically angled about 45° but can vary from circumferential to transverse
  - often cracks are curved
    - close to transverse near the centre of the tread
    - close to circumferential toward the field side
  - cracks can join up and lumps of material fall out
    - cavities / shelling / spalling
- A second band of cracks can initiate close to the flange root
  - usually these do not propagate
- Wear can counteract the effects of crack growth



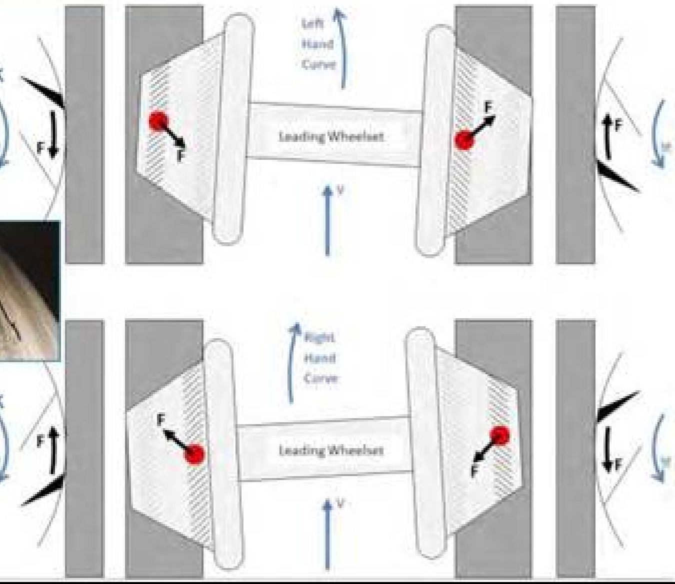
Wheel RCF: Observations

- Wheel tread cracks can be associated with other forms of damage
  - flats / thermal damage
  - impact damage
- Occasionally transverse cracks are seen in the centre of the tread
  - associated with high braking forces
  - locomotives with dynamic braking

Formation of Two Crack Bands

Creep force opens crack before it contacts rail
- hydrostatic pressure propagates crack

Creep force opens crack after it contacts rail
- crack does not propagate



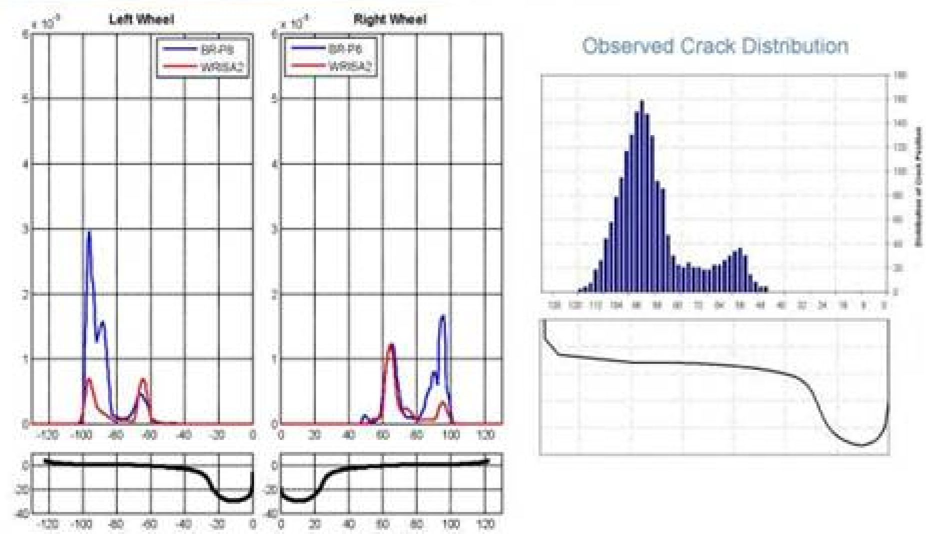
Observed Trends

- Traction and Braking forces can have a big influence on wheel RCF
  - Braking forces increase wheel RCF
  - Traction forces increase wear and 'remove' RCF
  - Type of damage, and damage rate are different on powered and trailer axles on the same train
  - Essential to model these forces in any simulations
- Leading wheelsets suffer worse RCF damage
  - More fluids present in wheel/rail contact – hydrostatic pressure in cracks
  - More prone to wheel slip/slide – thermal damage
- Smaller diameter wheels (near end of life) suffer worse RCF
  - Higher contact stresses
  - More wheel rotations
  - Material properties less good
- Damage does not grow linearly with mileage / wheel wear
  - Many complex effects have influences here

Complexity of Modelling Wheel RCF

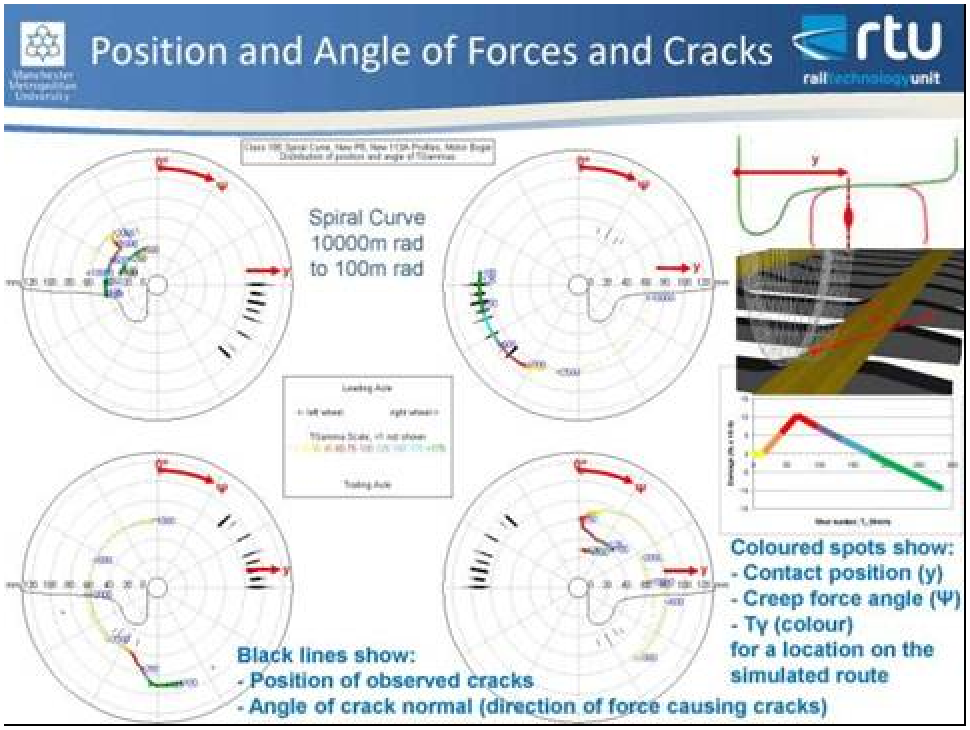
- Comparing the contact conditions and forces for a wheel and rail:
- Rail:
  - is installed as either high rail or low rail on a given curve radius
  - usually experiences fairly consistent traffic
    (vehicle types, direction, speed, traction/braking etc)
  - so the forces and damage mechanisms on a length of rail are fairly consistent
- Wheel:
  - experiences much more varied running conditions
  - runs in both directions
  - experiences a wide range of curve radii (on both left and right hand curves),
  - carries both traction and braking forces
  - all the damage from these different running conditions is superimposed on the wheel tread
  - overall damage rates are therefore much more sensitive to the relative rates of wear and crack growth

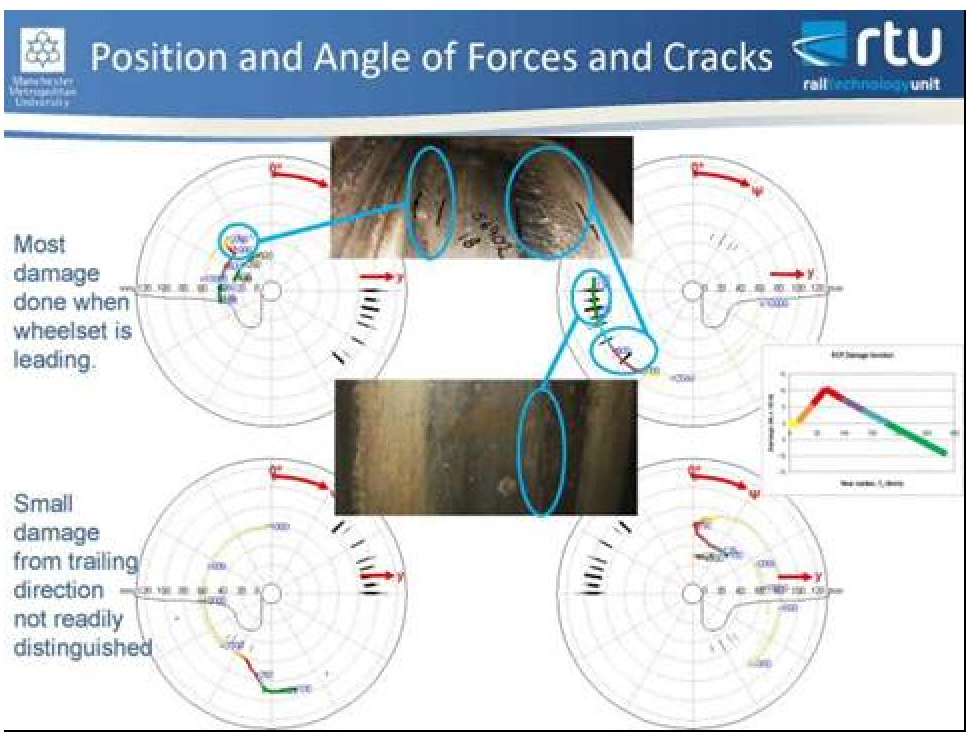
Wheel Profile Damage Model

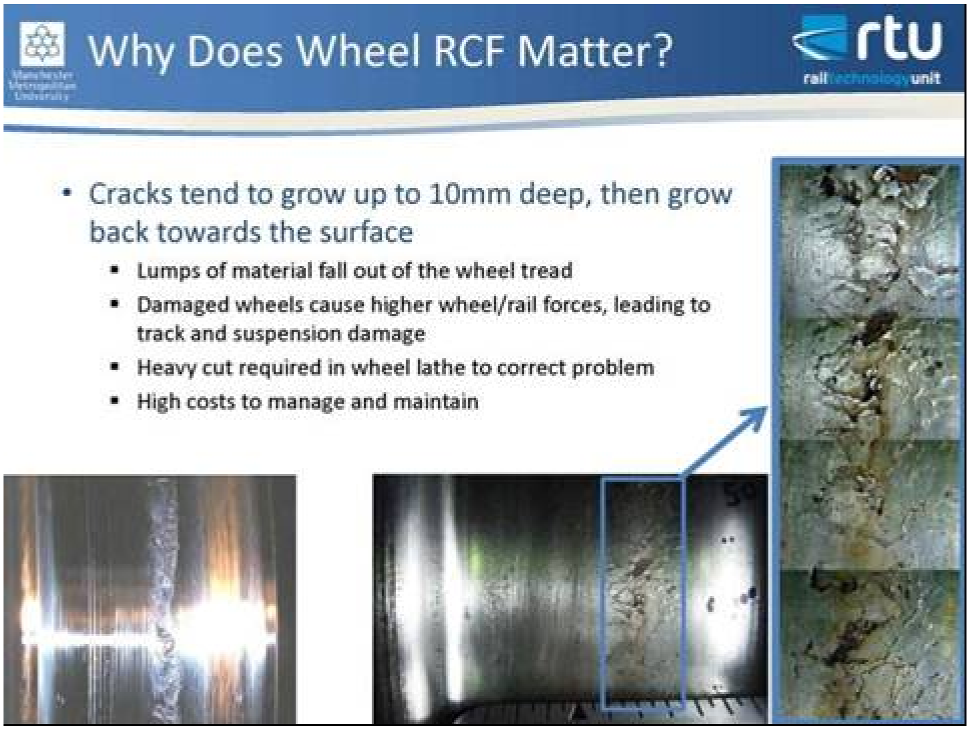


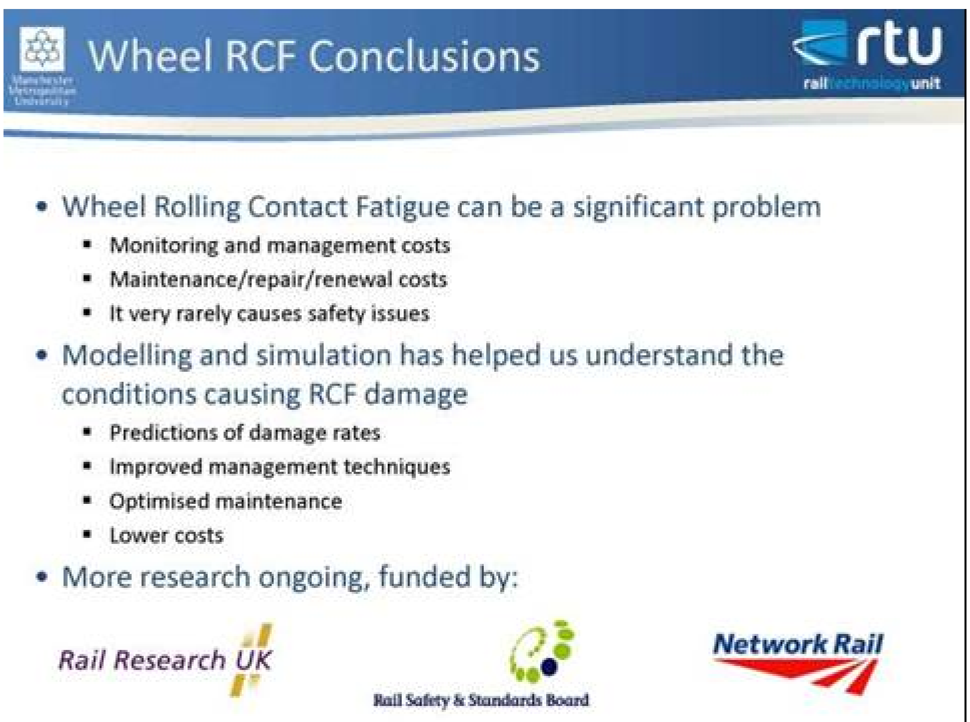
Simulated accumulated damage running on a typical route

Observed RCF Locations


Position and Angle of Forces and Cracks
rtu
railtechnologyunit
Manchester Metropolitan University
Spiral Curve
10000m rad
to 100m rad
Coloured spots show:
- Contact position (y)
- Creep force angle (Ψ)
- Tγ (colour)
for a location on the simulated route
Black lines show:
- Position of observed cracks
- Angle of crack normal (direction of force causing cracks)


Position and Angle of Forces and Cracks
rtu
railtechnologyunit
Manchester Metropolitan University
Most damage done when wheelset is leading.
Small damage from trailing direction not readily distinguished


Why Does Wheel RCF Matter?
rtu
railtechnologyunit
• Cracks tend to grow up to 10mm deep, then grow back towards the surface
▪ Lumps of material fall out of the wheel tread
▪ Damaged wheels cause higher wheel/rail forces, leading to track and suspension damage
▪ Heavy cut required in wheel lathe to correct problem
▪ High costs to manage and maintain


Wheel RCF Conclusions
rtu
railtechnologyunit
• Wheel Rolling Contact Fatigue can be a significant problem
▪ Monitoring and management costs
▪ Maintenance/repair/renewal costs
▪ It very rarely causes safety issues
• Modelling and simulation has helped us understand the conditions causing RCF damage
▪ Predictions of damage rates
▪ Improved management techniques
▪ Optimised maintenance
▪ Lower costs
• More research ongoing, funded by:
Rail Research UK
Rail Safety & Standards Board
Network Rail

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Wheel and rail fatigue prediction

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www.chalmers.se/charmec

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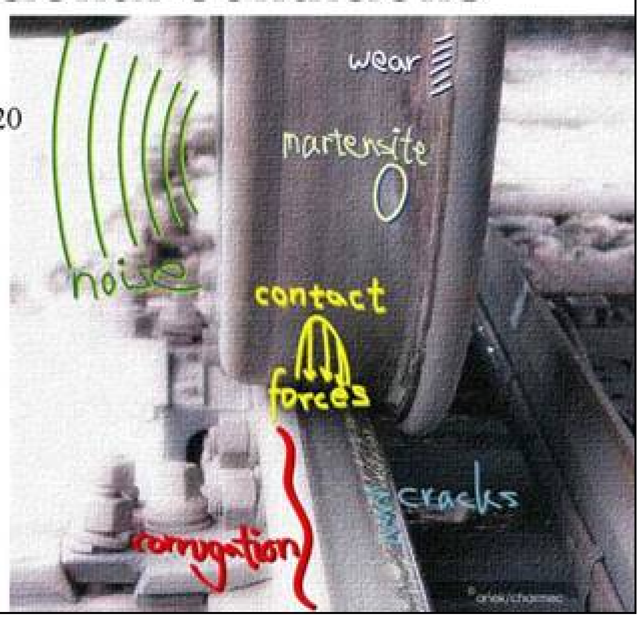
Operational conditions

x20



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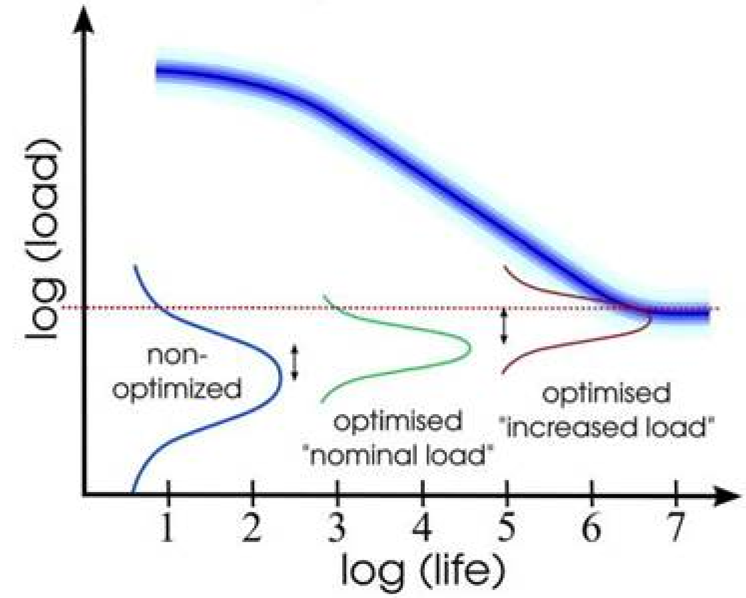
The fatigue dilemma



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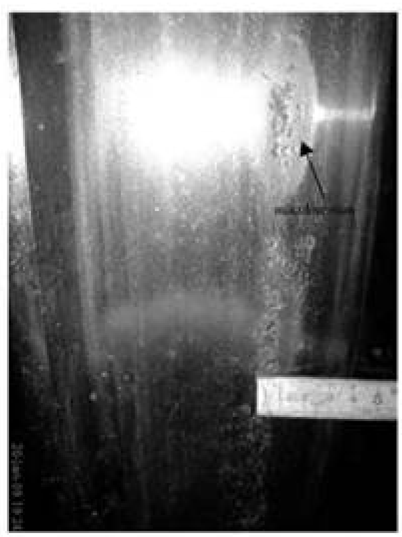
Sensitivity

- Large amount of wheels (large stretches of rail) + optimized solutions
- Deterioration in operational conditions causes damage epidemics

Picture: Banverket
(Per Gustafsson: Ökat slitage på hjulflänsar och räls på malmbanan)



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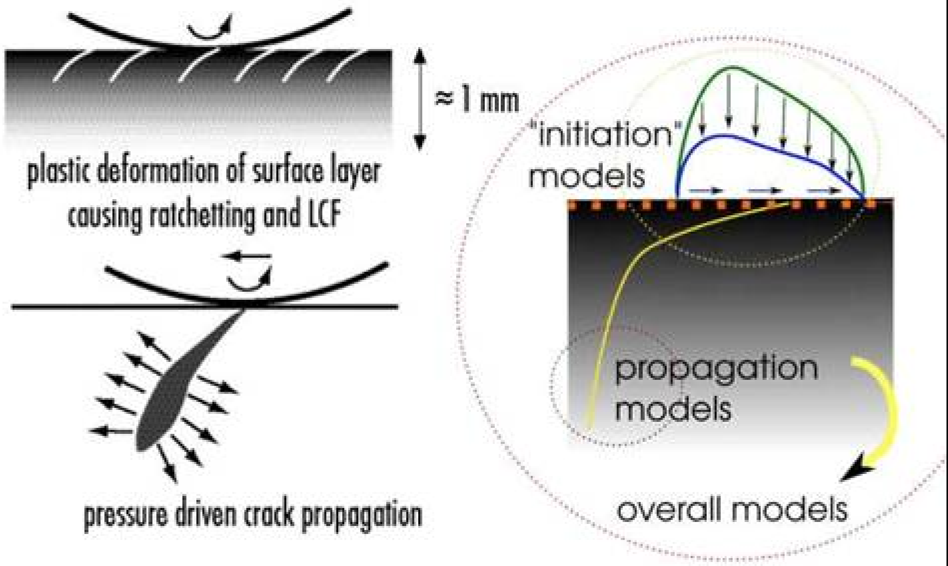
Surface initiated RCF



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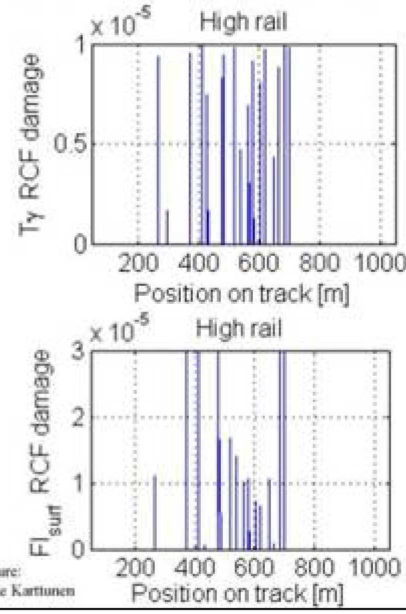
Two RCF "initiation" models

- $T\gamma$ – model
  - traction
  - slip
  - damage function accounting for wear
- $$FI_{\mathrm{surf}} = f - \frac{2\pi abk}{3F_z}$$
  - traction
  - contact patch size
  - cyclic yield stress
  - normal load
  - damage:

$$D_{i,\mathrm{surf}} = \frac{(FI_{\mathrm{surf}})^4}{10}$$



Picture: Kalle Karttunen

CHARMEC projects MU22, MU26, EU10

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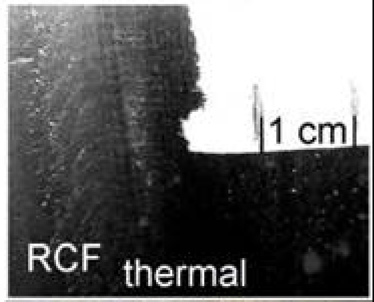
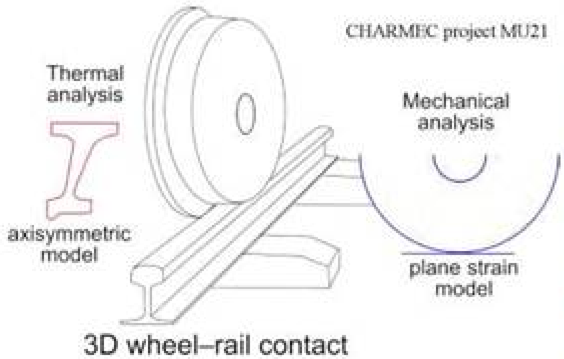
Thermal loading – wheels

- **Heat** induces compressive stresses that may cause tensile residual stresses
- Causes radial crack growth
- Cause of cracking ranges from (almost) purely thermal to (almost) purely mechanical





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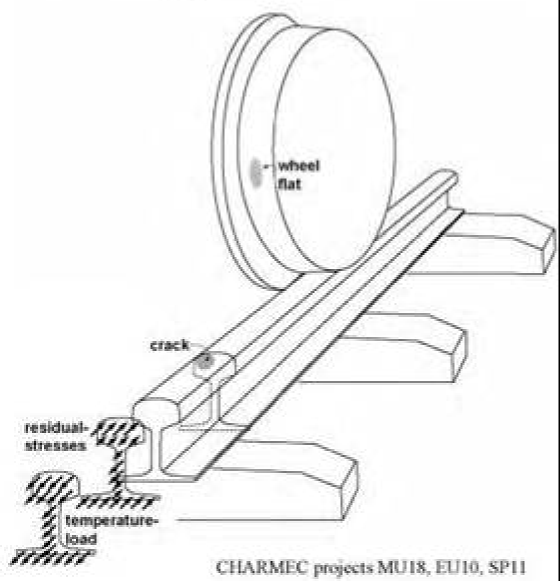
Thermal loading of rails

- **Cold** induces tensile stresses in all-welded rails
- Promotes crack growth and fracture
- Influence on initiation more unclear



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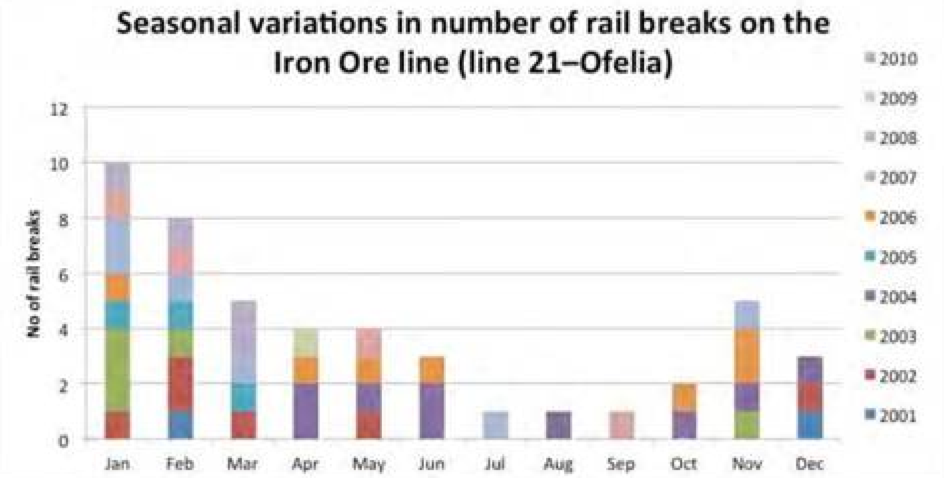
Picture: Kalle Karttunen

RCF in Sweden



- Problems with RCF (both on wheels and rails) are significantly related to winter conditions

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"Winter problems"

Influenced conditions

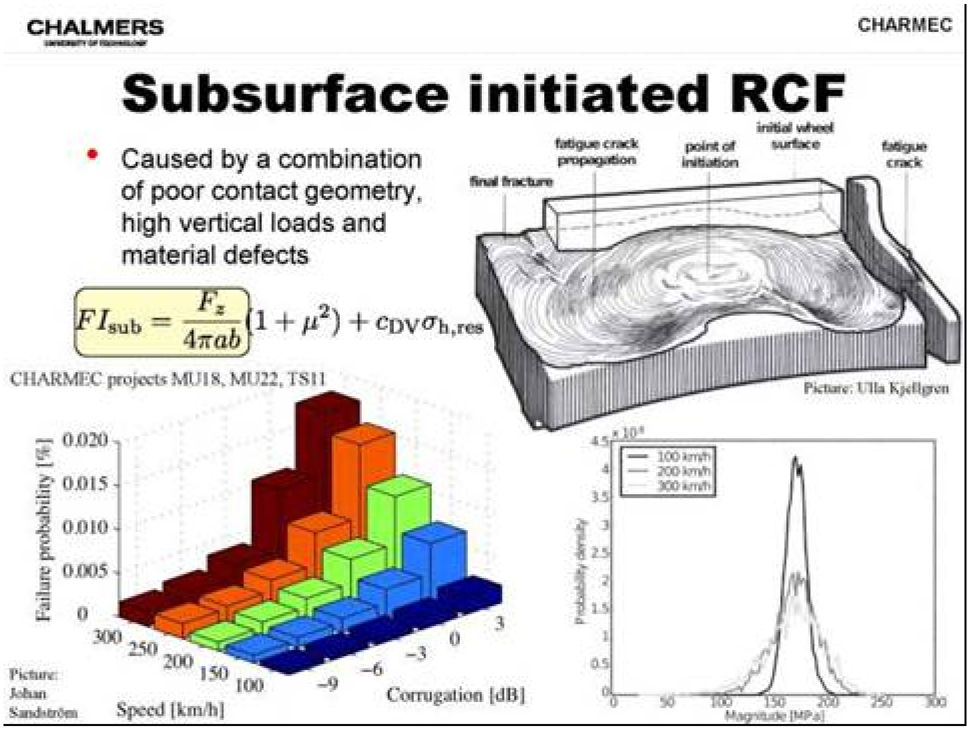
- Cold temperature
- Snow and ice
- Air humidity

Examples of problem types (not only RCF)

- Increased wear and fatigue of wheels and rails
- Malfunction and mechanical failures of switches and crossings
- Brake system malfunction causing wheel flats and wheel failures

Examples of root causes

- Changes in steel properties (ductility, toughness *etc*)
- Thermal stresses in rails
- Frozen track bed (increased vertical loads in cases of wheel flats, hanging sleepers *etc*)
- Increased friction causing wear, RCF initiation
- Melting snow promoting RCF crack growth
- Ice on trains, in switches *etc*
- Decreased suspension capabilities
- Ice coating on rails
- ...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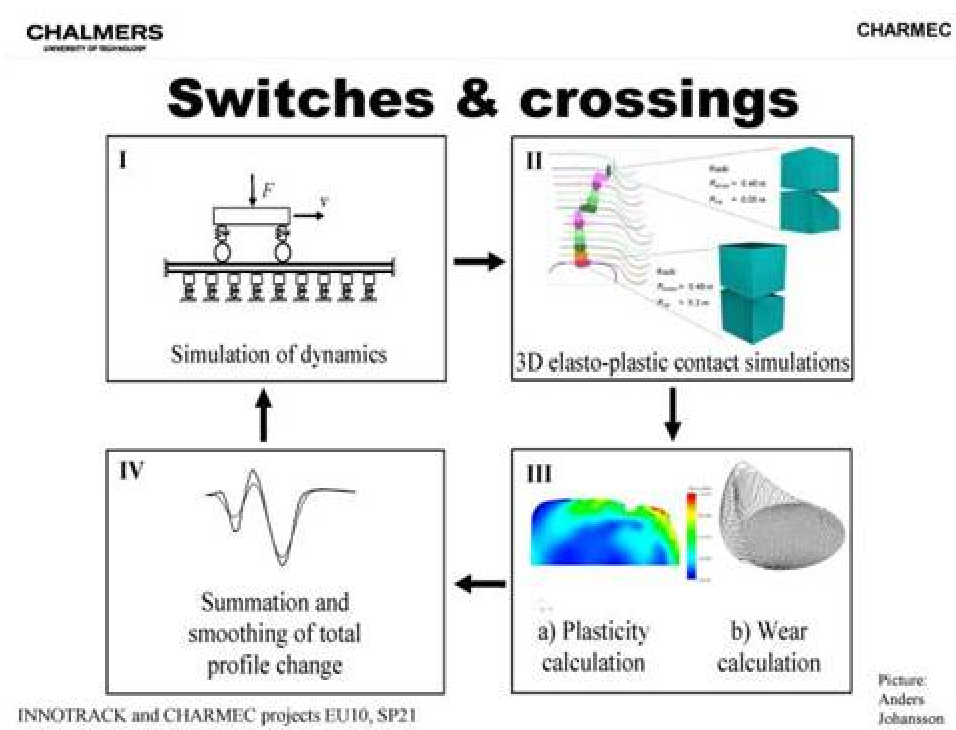
Subsurface initiated RCF
Caused by a combination of poor contact geometry, high vertical loads and material defects
$$FI_{\text{sub}} = \frac{F_z}{4\pi ab}(1+\mu^2) + c_{\text{DV}}\sigma_{\text{h,res}}$$
final fracture
fatigue crack propagation
point of initiation
initial wheel surface
fatigue crack
Picture: Ulla Kjellgren
CHARMEC projects MU18, MU22, TS11
Failure probability [%]
Speed [km/h]
Corrugation [dB]
Picture: Johan Sandström
100 km/h
200 km/h
300 km/h
Probability density
Magnitude [MPa]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Switches & crossings
I
Simulation of dynamics
II
3D elasto-plastic contact simulations
III
a) Plasticity calculation
b) Wear calculation
IV
Summation and smoothing of total profile change
INNOTRACK and CHARMEC projects EU10, SP21
Picture: Anders Johansson

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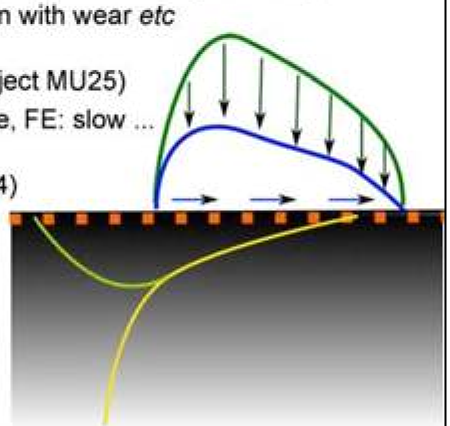
Some further aspects

- Anisotropy (CHARMEC project MU19)
  - influence on stress distributions and crack growth
- Crack growth close to the surface (CHARMEC project MU20)
  - branching, shielding, interaction with wear *etc*
- Contact stresses (CHARMEC project MU25)
  - Hertz: sometimes too imprecise, FE: slow ...
- Contact loads (TS11, TS12, TS14)
  - parametric influences (e.g. discontinuities), mitigation
- Materials (MU23, MU24)
  - understand, improve, quantify



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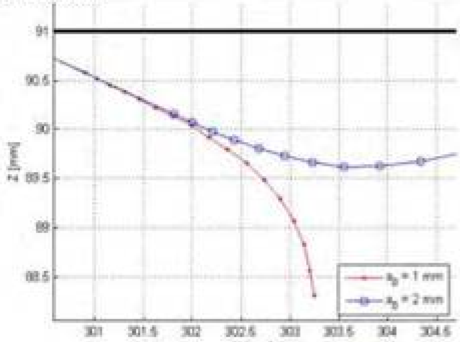
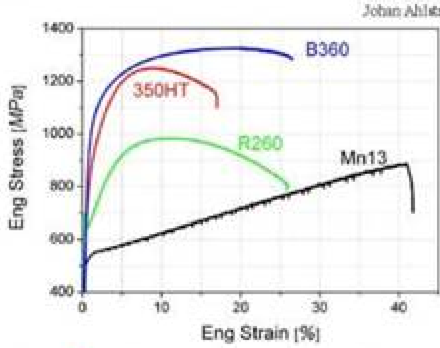
Examples of dilemmas

Picture:
Jim Brouzoulis



Picture:
Martin Schilke
Johan Ahlström



- Crack growth direction of two cracks (initial size 1 mm and 2 mm) propagating from the railhead

> How do we deal with such a sensitivity?

CHARMEC project MU20

- Stress–strain curves for some steels in use in crossing noses

> What is a suitable characteristic parameter?

INNOTRACK and CHARMEC projects EU10, MU24

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Food for thought

- Insulated joint section from UIC900A material
- R260 rail on the surrounding track
- No grinding
- Isolated ("squat-like") rail defects

Picture: Elena Kabo

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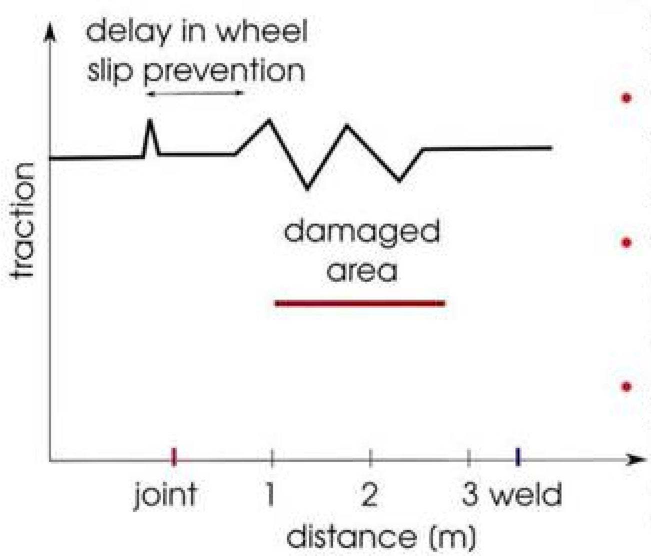
Possible reason



- The wheels have a high traction when setting out from the station
- The joint triggers the wheel slip protection, but there is a delay in the system
- The high peak traction causes surface initiated RCF ($FI_{sub} = f - 3F/(2\pi abk)$)
- After some 3 meters the traction stabilizes. This also coincides with reaching the softer rail (small cracks wear off)

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Avancez!

fundamental research — targeted research — applied research — development — implementation

- Needs for both more fundamental understanding and development / implementation of current knowledge

- Also need for management initiatives

  Example: Traction will not give much cracking on the wheel leading to little incentive for operators to decrease traction (since it will increase travel times *etc*)

  but this requires the knowledge and quantification!

- The crucial issue is to bridge the gaps....
  ... which is what we are doing now!

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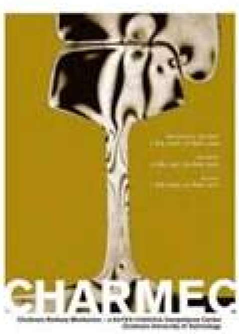
Thanks for your kind attention!



Check out
www.chalmers.se/charmec
and
www.innotrack.eu
for more info

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RCF prediction using Track-Ex:
Root causes & remedies for RCF focusing on the relationship between track alignment errors & incidence of RCF

Mark A Dembosky, Systems Engineering Network Rail

RCF Predictions using Track-Ex v1.ppt 1

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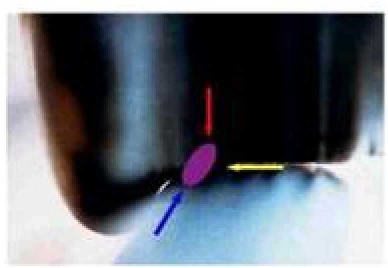
Managing the Wheel Rail Interface

- The forces generated at the wheel/rail interface are responsible for:
  - Degradation of the wheel and rail and other components
  - Changes to track geometry
  - Safe operation of the system
  - Ride quality



- Estimates of these forces are usually obtained from
  - Instrumented wheel sets
  - Comprehensive vehicle dynamics simulators such as NUCARS©
- Both of these methods are too complex, slow and require too much investment in staff and capital to provide a practical tool to manage the Wheel Rail Interface

28 July 2011 RCF Predictions using Track-Ex v1.ppt 2

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Managing the Wheel Rail Interface

- To address this need for a practical tool, Track-Ex© was designed to estimate damage:
  - Sacrificing some accuracy for simplicity & speed (80/20 rule)
  - Quick & easily obtained estimates by relatively untrained staff
  - In-house owned software running on typical PCs
  - Using new RCF findings from research sponsored by RSSB, VTSIC et al
- About 200 persons in the UK have been trained in Track-Ex so far:
  - 2 day introductory course
  - Various 1 day "top-up" courses
- Overall purpose is to help:
  - local staff identify/remediate damage & to become proactive
  - central staff optimize standards/SOPs/budgets/etc

28 July 2011 RCF Predictions using Track-Ex v1.ppt 3

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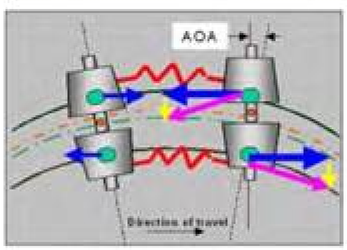
Curving Forces & RCF



Rail oriented Wheel/Rail forces

- In general, bogies negotiating a curve generate more Longitudinal and Lateral forces on the leading axle than on the trailing axle
- They are consequences of axle lateral shift and angle of attack
- The Longitudinal & Lateral contact patch forces are examples of 'creep forces' and are friction limited

- RCF cracks on the high rail usually grow at right angles to the resultant contact patch force
- Early research related the existence of RCF cracks to the force magnitudes using the "Shakedown Limit" concept
- But this approach did not readily lend itself to predicting actual crack length or <u>when</u> cracks would occur

28 July 2011 RCF Predictions using Track-Ex v1.ppt 4

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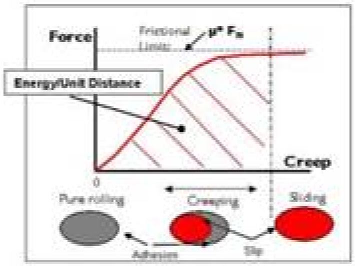
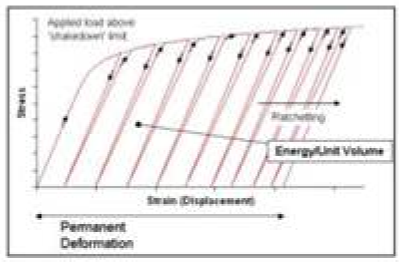
Curving Forces & Energy (TGamma)



- The Longitudinal & Lateral contact patch forces are examples of 'creep forces' and are friction limited
- Creep itself is a state of partial slip that is common between bodies in rolling contact
- Creep force times creep (TGamma) has units of Energy/Unit distance and represents the energy generated in the contact patch

- Repeated rolling contact can cause surface damage when the accumulated strain energy reaches a critical level
- Area under the stress-strain curve is the energy absorbed through the contact patch
- Thus RCF damage can be related to creep forces via an energy based Transfer Function



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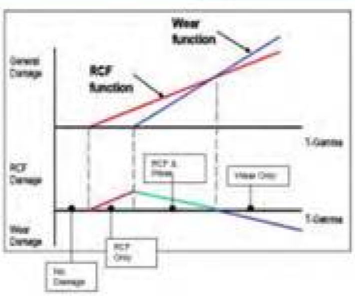
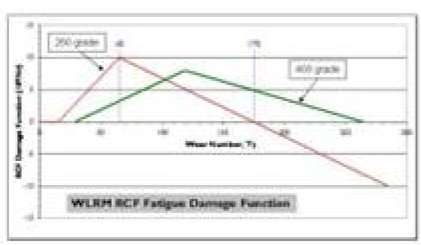
WLRM: the TGamma Transfer function



- The Whole Life Rail Model (WLRM) damage function assumes that TGamma drives 2 functions:
  - RCF starts at a relatively low TGamma level and has a moderate slope
  - Wear starts at a higher TGamma level and grows more aggressively
- When combined, these functions produce the WLRM RCF damage function

- Different grades of steel exhibit different WLRM damage functions due to their metallurgical properties
  - 260 Grade steel has been the standard rail grade in the UK
  - 400 represents the newer premium grade rail steels

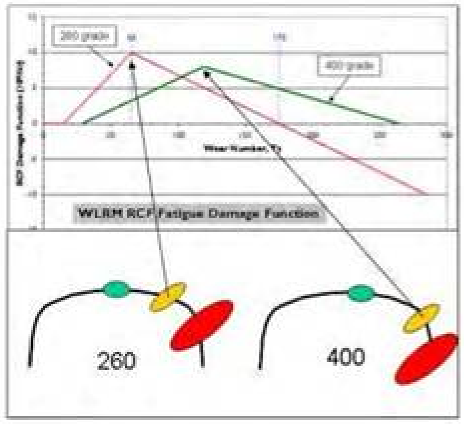


TGamma and steel grade

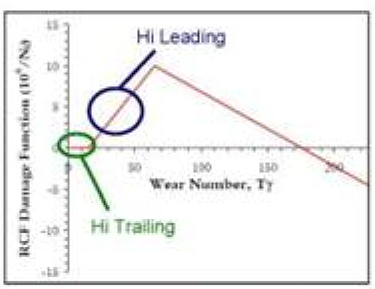
- Generally speaking, the Contact Patch Energy (TGamma) increases as the point of wheel/rail contact moves from top-of-rail to the gauge face on the **high rail leading axle**

- RCF damage, therefore, is most likely between the top-of-rail and the gauge face

  - 260 grade RCF is on the gauge shoulder
  - 400 grade RCF is on the gauge corner



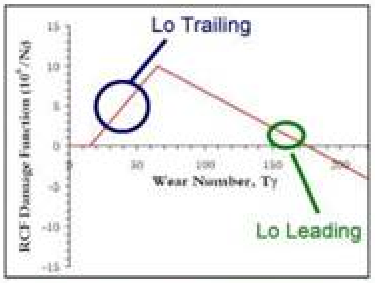
Typical UK RCF: High Rail



- The trailing axle High rail wheel usually does not have sufficient TGamma to generate RCF
  - This is generally true regardless of system factors

- In general the leading axle high rail wheel has a TGamma sufficient to generate RCF
  - The exact TGamma magnitude depends upon curve, cant, speed, primary yaw stiffness, wheel/rail profile and friction
  - The angle of the cracks becomes more longitudinal as contact approaches the gauge corner

Typical UK RCF: Low Rail

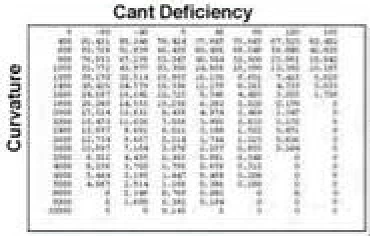


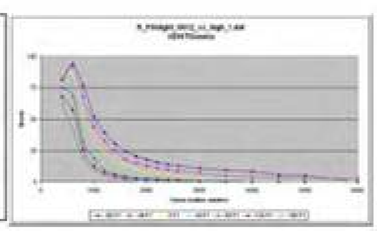
- In general the leading axle low rail wheel has a TGamma sufficient to generate wear and metal flow
  - The exact TGamma magnitude depends upon curve, cant, speed, primary yaw stiffness, wheel/rail profile and friction
  - The TGamma is mostly lateral and causes metal flow to the field

- The trailing axle Lo Rail does have sufficient TGamma to create RCF
  - This causes cracks in the displaced metal which eventually cause pits or spalls on the field side of the low rail

TGamma and VDM tables

- Track-Ex approximates TGamma by using tables called Vehicle Damage Matrixes (VDMS) pre-generated using Vampire© :
  - Tabulate TGamma for curvature and cant deficiency
  - Each table is specified for specific wheel/rail pairs, weight, axle, etc
- Since Track-Ex reads in curvature and cant deficiency from Track Recording Coach files:
  - It can estimate the quasi-static values of TGamma by interpolating the VDM tables
  - TGamma generally increases with curvature and cant surplus





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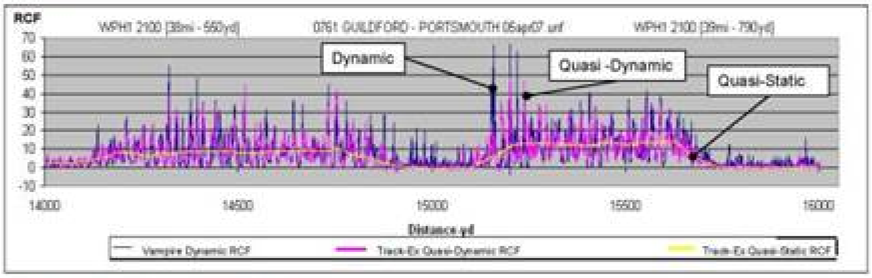
Quasi-static & Quasi-Dynamic TGamma

- A true **Dynamic prediction** requires the use of a program like Vampire with all of its complexity including all track geometry variations.
- The **Quasi-Static prediction** used in early Track-Ex simply interpolated the VDM using Curvature and Cant. It often underestimated RCF, especially in shallow curves because it took no account of track alignment variations.
- The Track-Ex **Quasi-Dynamic prediction** now used is a compromise: an 80/20 "cheat"



28 July 2011 RCF Predictions using Track-Ex v1.ppt 11

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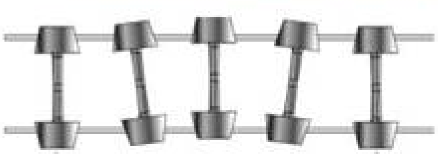
Track-Ex: Theory Klingel Motion

- Track-Ex makes Quasi-Dynamic Predictions by exploiting the inherent axle oscillations called "Klingel motion"
  - Klingel motion generates TGamma that imbeds itself in the Track by changing Alignment and Gauge
  - Track-Ex therefore uses Alignment as a proxy for true axle motion



- The question may be asked: Does the Klingel motion truly imbed itself in the track?

28 July 2011 RCF Predictions using Track-Ex v1.ppt 12

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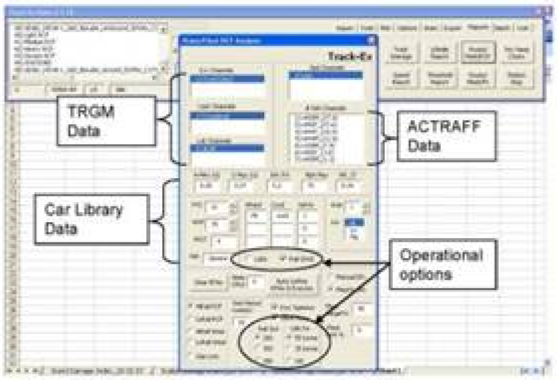
Track-Ex RFA : outputs & findings

- **R**oute/**F**leet **A**nalysis is a unique Track-Ex tool producing results from an entire fleet over an entire route for a specific period.



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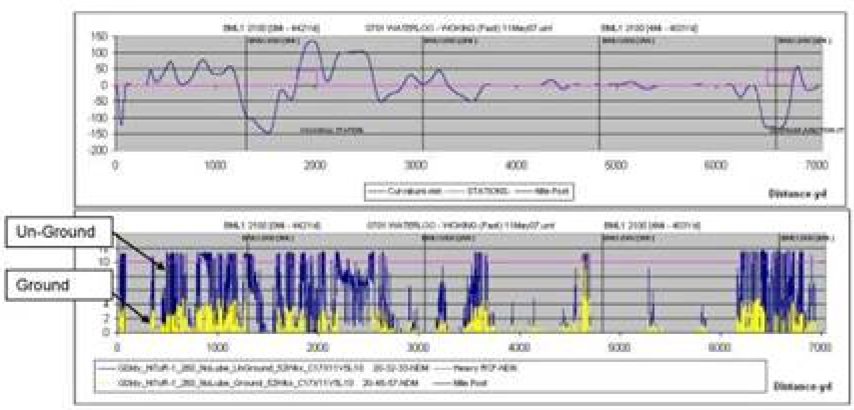
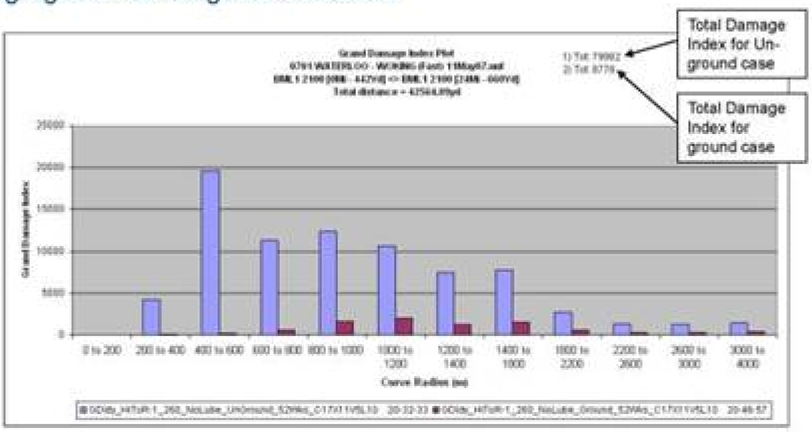
Track-Ex RFA : outputs & findings

- RFA produces RCF or Wear estimates for different operational conditions. Data can be presented as a function of track location



Track-Ex RFA: grinding vs no-grinding

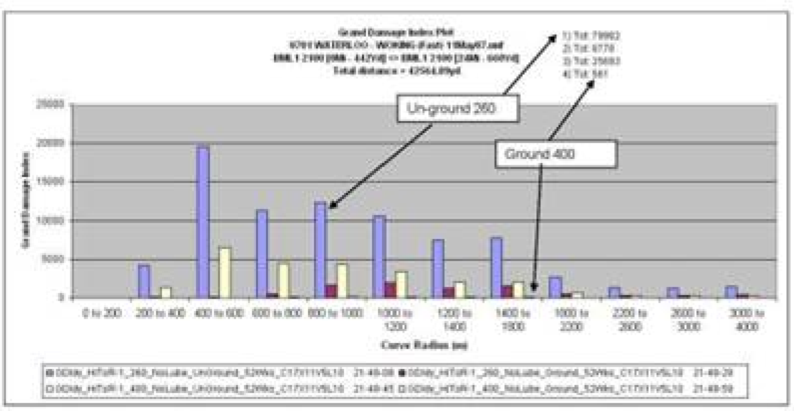
- The same data may also be summarized over an entire route and segregated into ranges of curvature



26 July 2011 RCF Predictions using Track-Ex v1.ppt 15

Track-Ex RFA: standard & premium rail

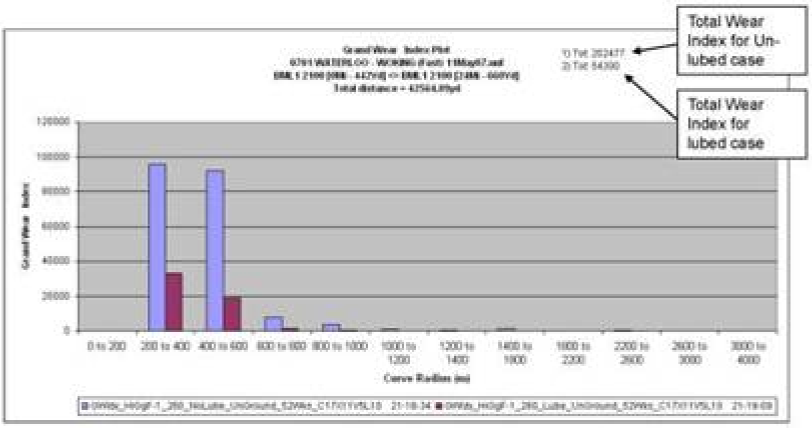
- The effects of grinding and steel grade can easily be summarized using the RFA report. Ground 400 = No RCF !!



26 July 2011 RCF Predictions using Track-Ex v1.ppt 16

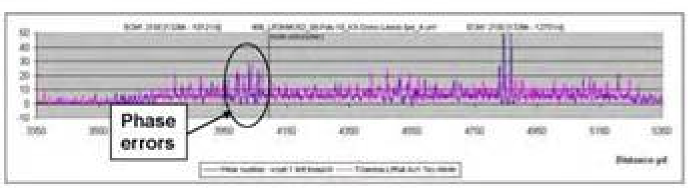
Track-Ex RFA: dry and lubricated rail

- The benefits of lubrication on wear can be easily summarized



Track-Ex accuracy: axle motion

- The primary reason that Track-Ex is called an "80/20" system is the inaccuracy of the Alignment used as an axle motion proxy.
  - The method is reasonable for mid range and shallow curves
  - Exhibits phase errors when flanging occurs due to tight curves or large geometric variations



- Most UK Track-Ex users state that such errors are of little consequence when managing track and are satisfied with the 80/20 compromise
- This raises the general question for other users: When is higher accuracy actually needed?
  - Proof of concept? accident investigation?

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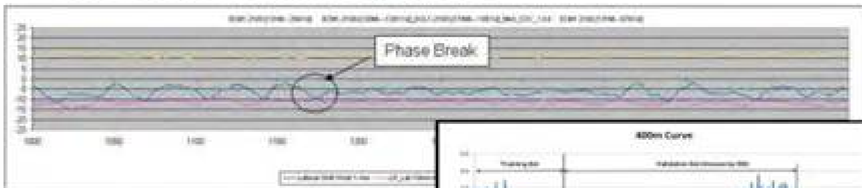
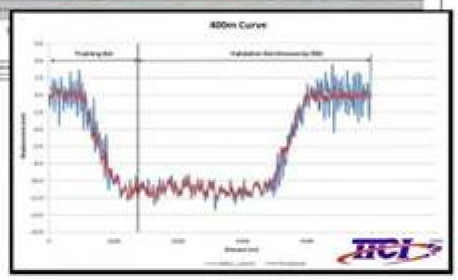
Track-Ex accuracy: axle motion

- A limited effort is underway to increase the accuracy of the Quasi-Dynamic TGamma by estimating axle dynamic motion:
  - An non-linear MKD system
  - Neural Nets trained form Vampire result





- Both show promise but suggest an "90/30" level of effort
- Priority has been dropped

28 July 2011 RCF Predictions using Track-Ex v1.ppt 19

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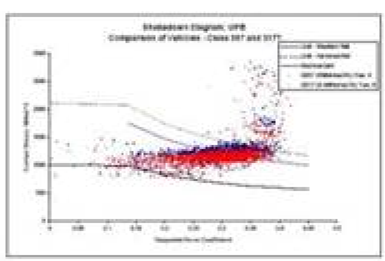
Track-Ex accuracy: WLRM

- When the WLRM was developed, predicted results were compared to "shakedown limit" damage estimates
  - Results correlated well
  - Test cases were dominated by UK passenger stock vehicles
  - Most cases exhibited high traction coefficients but low Po
- As a result, the WLRM has a creepage term that is relatable to the traction coefficient but has no term equivalent to Po
- This formulation is now in question because of:
  - Increased heavy axle UK freight vehicles
  - Interest in Track-Ex by non-UK parties with heavier axle loads



28 July 2011 RCF Predictions using Track-Ex v1.ppt 20

Track-Ex: Status as a UK tool

- In the UK rail industry, TGamma and the WLRM are accepted as a proven and productive method to predict rail damage
  - Some research is probable to upgrade the WLRM
  - Research into RCF using finite element or other fundamental concepts is no longer deemed necessary
- The TGamma/WLRM algorithm is used:
  - In high precision models such as Vampire for investigating new phenomenon such as low rail RCF or unique damage situations
  - In Track-Ex by Network Rail, design and maintenance firms for:
    - Line speed upgrades
    - Curve design
    - New stock specification and introduction
    - Regional maintenance

Track-Ex: Status as a global tool

- Network Rail is presently engaged in several discussions to make Track-Ex available to parties other than the UK surface line industry
- Potential users should carefully consider their own expectations:
  - Is high accuracy really needed? Is high accuracy input data available?
  - Is an 80/20 solution sufficient?
  - Is a research or practical tool most necessary?
- If the answer is that an 80/20 tool is desirable then Track-Ex could be modified:
  - Read new Track Geometry files
  - Generate VDM tables for new rolling stock
  - Modify the WLRM for new steels
- Track-Ex represents a departure from the classical method of maintaining track by tables of track quality
- By including the vehicles in the algorithm, Track-Ex represents a generalized system level tool that support performance based design and maintenance

Joint FRA/ TTCI Workshop on Rolling Contact Fatigue (RCF), July 26-27, 2011 in Chicago

Katrin Mädler, Detlev Ullrich, Rene Heyder, Andreas Zoll, Marcel Brehmer, Henri Bettac
Deutsche Bahn AG, DB Systemtechnik, Germany

Wheel and Rail Material Concepts to control Rolling Contact Fatigue (RCF) and Wear

DB Systemtechnik
Material engineering & failure analysis
Dr. Katrin Mädler
Brandenburg-Kirchmöser, 24.07.2011

Introduction
DB Systemtechnik

Main Locations

- Minden (Head quarter)
- Munich
- Brandenburg-Kirchmoeser

DB Systemtechnik

- Technical engineering and approval test and certification center for Deutsche Bahn AG and other customers in Germany and Europe

DB Systemtechnik Kirchmoeser

Maintenance engineering

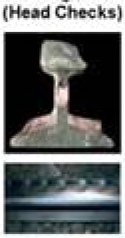
- Maintenance infrastructure planning
- Non-destructive testing
- Materials engineering and failure analysis
- Calibration technology (Branch office, Chemnitz)

Deutsche Bahn AG
Data and Facts

- 67,440 km (41,900 miles) total track length and 66,875 S&C´s
- Passenger & freight (mixed) traffic:
  - ~27,000 trains/ day in passenger traffic
  - ~ 5,000 trains/ day in freight traffic
- Passenger traffic operates with max. speed of 300 kmh (185 mph)
- Freight traffic operates with max. speed of 120 kmh and max. axle load of 22.5 tons (average 20 tons)
- Ballasted track on normal lines and slab track on high speed lines
- Rail profiles: UIC60/ S54 rails (60/ 54 kg (132/ 119 lb))
- Wheel profile: S 1002
- Vehicle mounted lubrication on all traction units
- Stationary rail lubricators only at some locations

Deutsche Bahn AG, T.TVI 53, 24.07.2011 3

RCF and wear on Rails
Standard Material Concepts

Wear, Corrugation (Head Checks)	Wear and Head Checks	Head Checks	Corrugation, Belgrospis, Squats (Head Checks)
			

150 500 1.500 3.000 **Radius [m]** 5.000 Straight

Since Dec. 2008 for R ≤ 1.500 m **R350HT** R = 700–1500 m and ≤ 50.000 tons per day: **R260**	Since Sep. 2009 extended field test **R350HT** No Head-check problems: **R260**	According to DB guidelines RiL820 **R260**

Fotos: DB Systemtechnik, Heyder/ Kühn

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RCF on Rails

Occurence and findings of Head checks (HC)

- First noticed in the 1980s
- Enormous increase of HC occurence in last 10 years on heavily loaded track sections
- Maintenance efforts increased:
  - NDT (Eddy current testing)
  - Rail grinding

- Mainly on electrified track sections, influenced by modern electrical locos and traction units, resp.
- Mainly on high rails in curves: 75% of all HC findings in curves between 500 m (550 yds.) and 5,000 m (5,500 yds.)
- HC also occur in the straight track sections where trains accelerate or decelarate
- Worn wheel and rail profiles promote HC development
- Rail material has a strong influence on RCF damages of rails

Deutsche Bahn AG, T.TVI 53, 24.07.2011 5

Rails

Standard and New Materials

Specification	Grade	C max, %	Si max, %	Mn max, %	Rm min, MPa	A min, %
DIN EN 13674-1	R200	0,60	0,58	1,20	680	14
DIN EN 13674-1	R220	0,60	0,60	1,25	770	12
DIN EN 13674-1	R260	0,80	0,58	1,20	880	10
DIN EN 13674-1	R260Mn	0,75	0,60	1,70	880	10
DIN EN 13674-1	R320Cr	0,80	1,10	1,20	1080	9
DIN EN 13674-1	R350HT	0,80	0,58	1,20	1175	9
DIN EN 13674-1	R350LHT	0,80	0,58	1,20	1175	9
DIN EN 13674-1	R370CrHT	0,82	1,00	1,10	1280	9
DIN EN 13674-1	R400HT	1,00	0,40	1,30	1280	9
Tata France	B360	0,30	1,20	1,60	1250	14
Voest Alpine	MP380	0,55	0,45	1,20	1250	9
NMH (TSTG)	1400CrB	0,35	0,80	0,80	1400	12

RCF and Wear on Rails
Testing new Materials

First long-term field test (Optikon) from 1999-2009

- 8 perlitic and 3 baintic rail steels
- Test rails of 15m length each, welded and installed as the high rail
- 7 curve sections with radii of R = 520 - 1,570 m (600 – 1,700 yds.)
- Daily loadings from 25,000 - 55,000 tons (mixed traffic)
- Track inspection every 6 months in the first 3 years, thereafter annually

Measurements:

- At two points of each rail
  - Transverse profile (Miniprof)
  - Length of head checks (MPI)
  - Depth of head checks (Eddy-current testing)
  - Finally: Metallurgical investigation

Fotos: DB Systemtechnik, Heyder

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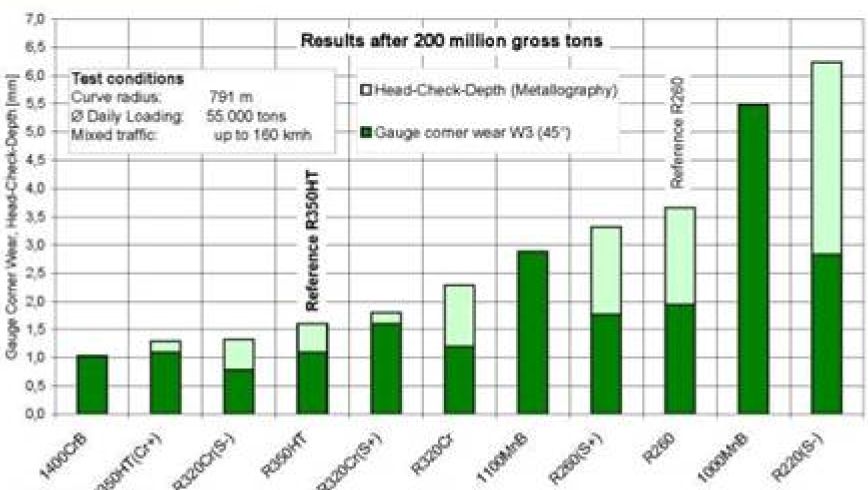
RCF and Wear on Rails
Field test Optikon – Final results



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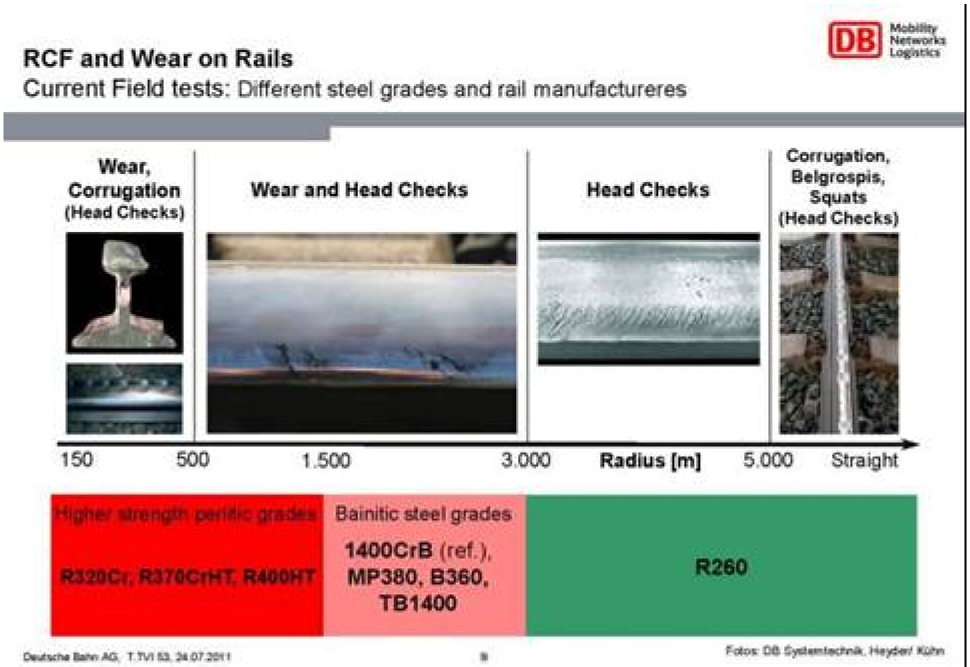
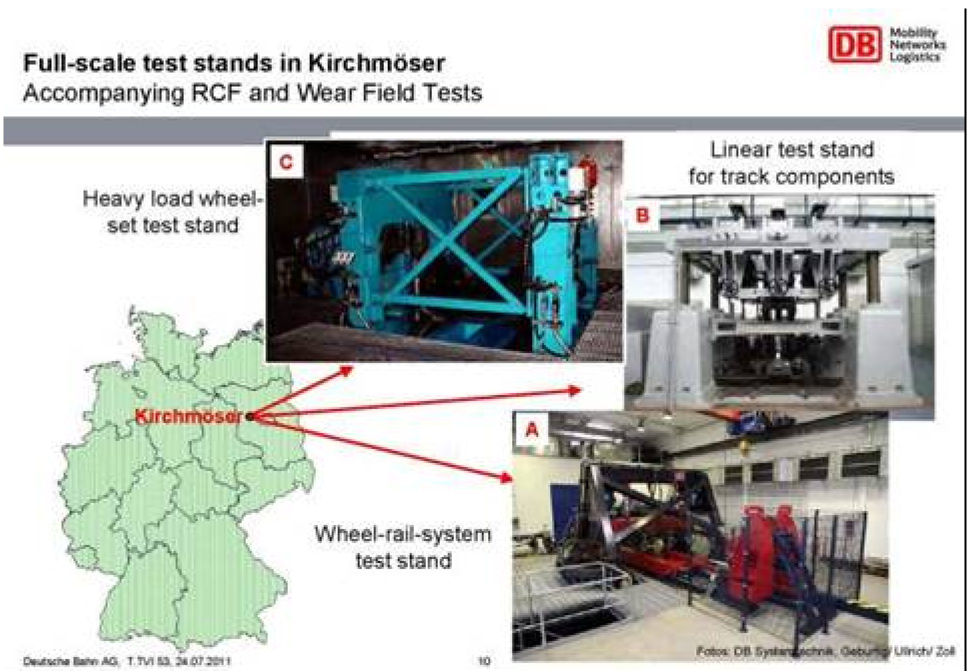

RCF and Wear on Rails
Current Field tests: Different steel grades and rail manufactureres
Mobility Networks Logistics
Wear, Corrugation (Head Checks)
Wear and Head Checks
Head Checks
Corrugation, Belgrospis, Squats (Head Checks)
150
500
1.500
3.000
Radius [m]
5.000
Straight
Higher strength perlitic grades
R320Cr, R370CrHT, R400HT
Bainitic steel grades
1400CrB (ref.), MP380, B360, TB1400
R260
Deutsche Bahn AG, T.TVI 53, 24.07.2011
9
Fotos: DB Systemtechnik, Heyder/ Kühn


Full-scale test stands in Kirchmöser
Accompanying RCF and Wear Field Tests
Mobility Networks Logistics
Heavy load wheel-set test stand
C
Linear test stand for track components
B
Kirchmöser
A
Wheel-rail-system test stand
Deutsche Bahn AG, T.TVI 53, 24.07.2011
10

Wheel-rail-system test stand

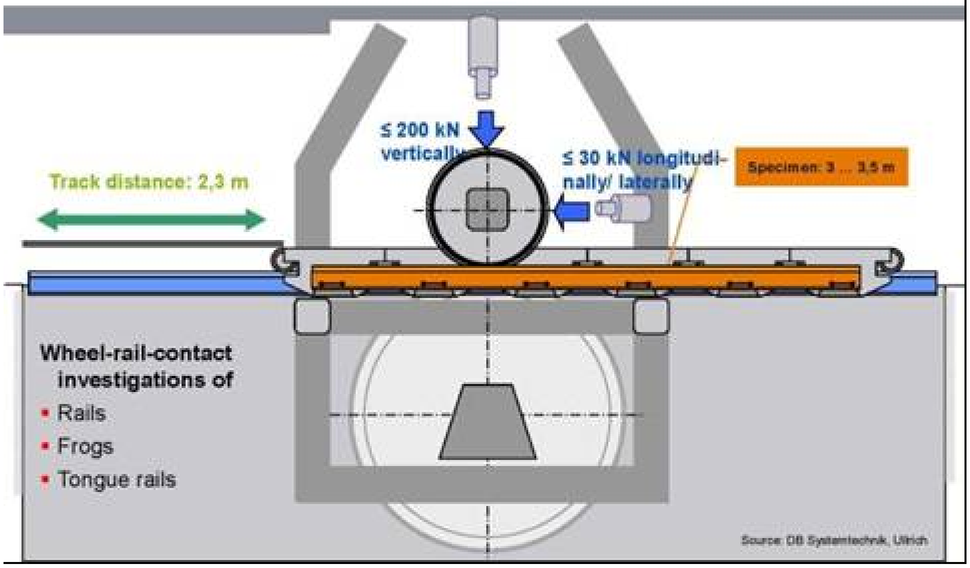
Accompanying RCF and Wear Field Tests

Starting 1999 as a rolling test stand ...

... It was 2010 extended to a linear test stand for testing of track components

Deutsche Bahn AG, T.TVI 53, 24.07.2011 11 Fotos: DB Systemtechnik, Ulrich/ Zoll

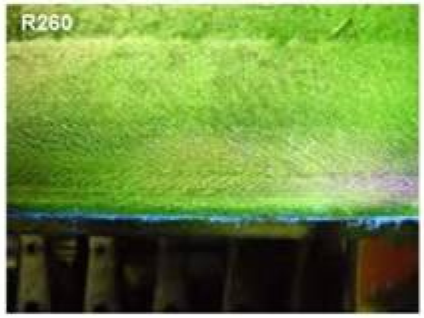
Wheel-rail-system test stand



Material testing on the wheel-rail-system test stand
Current Tests on Rails

Initiation and growth of Head Checks

Normal grade (R260) – Head-hardened rails (R350HT) – Bainitic rails



Crack-pattern (left) and magnetic particle image (right)
after 37,000 wheel passes (~1 million tons)

Fotos: DB Systemtechnik, Ullrich/ Brehmer

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Material testing on the wheel-rail-system test
Current tests on S&C

Comparison of R260 and 1400CrB

Frog testing on the linear test stand...

... and on the track test site Haste (near Hannover) with 19 frogs

Test duration

about **2 weeks** (24 Mio t)

about **18 month** (30-40 Million t)

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Fotos: DB Systemtechnik, Zoll

DB Mobility Networks Logistics

RCF on Wheels

Occurence and findings of tread damages

- RCF – Surface cracks
  - Enormous increase in last 10 years
  - Modern electrical and diesel traction units especially concerned
  - Driving and driven wheelsets concerned
  - With and without martensitic transformation
- RCF - Sub-surface cracks
  - Sub-surface cracks and total tread collapses are slightly increasing
  - Cleanliness of steel is important!
  - Frequent ultrasonic testing of concerned vehicles
- Wheel material grade has a strong influence on RCF damages of wheels

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DB Mobility Networks Logistics

Wheel Materials

Standard and new materials

Spezification	Grade	C max, %	Si max, %	Mn max, %	Rm, MPa	A min, %
EN 13262	ER7	0,52	0,40	0,80	820-940	14
JIS E 5402	C48	0,58	0,40	0,90	820-940	14
EN 13262	ER8	0,56	0,40	0,80	860-980	13
Lucchini	Superlos	0,56	1,10	1,10	920-1020	14
GHH-Valdunes	R8TUCS	0,54	1,10	1,10	920-1000	13
BVV	Excellent	0,54	1,00	1,10	900-1050	14
GOST 10791	Grade 1	0,52	0,65	1,20	880-1080	12
JIS E 5402	C51	0,54	0,40	0,90	860-980	13
AAR M107	Class A	0,57	1,00	0,90	-	-
EN 13262	ER9	0,60	0,40	0,80	900-1050	12
JIS E 5402	C55	0,58	0,40	0,90	900-1050	12
GOST 10791	Grade 2	0,65	0,45	0,90	910-1110	8
GHH-Valdunes	VHISplus	0,65	0,40	0,85	950-1100	11
JIS E 5402	C64	0,67	0,40	0,90	940-1140	11
AAR M107	Class B	0,67	1,00	0,90	-	-

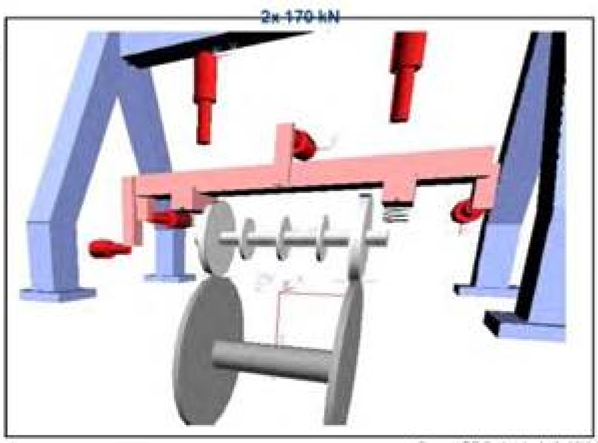
Material testing on the wheel-rail-system test stand

Previous Tests on Wheels

DB Mobility Networks Logistics

- **RCF and wear investigations on wheels of different materials:**
  - ER7 (DIN EN 13262)
  - ER8 (DIN EN 13262)
  - „Excellent" (with higer Mn and Si contents)
  - C64 (JIS E 5402)
  - Austempered ductile iron

„Wheelset on rails" test configuration



Source: DB Systemtechnik, Ullrich

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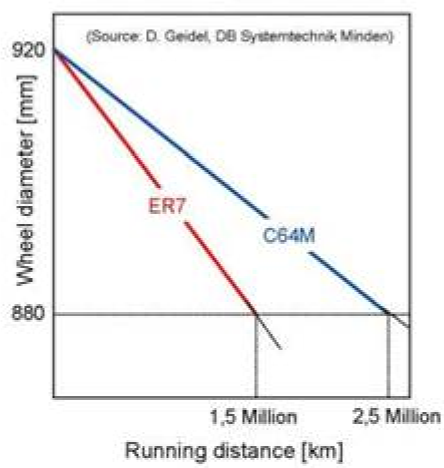
RCF and Wear on Wheels

Testing of high-strength steel C64M for ICE 1 and 2 driven wheels

DB Mobility Networks Logistics

- Standard material: ER7 (DIN EN 13262)
- Test material (since 2002): C64 (JIS 5402)
- First results 2004:
  - With the harder material C64 almost no wear problems (wheels getting un-round, transversal profile deviations) and RCF damages
  - ⇨ Reduction of reprofiling expenses up to 50 %
  - ⇨ Up to 50 % higher running performance
- Extended field test starting 2005
- Nowadays, the use of C64M as a standard material according to German standard DBS 918 277 is possible

Field test ICE 2 (Driven wheels)



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Summary and conclusions

DB Mobility Networks Logistics

Higher-strength materials for rails and wheels can offer

- Less wear and RCF problems
- Less maintenance expenses
- Higher life times

⇨ Less wear means also longer stability of profiles and that means less wear at the contact „partner“ due to lower contact stresses

However, higher-strength materials have a higher notch-sensivity

⇨ That means one has to consider the higher risk of fatigue crack initiation on surface defects in maintenance strategy.

⇨ Therefore, use of higher-strength materials only if necessary due to RCF and wear problems

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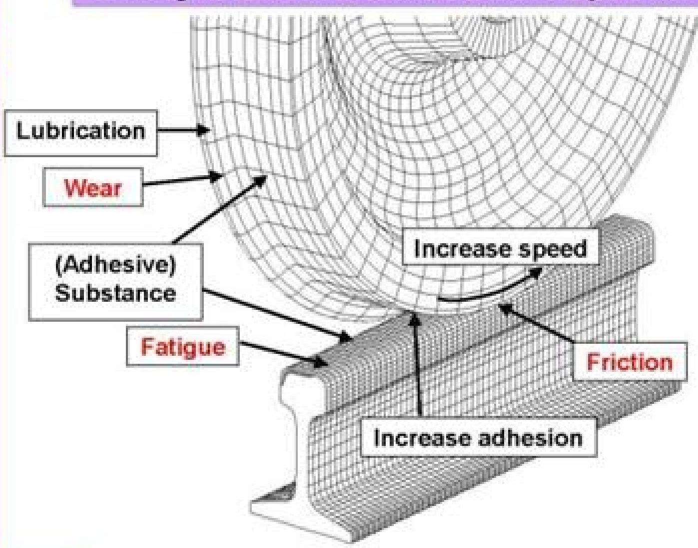
Joint FRA/TTCI Workshop on RCF in North America, July 26th-27th 2011

RCF in Japan & application of twin disk machines : Nature of wheel & rail RCF, root causes & remedial action in Japan

Railway Technical Research Institute
Railway Mechanics & Track Technology
Makoto Ishida

Railway Technical Research Institute

Study on wheel/rail contact problems



Railway Technical Research Institute

Rolling Contact Fatigue (RCF)

Rail - Squat plastic deformation ?
white etching layer
- Gauge corner crack → Squat
- Head check

Wheel - Deep shell white etching layer
- Heat check

Balance between RCF and wear

Railway Technical Research Institute

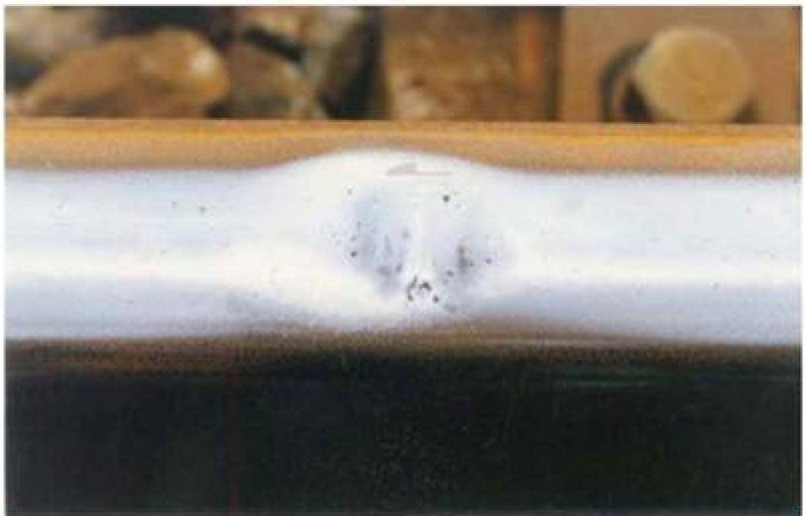
Rail

Squat
=Rail surface shelling

Railway Technical Research Institute

Rail

Squat : appearance (dark spot)



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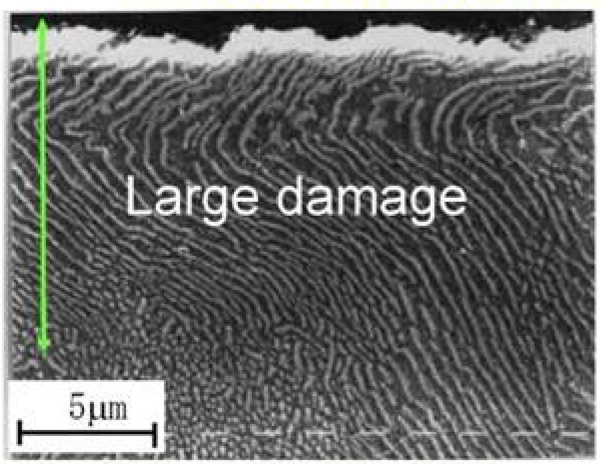
Plastic deformation in the surface layer of rail



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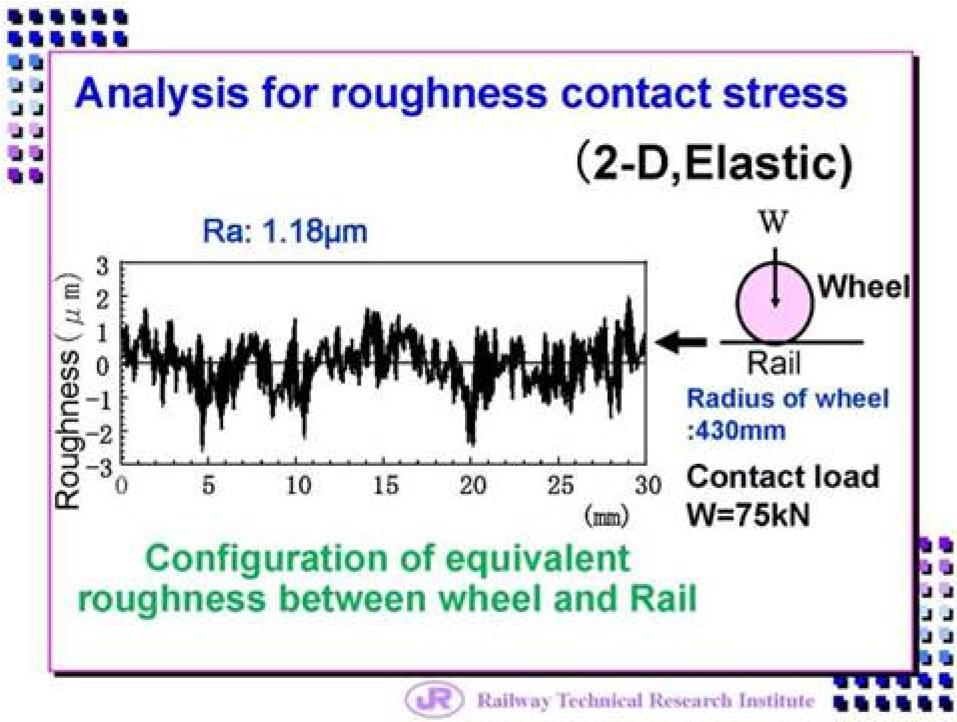
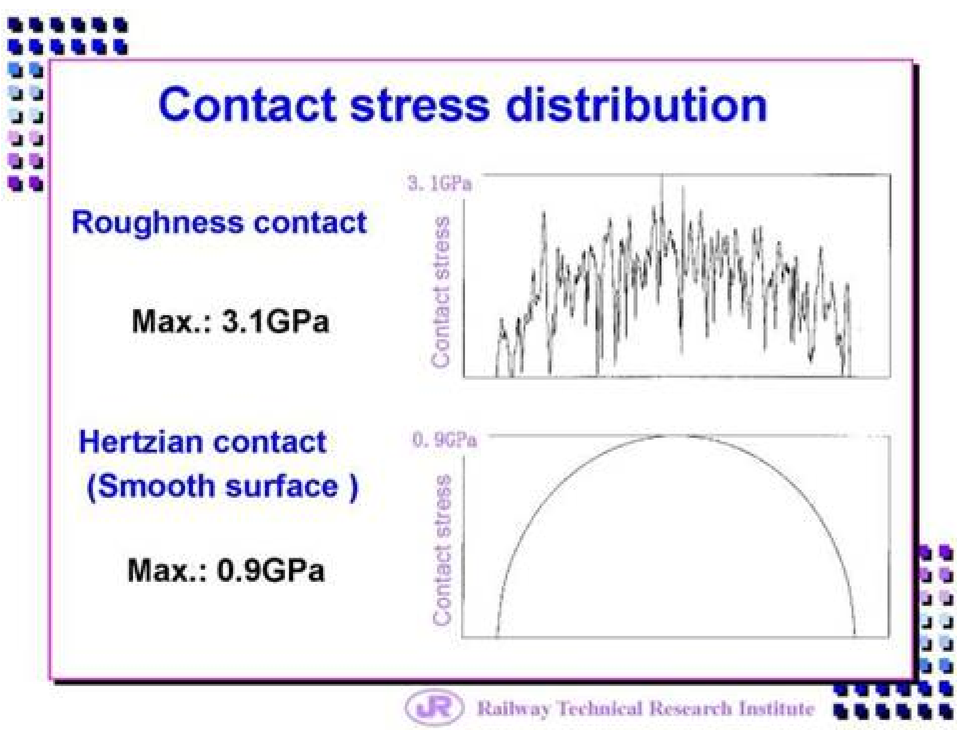
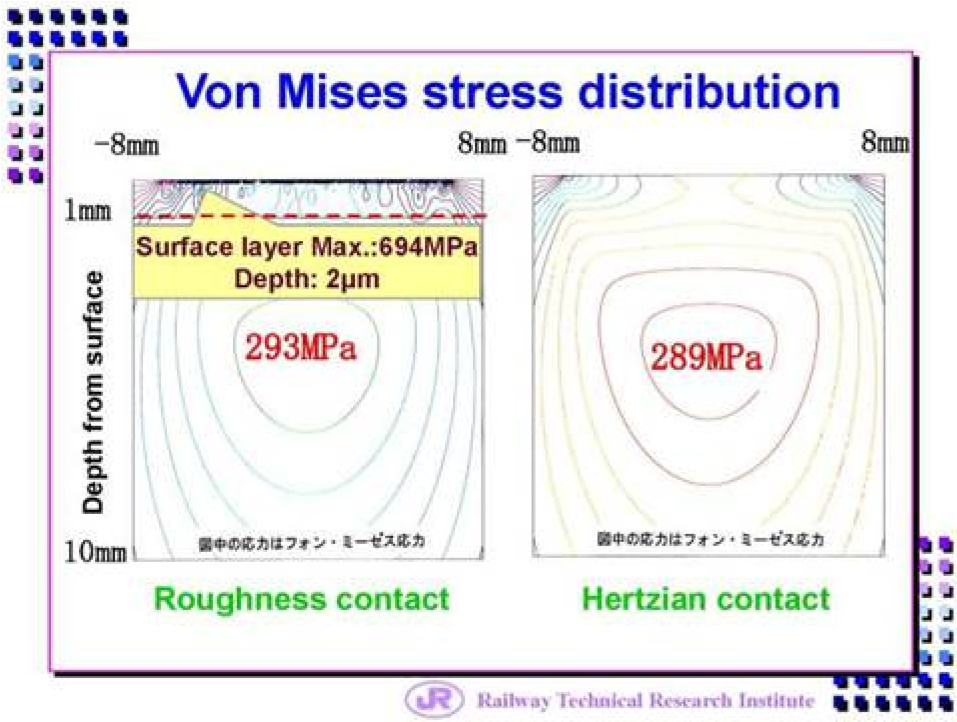
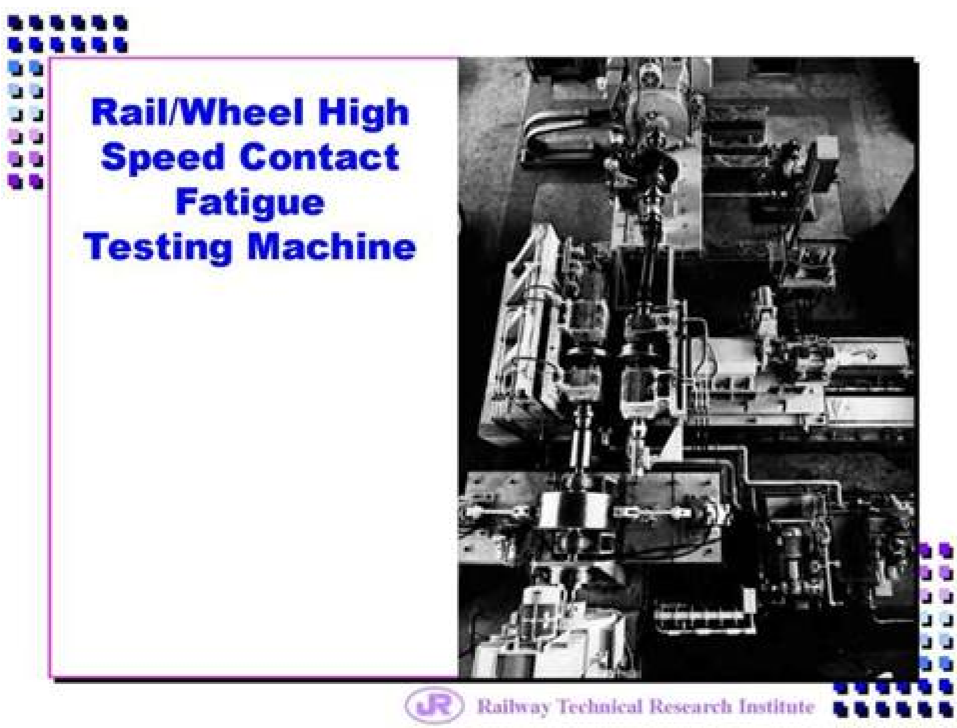
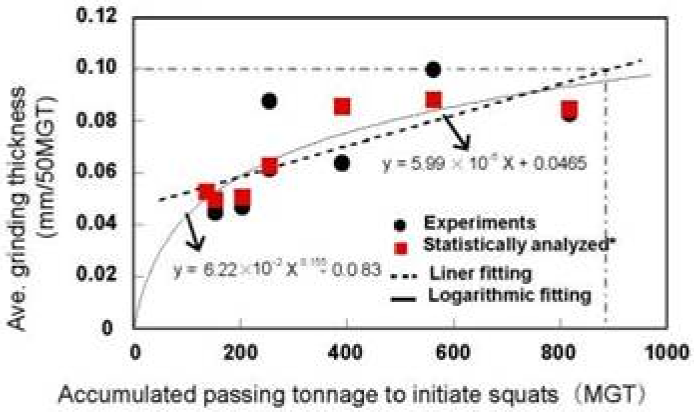

Analysis for roughness contact stress
(2-D,Elastic)
Ra: 1.18μm
Roughness (μm)
3
2
1
0
−1
−2
−3
0
5
10
15
20
25
30
(mm)
W
Wheel
Rail
Radius of wheel :430mm
Contact load W=75kN
Configuration of equivalent roughness between wheel and Rail
Railway Technical Research Institute


Contact stress distribution
Roughness contact
Max.: 3.1GPa
3. 1GPa
Contact stress
Hertzian contact (Smooth surface)
Max.: 0.9GPa
0. 9GPa
Contact stress
Railway Technical Research Institute


Von Mises stress distribution
-8mm
8mm
-8mm
8mm
1mm
10mm
Depth from surface
Surface layer Max.:694MPa
Depth: 2μm
293MPa
289MPa
図中の応力はフォン・ミーゼス応力
図中の応力はフォン・ミーゼス応力
Roughness contact
Hertzian contact
Railway Technical Research Institute

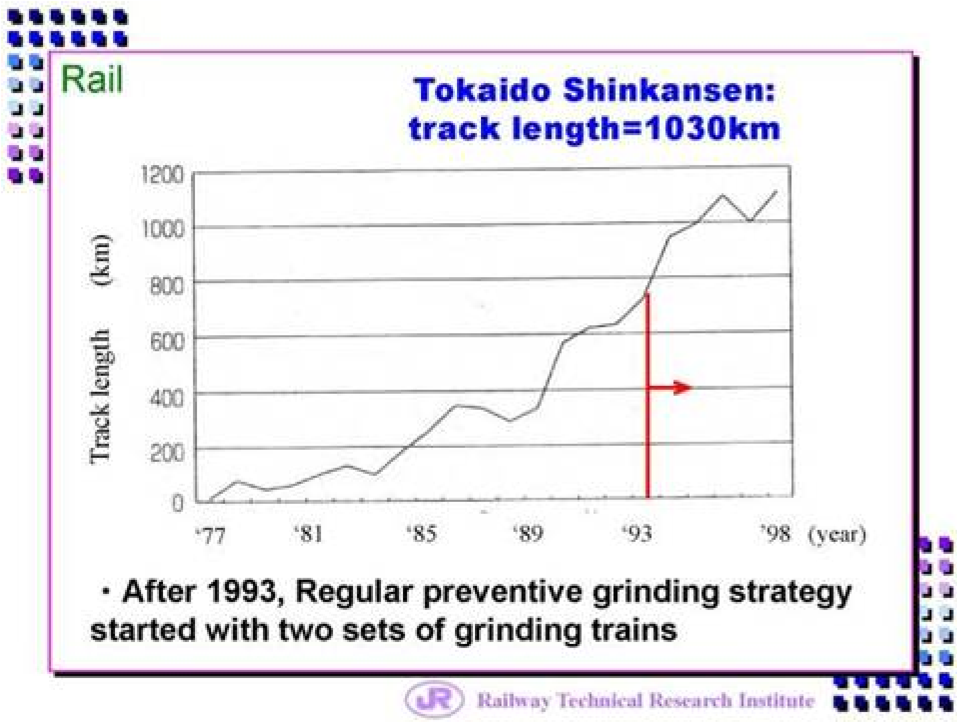

Rail/Wheel High
Speed Contact
Fatigue
Testing Machine
Railway Technical Research Institute

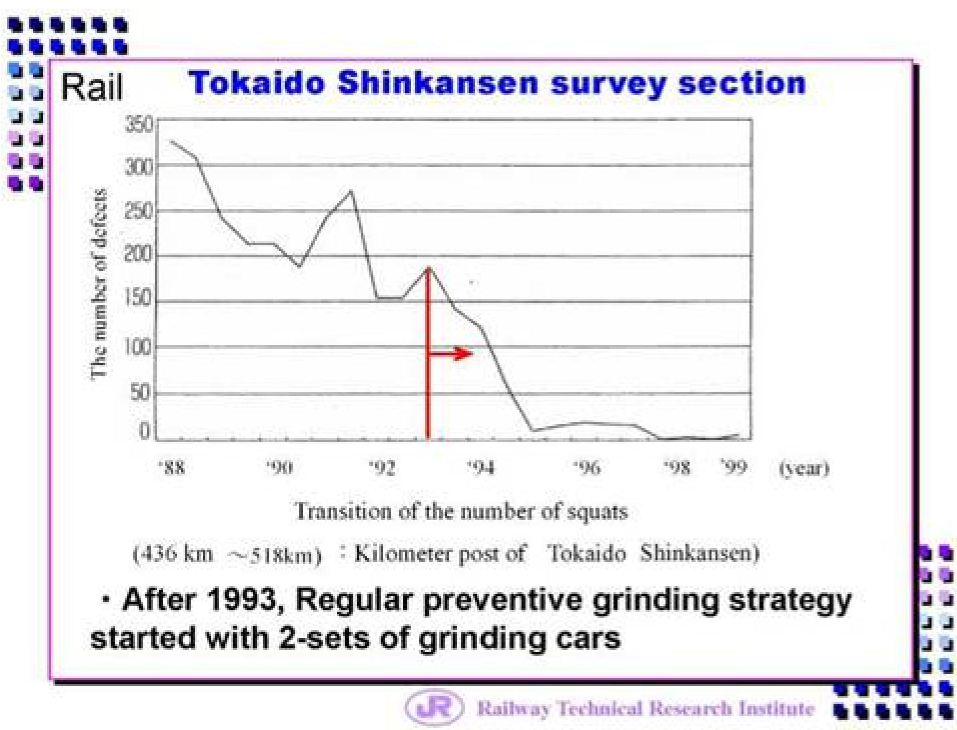
Effect of Preventive Grinding on Squat Initiation - Rolling fatigue test results (Twin Disc Machine)



*; Assuming the distribution of each accumulated passing tonnage, 50%estimation was obtained by statistical analysis

Rail grinding


Rail
Tokaido Shinkansen:
track length=1030km
Track length (km)
1200
1000
800
600
400
200
0
'77
'81
'85
'89
'93
'98 (year)
・After 1993, Regular preventive grinding strategy started with two sets of grinding trains
Railway Technical Research Institute


Rail
Tokaido Shinkansen survey section
The number of defects
350
300
250
200
150
100
50
0
'88
'90
'92
'94
'96
'98
'99
(year)
Transition of the number of squats
(436 km ～518km) : Kilometer post of Tokaido Shinkansen)
・After 1993, Regular preventive grinding strategy started with 2-sets of grinding cars
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Rail

Many squats caused continuously in longitudinal direction

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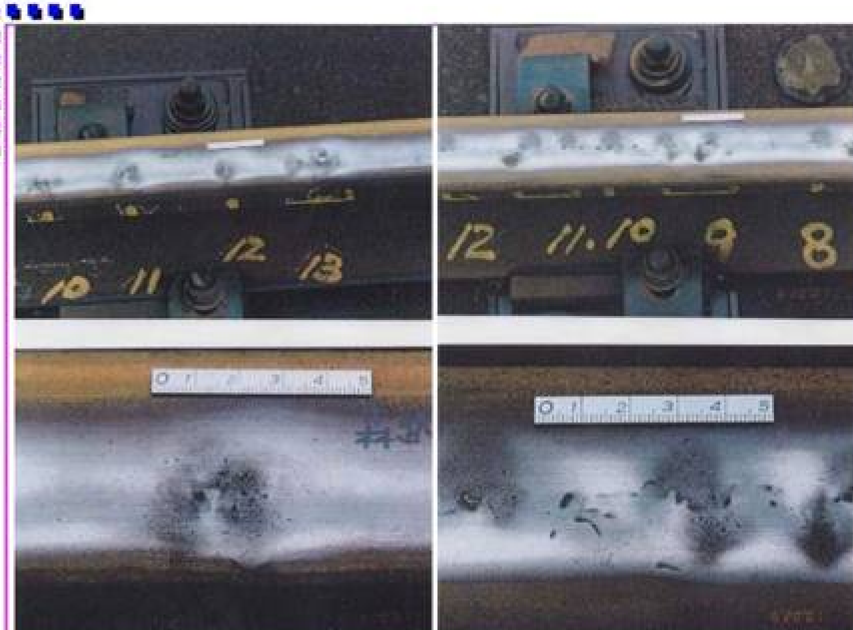

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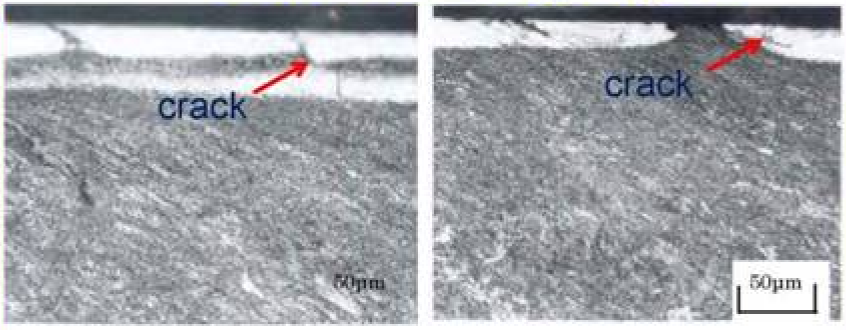
Rail

White etching layer



-White etching layer has a great influence on crack initiation

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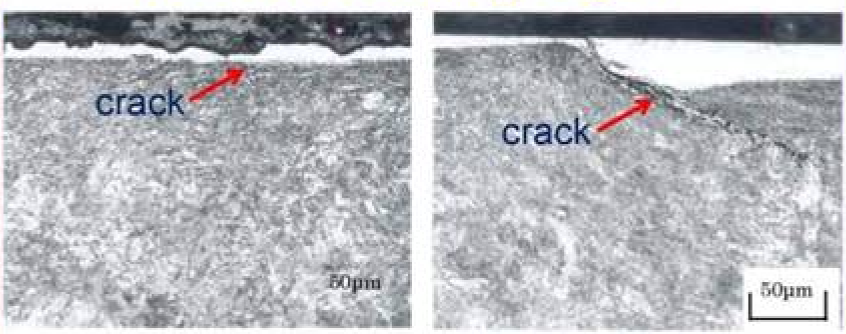
Rail

White etching layer



- Crack caused at the end of the layer propagates deeper than the one caused in the middle of the layer

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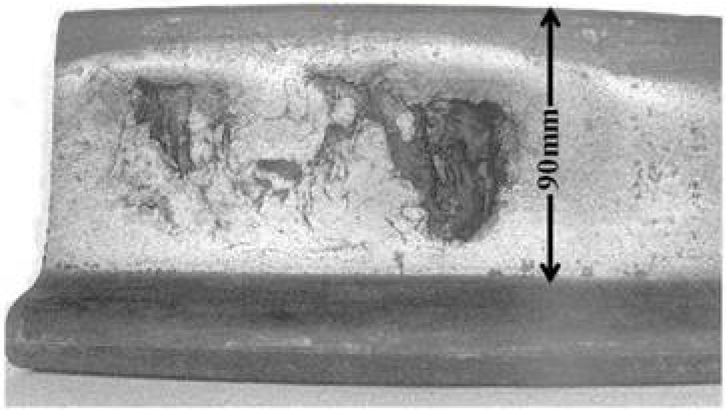
Wheel

Deep shell



Crack is caused by formation of white etching layer and water

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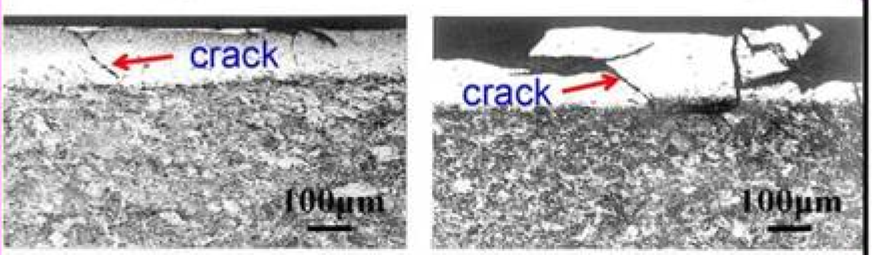
Wheel

White etching layer (wheel tread surface)



- White etching layer has a great influence on crack initiation as well as rail

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Wheel

Heat check

- Heat check is caused by heat generated by wheel/brake shoe friction and wheel/rail traction force

Railway Technical Research Institute

Rail

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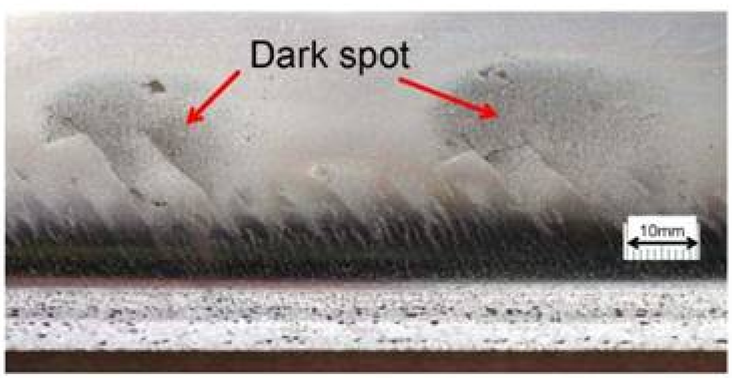
Rail

Head Hardened rail : head check

Railway Technical Research Institute

Rail

Gauge corner crack



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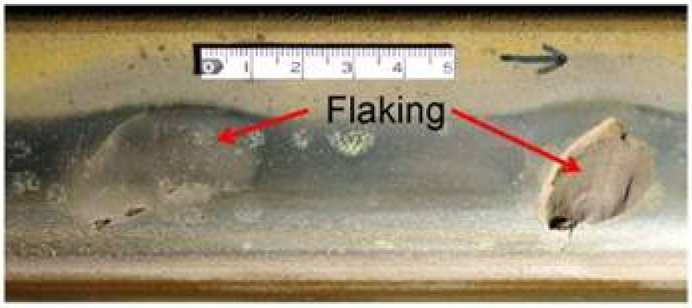
Rail

Flaking can be occasionally caused



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Rail

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Rail

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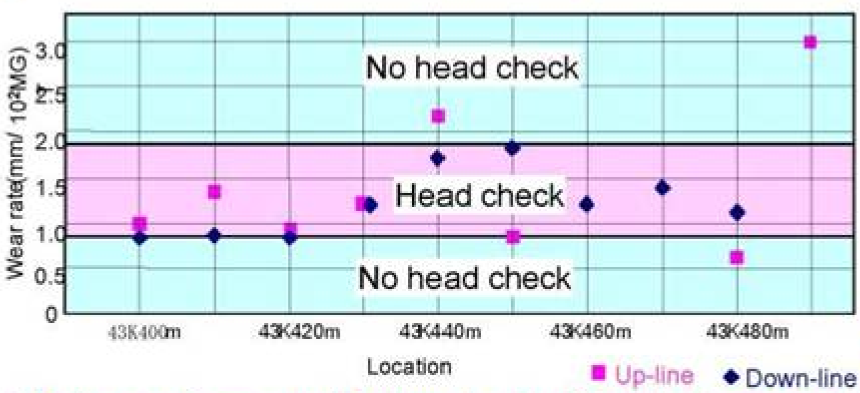
Rail

Head check and Wear rate

Head hardened rails (R800, double track)



Balance of wear and fatigue is significantly important

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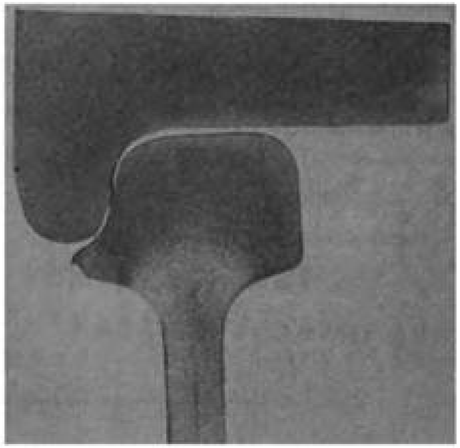
Rail gauge face / Thin flange Wear



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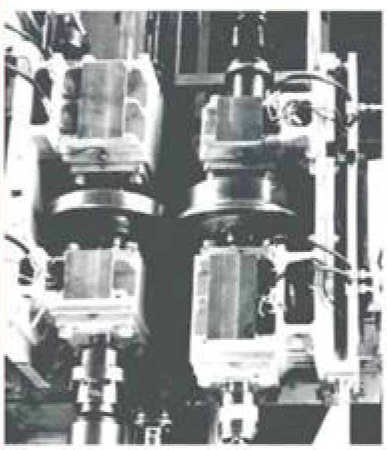
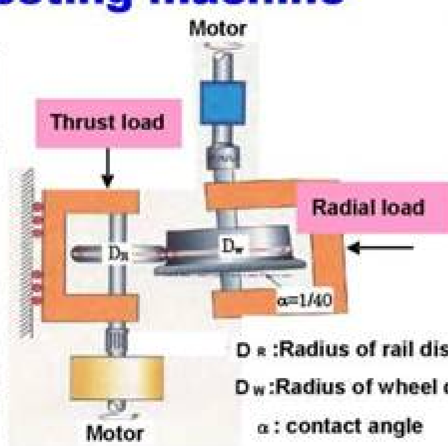
Rail/Wheel high speed contact Fatigue testing machine





D_R :Radius of rail disc

D_W :Radius of wheel disc

α : contact angle

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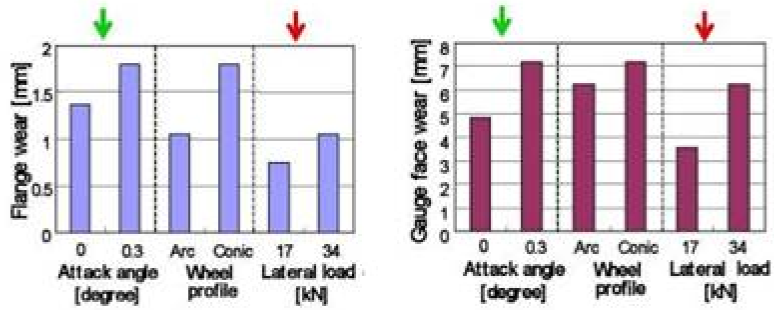
Variation of wear with some experimental arrangements of laboratory simulation



(a) Flange wear amount at 1.68×10^6 cycles corresponding to 2638km of running distance

(b)Gauge face wear at 2.4×10^6 cycles corresponding to 2638km of running distance corresponding to 40MGT

(the profile of rail disc: JIS60kg)

Railway Technical Research Institute

Study on wear simulation

best practice for wheel-rail maintenance;

selection of materials

suitable for local conditions such as vehicle/track interaction, atmosphere and/or climate and others;

specification of grinding and lubrication

based on wear rate focusing on balance between RCF and wear

Railway Technical Research Institute

ASSOCIATION OF AMERICAN RAILROADS

U.S. Department of Transportation
Federal Railroad Administration

TTCI. Transportation Technology Center, Inc.

Joint AAR / FRA Workshop

on Wheel & Rail Rolling Contact Fatigue in North America

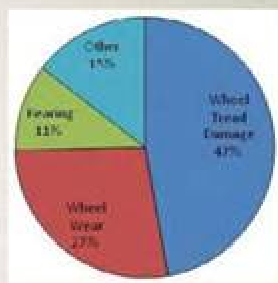
July 26-27, Chicago

Understanding the Root Causes & Remedies for Wheel & Rail RCF in Freight Service in North America

Harry Tournay, TTCI

Problem Size

- **RCF Definition**
  - **Crack Initiation & Propagation**
  - **Material Flow**
  - **Wear**
- **Wheel RCF**
  - **Wheel set replacement costs in North America: $800 million**



- **2009: Capital & operating spending per year on rail replacement & grinding US railroads: $3.2billion**
  - Rail replacement on mainline ($920million) & other track; special track work; rail grinding
  - Estimated contribution of RCF: 2% = $18billion (conservative)
  - Head loss due to grinding low rail could be as high as 50% of total loss due to crack generation, wear & material flow

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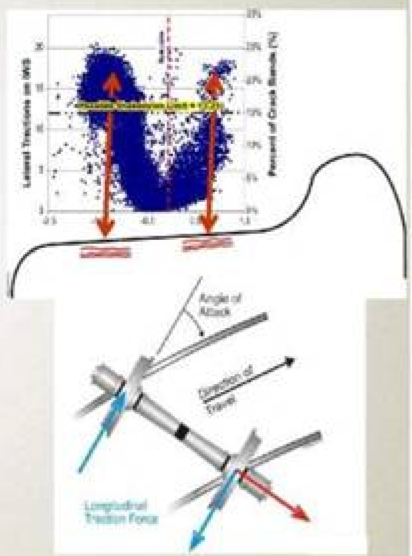
Wheel RCF

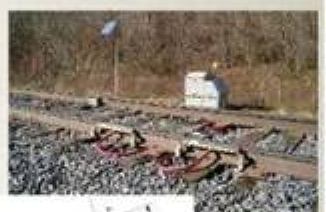
- **Thermal Mechanical Fatigue (TMS):**
  - **± 50% of all High Impact Wheels (HIW)**
    - Dominates HH unit train traffic
    - (Wheel skids from unreleased hand brakes contribute to other 50%)
  - **Root Causes**
    - High Steering Tractions (non-steering trucks, high contact friction, poor wheel/rail contact geometry, excess cant, stringlining)
    - High Wheel Temperatures ("stuck" brakes – valves, leaks, rigging)

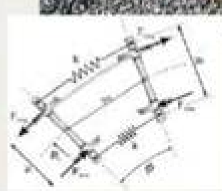


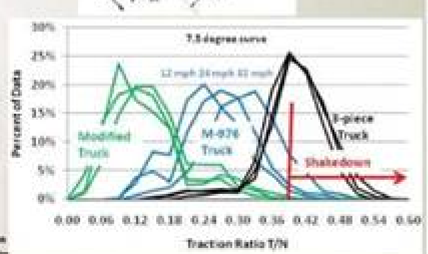
Wheel RCF

- **Thermal Mechanical Fatigue (TMS):**
  - **Solutions:**
    - Controlled Friction
    - Controlled Rail Profiles
    - Improved Wheel Steels
    - Improved Steering Trucks
    - Reduced / Controlled Wheel Temperatures
  - **Dilemma:**

    How to quantify the benefits & (in combination) the relative benefits of each of these preventative measures?

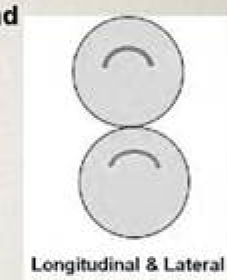






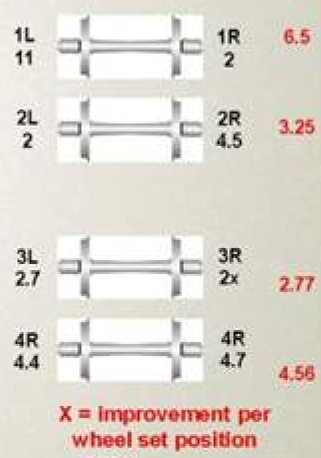
Wheel RCF

- **Thermal Mechanical Fatigue (TMS):**
  - **Experimental Tools: Twin Disk & Rolling Load Machines:**
    - Applied to the development of wear models
    - How successful with establishment of crack initiation?
    - Is it possible to control "wheel" temperature while controlling coefficient of friction?
    - Control of profiles & wear debris while controlling coefficient of friction?
    - How to simulate the spectrum of load & temperature conditions?
    - How to relate to the prevailing service load?
    - How to anticipate material improvements?



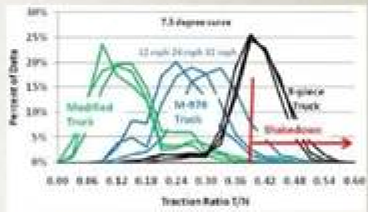
Wheel RCF

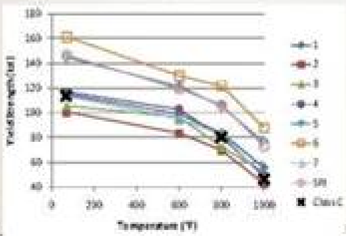
- **Thermal Mechanical Fatigue (TMS):**
  - **In-service Monitoring (comparison between 2 fleets):**
    - Apparent reduction in wheel removals & overall miles / removal (well beyond 400k miles)
    - Improvement greatest on axles 1 & 4 indicating a strong correlation with steering tractions
    - No apparent improvement in net miles / wheel for *failed* wheels
    - No indication of the role of temperature on wheel performance
    - No data separation from a major "other" removal cause: AWFW
    - No quantification of steering tractions (curvatures & speeds)

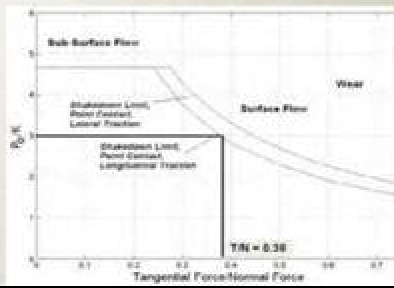


Wheel RCF

- Thermal Mechanical Fatigue (TMS):
  - Shakedown-based Analytical Tools:
    - Analysis / Instrumented Wheel Set (IWS) tests used to quantify tractions; expressed in terms of probability
    - Shakedown map used to determine Shakedown Limit for P_0/K in low rail contact at given wheel temperatures (related through yield vs. temperature)







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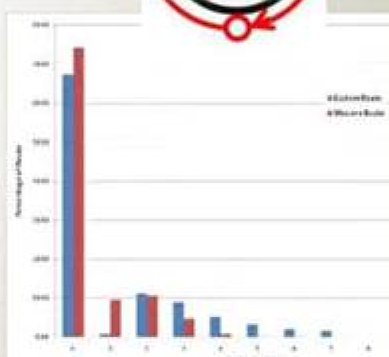
Wheel RCF

- Thermal Mechanical Fatigue (TMS):
  - Shakedown-based Analytical Tools:
    - Probability of a contact "encounter" between an element on the wheel profile & the rail calculated based on:
      - Cycles above shakedown/curve
      - Route Curvature Distribution
      - Assumed equal:
        - Left- & Right Hand Curves
        - Car Directionality
      - Ratio of Contact Patch Dimensions to Wheel Circumference
      - *No accounting for gage variation*



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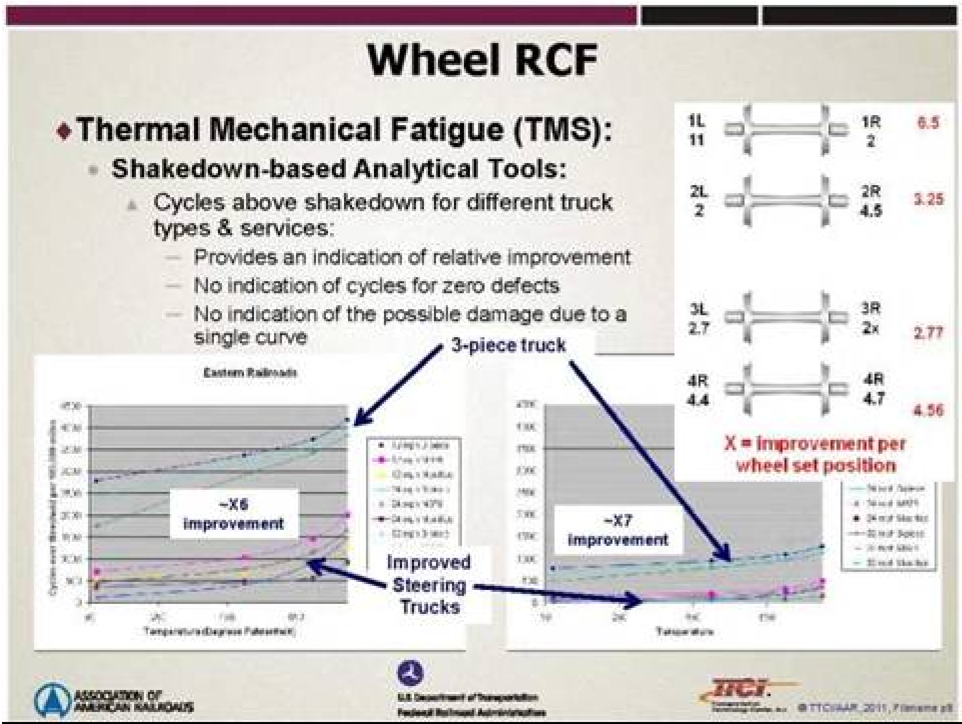
Wheel RCF
Thermal Mechanical Fatigue (TMS):
Shakedown-based Analytical Tools:
Cycles above shakedown for different truck types & services:
Provides an indication of relative improvement
No indication of cycles for zero defects
No indication of the possible damage due to a single curve
3-piece truck
Eastern Railroads
~X6 improvement
~X7 improvement
Improved Steering Trucks
1L 11
1R 2
6.5
2L 2
2R 4.5
3.25
3L 2.7
3R 2x
2.77
4R 4.4
4R 4.7
4.56
X = improvement per wheel set position
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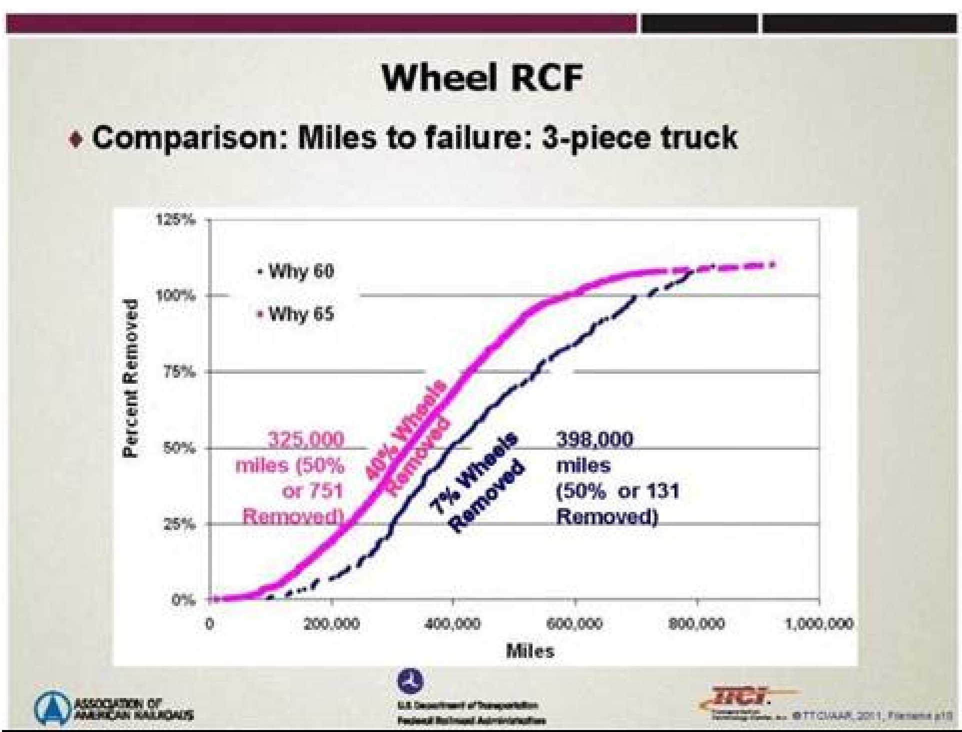
Wheel RCF
Comparison: Miles to failure: 3-piece truck
Why 60
Why 65
Percent Removed
125%
100%
75%
50%
25%
0%
325,000 miles (50% or 751 Removed)
40% Wheels Removed
7% Wheels Removed
398,000 miles (50% or 131 Removed)
0
200,000
400,000
600,000
800,000
1,000,000
Miles
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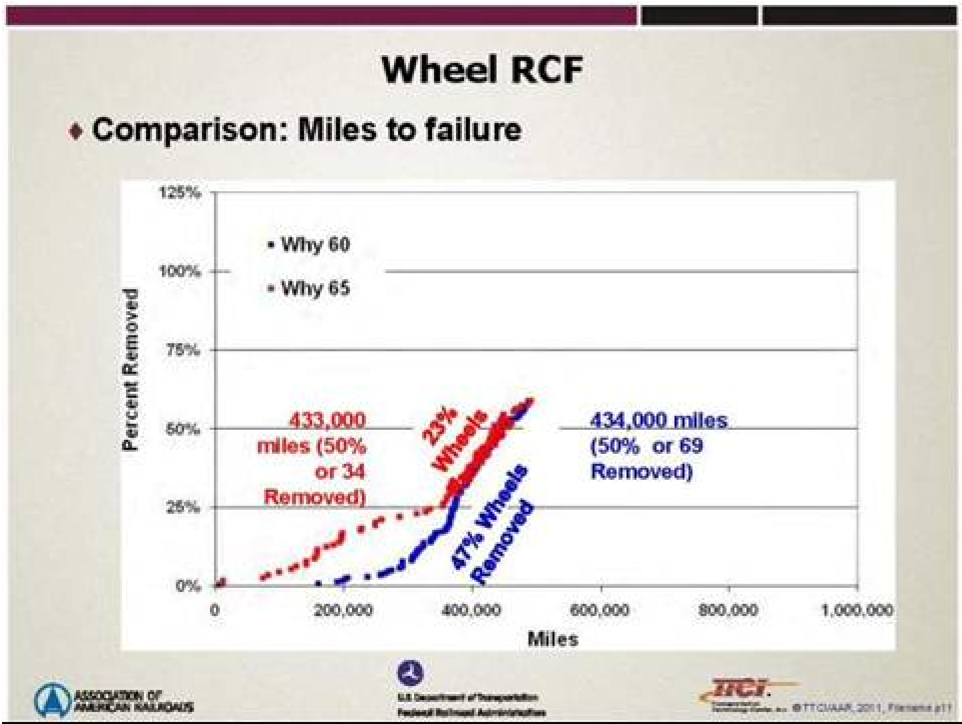
Wheel RCF
Comparison: Miles to failure
Why 60
Why 65
Percent Removed
433,000 miles (50% or 34 Removed)
23% Wheels Removed
47% Wheels Removed
434,000 miles (50% or 69 Removed)
Miles
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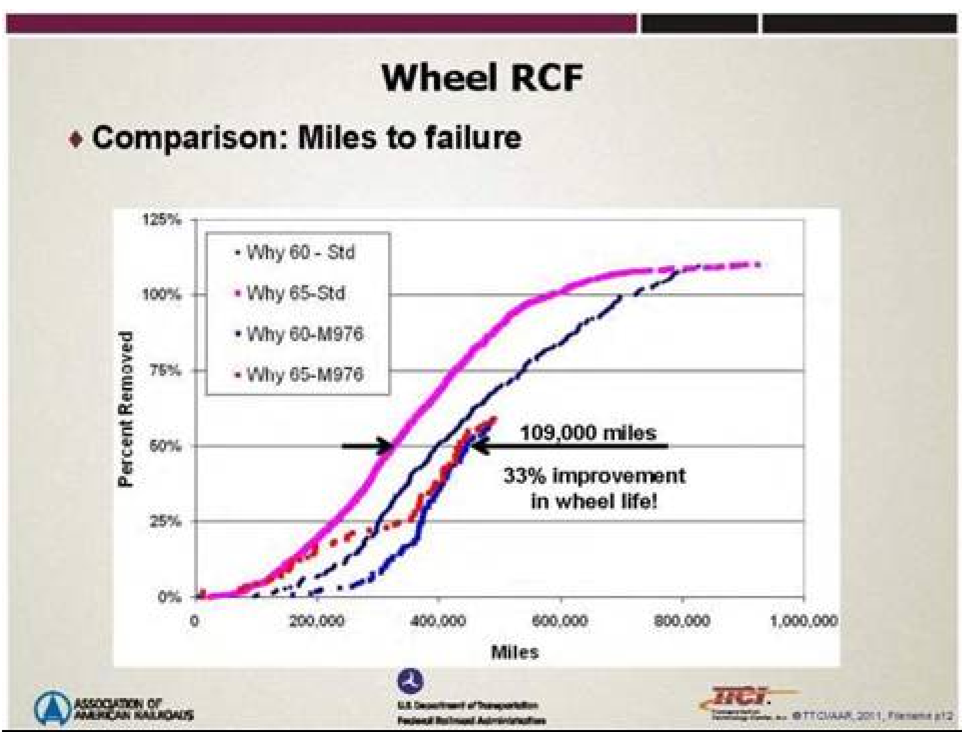
Wheel RCF
Comparison: Miles to failure
Why 60 - Std
Why 65-Std
Why 60-M976
Why 65-M976
Percent Removed
109,000 miles
33% improvement in wheel life!
Miles
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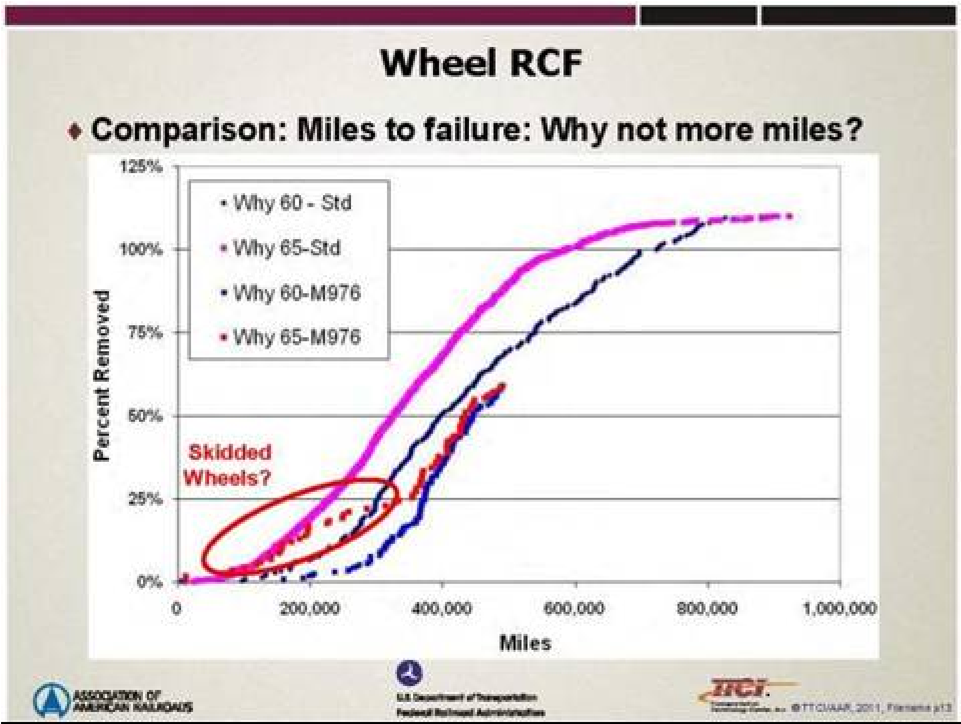
Wheel RCF
Comparison: Miles to failure: Why not more miles?
Why 60 - Std
Why 65-Std
Why 60-M976
Why 65-M976
Skidded Wheels?
Percent Removed
125%
100%
75%
50%
25%
0%
0
200,000
400,000
600,000
800,000
1,000,000
Miles
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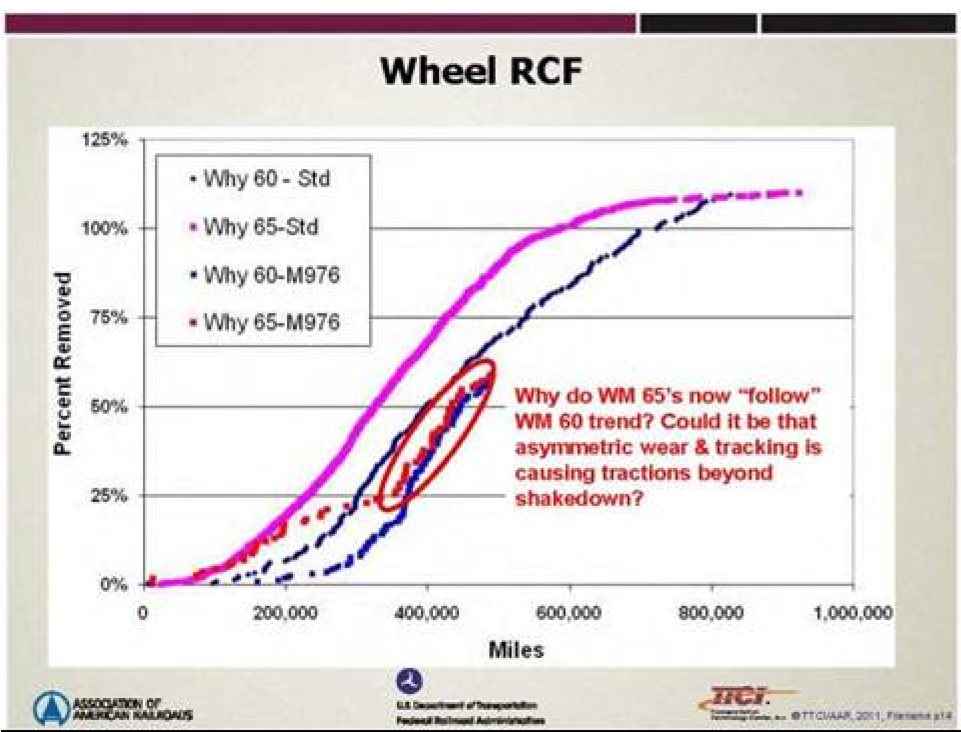
Wheel RCF
Why 60 - Std
Why 65-Std
Why 60-M976
Why 65-M976
Why do WM 65's now "follow" WM 60 trend? Could it be that asymmetric wear & tracking is causing tractions beyond shakedown?
Percent Removed
125%
100%
75%
50%
25%
0%
0
200,000
400,000
600,000
800,000
1,000,000
Miles
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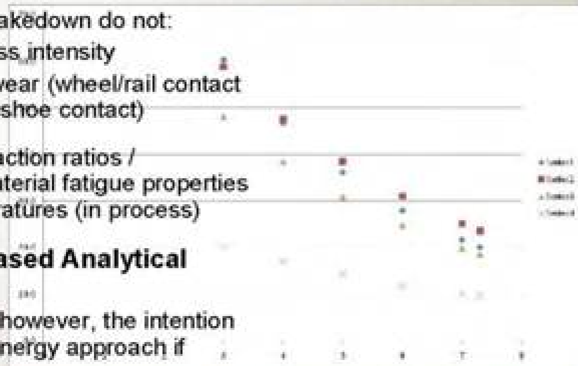
Wheel RCF

- **Thermal Mechanical Fatigue (TMS):**
  - **Shakedown-based Analytical Tools:**
    - Way Forward:
      - Counts above shakedown do not:
        - Account for stress intensity
        - Accommodate wear (wheel/rail contact & wheel / brake shoe contact)
      - Relate surface traction ratios / shakedown to material fatigue properties at various temperatures (in process)
  - **Energy (T-gamma)-based Analytical Tools:**
    - No progress to date; however, the intention is to incorporate an energy approach if possible



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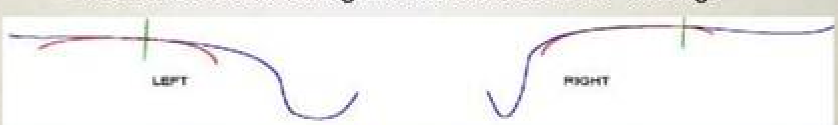
Wheel RCF

- **Wear**
  - Wheel / Rail Contact
    - Tread contact appears minimal for mileages up to 450,000; however this needs quantification
    - Flange wear significant on Eastern railroads & appears significant in association with asymmetric wheel tread wear
  - Wheel / Shoe Contact
    - Appears to be significant beyond 400,000 miles in Western service & appears to be associated with:
      - Asymmetric brake rigging
      - Insufficient lateral guidance of the shoe relative to the wheel tread
    - Considered to be a significant source of RCF damage



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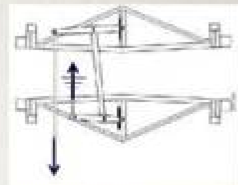
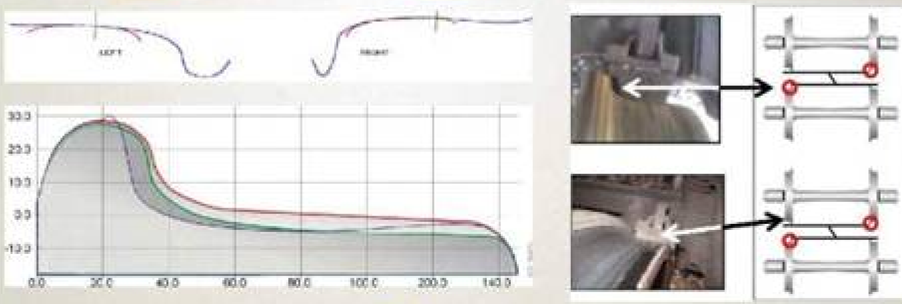
Wheel RCF

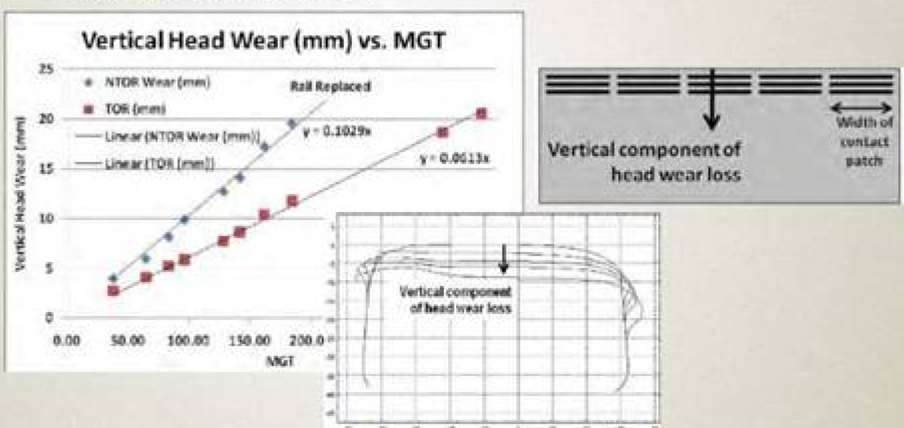
- **Wear**
  - Asymmetric Wheel Wear





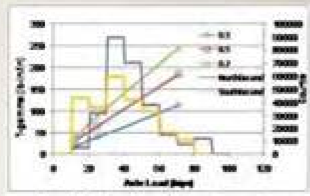
Rail RCF

- **Wear:**
  - Vertical head wear on the low rail can be quantified / predicted
  - Illustrates benefits of TOR



Rail RCF

- **Wear:**
  - Comparison: actual vs. predicted wear is consistent using an energy approach
  - Based on measured vertical load spectrum & NUCARS modeling
  - Accounts for top-of-rail friction control
  - Measured low rail L/V data for the curves is being analyzed to understand the role of truck "outliers" in wear performance



Typical vertical load spectrum

	Tehachapi TOR +GL	Tehachapi GL	East Meg TOR + GL	NS GL
Curvature (degree)	10	10	10.5	6
MGT	339	184	230	65
Wear (mm²/MGT)	2.814	4.149	0.5049	1.246
Theoretical / Measured	0.96	1.05	1.17	0.98
Rail Steel Ke-BHN	< 80ksi 400BHN >		80ksi 420BHN	70ksi 370BHN

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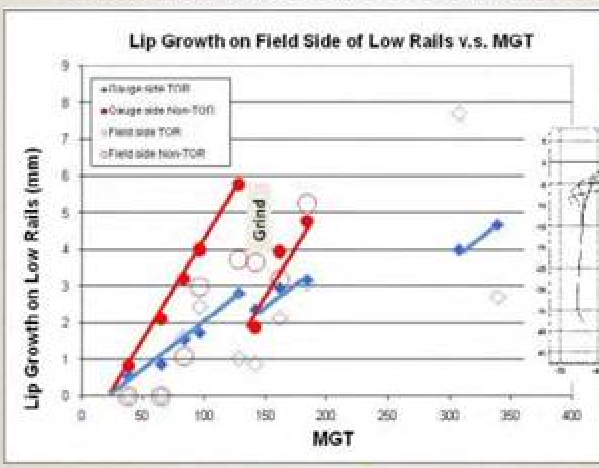
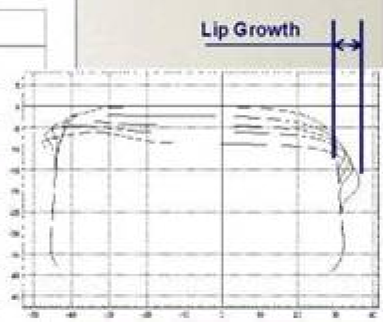
Rail RCF

- **Material Flow**
  - Material flow (lip growth) on the low rail can be quantified / predicted





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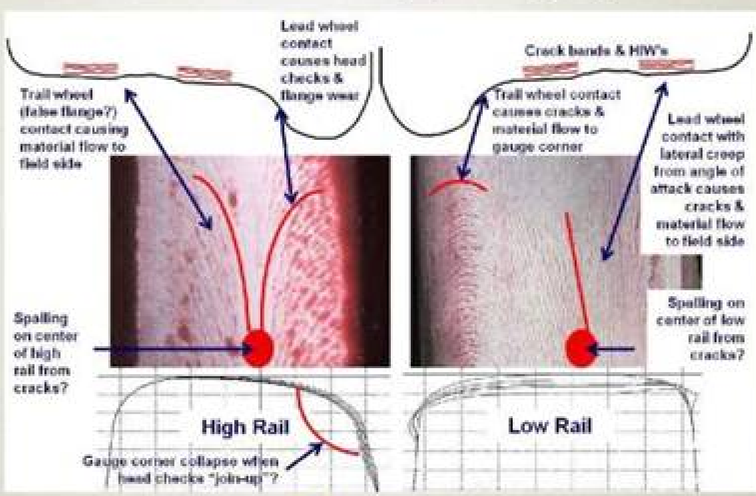
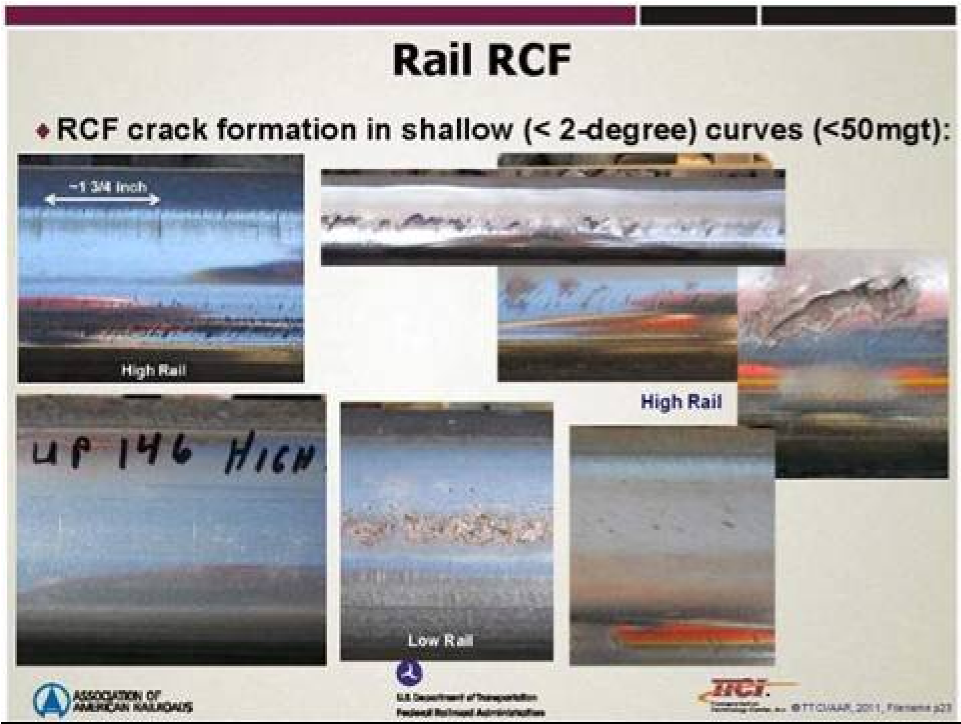
Rail RCF

- **Crack Formation:**
  - Crack direction indicates dominant creepage
  - Initiation remains difficult to quantify
  - Freight environment is variable:
    - Profiles
    - Lateral & vertical loads
    - Truck condition

Rail RCF

- **RCF crack formation in sharp (> 5-degree) curves:**




Rail RCF
RCF crack formation in shallow (< 2-degree) curves (<50mgt):
~1 3/4 inch
High Rail
UP 146 HIGH
Low Rail
High Rail
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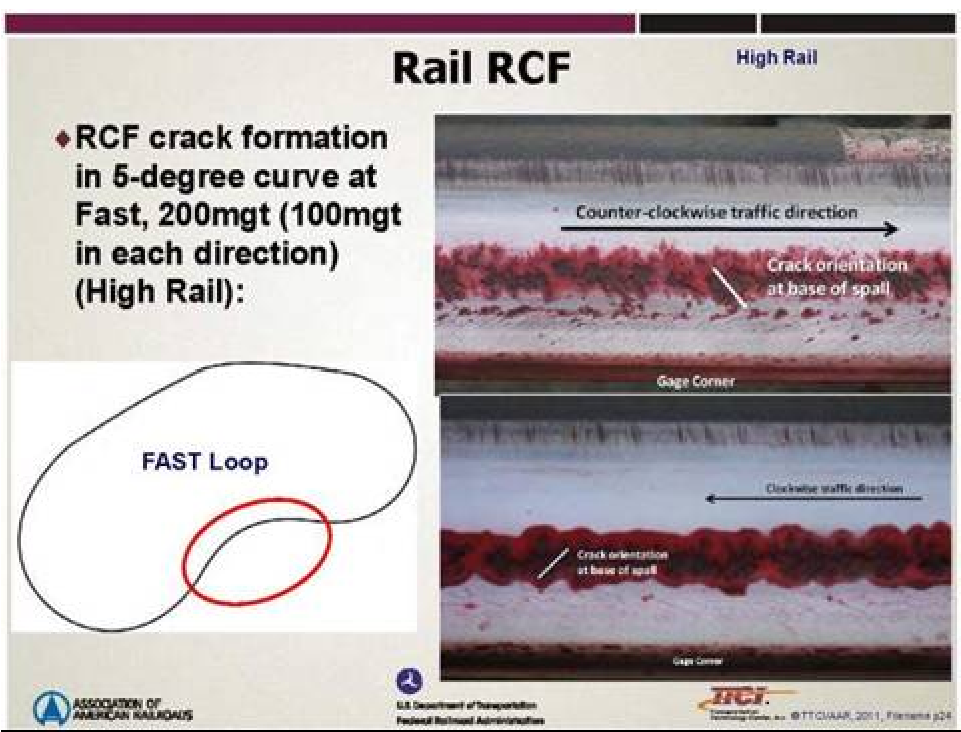
Rail RCF
High Rail
RCF crack formation in 5-degree curve at Fast, 200mgt (100mgt in each direction) (High Rail):
Counter-clockwise traffic direction
Crack orientation at base of spall
Gage Corner
Clockwise traffic direction
Crack orientation at base of spall
Gage Corner
FAST Loop
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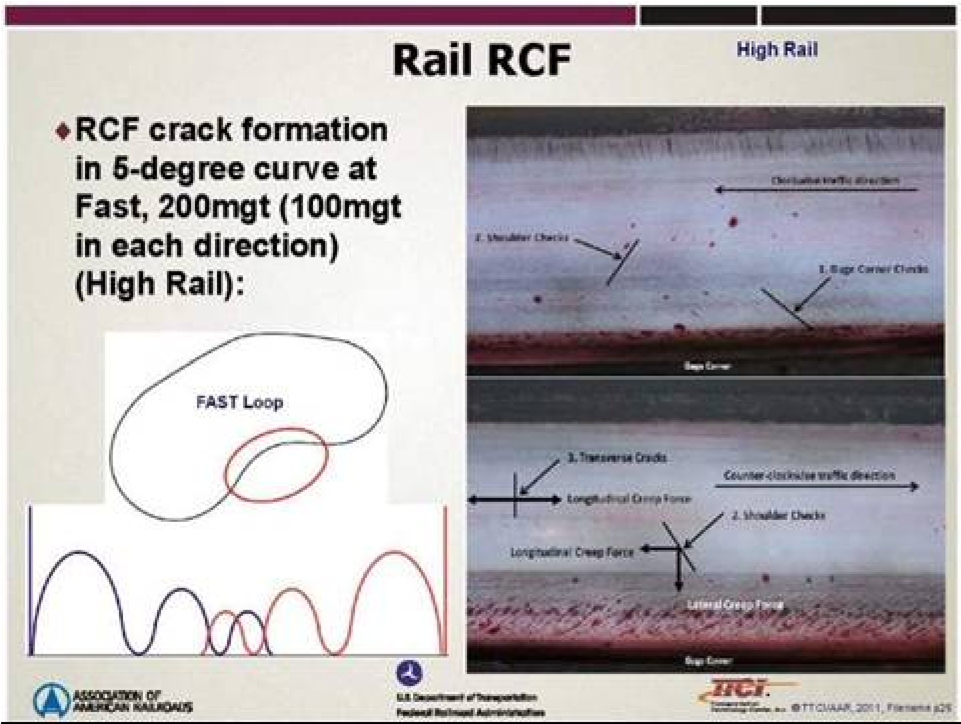
Rail RCF
High Rail
♦RCF crack formation in 5-degree curve at Fast, 200mgt (100mgt in each direction) (High Rail):
FAST Loop
3. Transverse Cracks
Longitudinal Creep Force
Counter-clockwise traffic direction
2. Shoulder Checks
Longitudinal Creep Force
Lateral Creep Force
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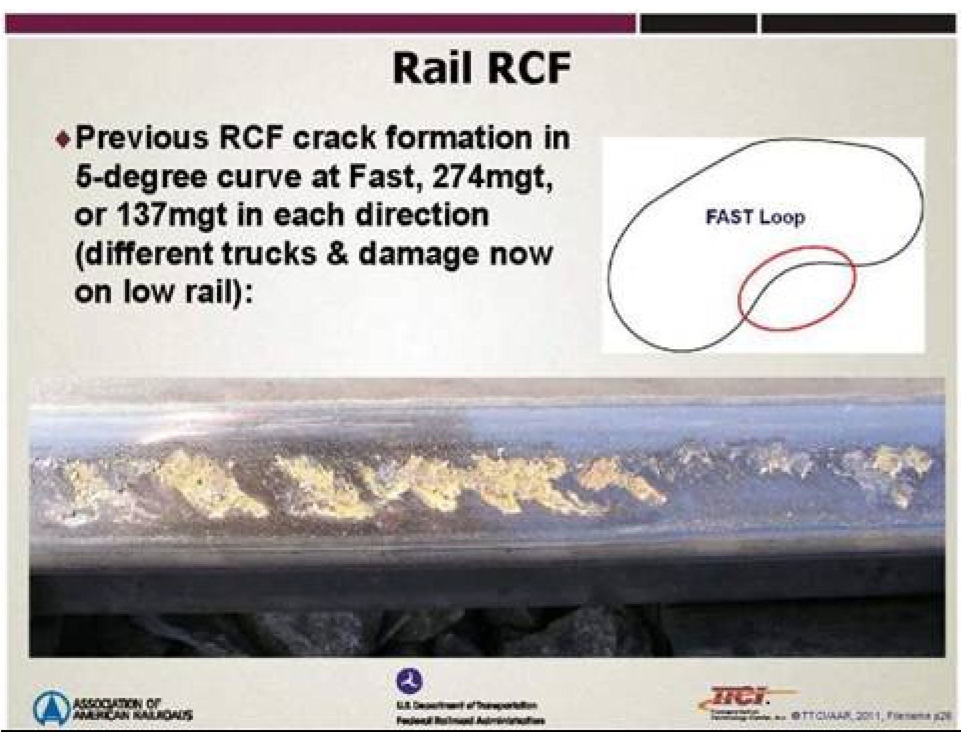
Rail RCF
♦Previous RCF crack formation in 5-degree curve at Fast, 274mgt, or 137mgt in each direction (different trucks & damage now on low rail):
FAST Loop
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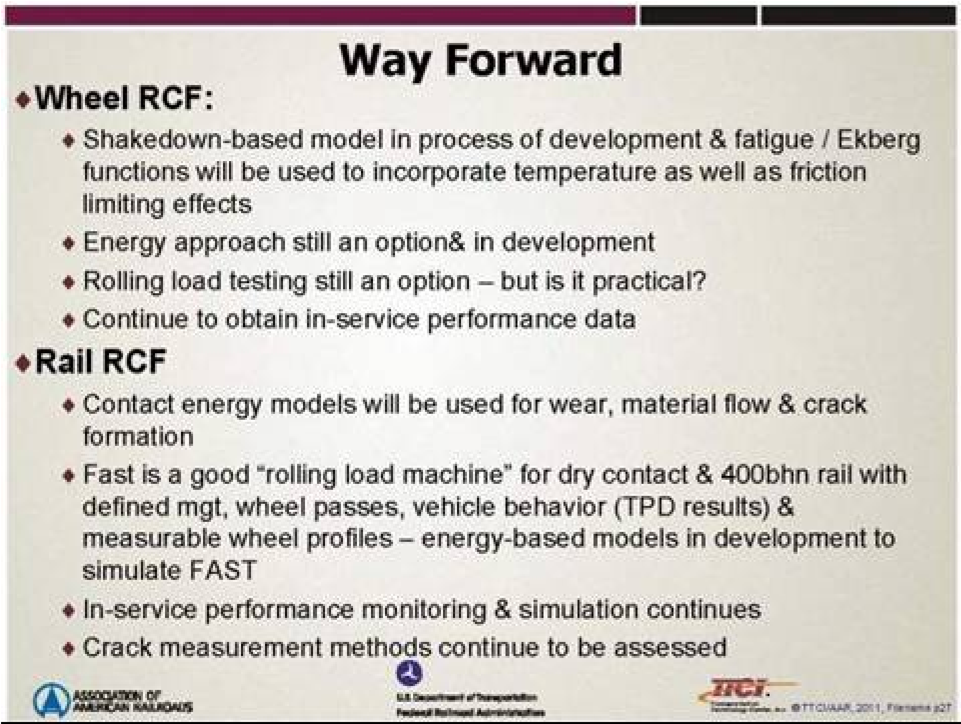
Way Forward
Wheel RCF:
Shakedown-based model in process of development & fatigue / Ekberg functions will be used to incorporate temperature as well as friction limiting effects
Energy approach still an option& in development
Rolling load testing still an option – but is it practical?
Continue to obtain in-service performance data
Rail RCF
Contact energy models will be used for wear, material flow & crack formation
Fast is a good "rolling load machine" for dry contact & 400bhn rail with defined mgt, wheel passes, vehicle behavior (TPD results) & measurable wheel profiles – energy-based models in development to simulate FAST
In-service performance monitoring & simulation continues
Crack measurement methods continue to be assessed
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Rolling contact fatigue in wheels and rails: Australian heavy haul operations

Peter Mutton
Institute of Railway Technology, Monash University

Ajay Kapoor
Swinburne University of Technology

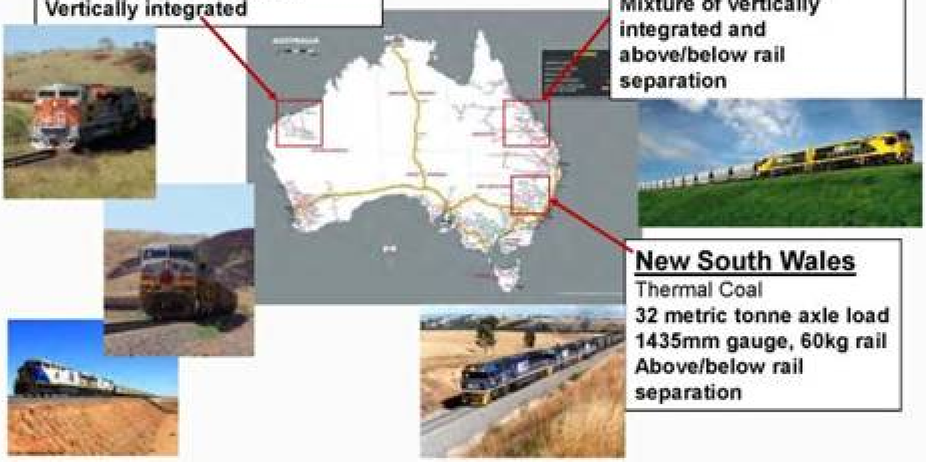
Outline

- Australian heavy haul rail systems
  - Overview of haulage operations
  - Wheel-rail interface: previous developments
- Rolling contact fatigue damage
  - Wheels
  - Rails
  - Rail welds
- Current issues and challenges
- Research activities
- Acknowledgements

Australian heavy haul today

Pilbara
Iron Ore
35-40 metric tonne axle loads
1435mm gauge, 68kg rail
Vertically integrated

Queensland
Metallurgical Coal
28 metric tonne axle load
1067mm gauge, 60kg rail
Mixture of vertically integrated and above/below rail separation



New South Wales
Thermal Coal
32 metric tonne axle load
1435mm gauge, 60kg rail
Above/below rail separation

Wheel-rail interface

- Modified (wear-adapted) wheel and rail profiles to minimise wheel flange/rail gauge face wear
- Forged multi-wear wheels
- Heat treated rail grades
- Preventative rail grinding

- Iron ore systems
  - Improved alignment for new track construction
  - Increased use of hypereutectoid rail steels
  - No gauge face lubrication in high degree (400-900m radius) curves
  - Micro-alloyed (360-400HB) wheel grades
- Coal systems
  - Extensive use of gauge face lubrication

FRA/TTCI Workshop on Rolling Contact Fatigue: July 2011

Rolling contact fatigue damage: Wheels

Iron Ore systems

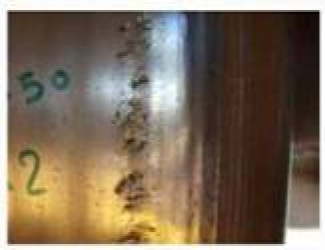
- Rim shelling ("shattered rim") defects
- Major problem in mid-1990's
- Defect initiation
  - Segregation/Micro-porosity in lower rim
- *Eliminated* through:
  - New wheels
    - Tighter wheel quality requirements
      - Reduced maximum discontinuity size (1mm FBH equivalent reflectivity)
    - Pre-qualification of wheel suppliers
      - Cleanliness assessment using phased array ultrasonic testing
  - Existing wheel fleet
    - Ultrasonic testing prior to reprofiling

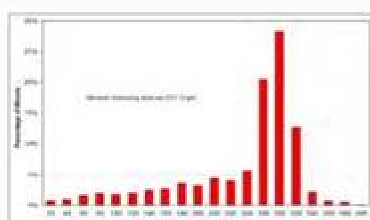
FRA/TTCI Workshop on Rolling Contact Fatigue: July 2011

Rolling contact fatigue damage: Wheels

Iron Ore systems

- Develops in high mileage wheels due for reprofiling
  > 200,000-250,000 km @ 37tonne axle loads
- Defect initiation due to plastic deformation and ratcheting failure at tread surface
- Addressed through:
  - Implementation of micro-alloyed wheel grades
  - Wheel maintenance
    - Reprofiling at ~200,000-250,000km
    - Limit tread hollowing to 3-4mm
    - Minimise metal removal during machining





FRA/TTCI Workshop on Rolling Contact Fatigue: July 2011

Rolling contact fatigue damage: Rails

- Damage initiation due to plastic deformation and ratcheting failure at rail surface
- Currently main rail damage mode in high traction locations:
  - Reduced rail wear rates resulting from profile optimisation and use of higher strength rail steels
- Addressed through:
  - Preventative rail grinding strategies
    - Grinding intervals based on track alignment (curves/grades)
    - Minimum metal removal rates to control extent of cracking
  - Monitoring of rail surface condition
    - Increasing use of non-contact measurement systems

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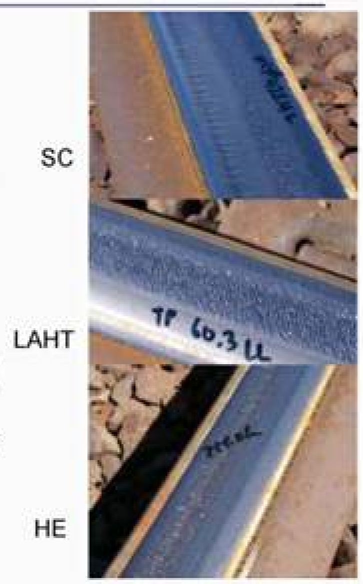
Rolling contact fatigue damage: Rails

- Influence of rail grade
  - Coarser crack spacing in older standard carbon (280HB) rails
  - Finer spacing, and increased tendency for surface spalling, in low alloy heat treated grades
  - HE grades exhibit much finer crack spacing, shallower crack depths
- Grinding requirements
  - Increased tendency for spalling if rail grinding inadequate
  - Increased depth of metal removal for HE rail grades



FRA/TTCI Workshop on Rolling Contact Fatigue: July 2011

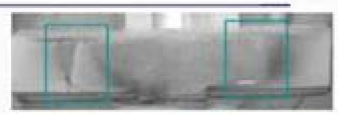
Rolling contact fatigue damage: Rails

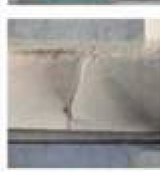
- Transverse defect (TD) development from surface-initiated RCF damage
  - Increased tendency to occur at higher rail head losses
  - Some rail grade effects apparent
  - Factors contributing to RCF crack propagation into transverse defect not clearly understood
    - Residual stress distribution
      - New vs worn condition
    - Longitudinal bending stresses in rail head

Rolling contact fatigue damage: Rail welds

- Localised RCF damage associated with aluminothermic welds
  - Increased cracking in softened zones, due to reduced material strength
  - Crack propagation down through rail head

- Localised spalling associated with flashbutt welds
  - Evident in some hypereutectoid rail grades
  - Damage can be exacerbated by extended rail grinding intervals achievable with HE rail grades





Issues and challenges

- Understanding and managing the risks associated with RCF versus wear as the main damage mode
- More effective means of quantifying surface-initiated RCF damage during rail inspection
  - Crack depth data is required for rail grinding
- Hypereutectoid rail grades
  - Influence of material properties on RCF initiation
  - Grinding requirements to offset reduced wear
- Development of transverse defects from RCF damage in rails
- Localised RCF damage associated with rail welds

Current research activities

- Rail utilisation and rail grinding strategies

  (Monash-IRT/Rio Tinto Iron Ore)

- Wear and RCF prediction in rail steels

  (Monash-IRT/Swinburne)

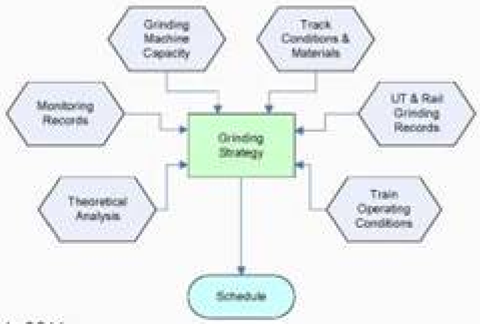
- RCF/transverse defect development

  (Monash/Swinburne)

Whole-of-Life Rail Model

Rail utilisation and rail grinding strategies

- Develop a revised rail grinding strategy pertaining to mainline heavy haul rail operations.
  - Control surface defects and maintain an ultrasonically testable rail condition
  - Realise investment in premium rail grades.
  - Improve rail maintenance effectiveness through better utilisation of grinding resources.



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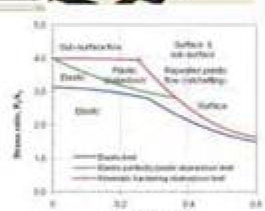
Rail utilisation and rail grinding strategies

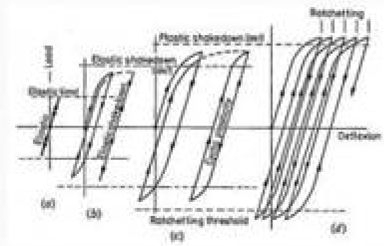
Five stage process:

1. Data acquisition and assessment.
2. Detailed simulation and analysis.
3. Preliminary strategy development.
4. Trial & monitoring.
5. Scheduling and implementation.



Wear and RCF prediction in premium rail grades

- Objective
  - Improved prediction of RCF damage for premium rail grades
  - Extend Whole-of-Life Rail Model to heavy haul conditions
- Activities
  - Preliminary mechanical testing of rail grades in parallel with in-service evaluation
  - Ratcheting tests on high strength rail steels under cyclic loading conditions
  - Computer simulation of material properties' effect on rail wear & cracking



Kapoor, K. and Johnson, K. L. (1994). Plastic ratchetting as a mechanism of metallic wear. Proc. R. Soc. Lond. A445, 367-381

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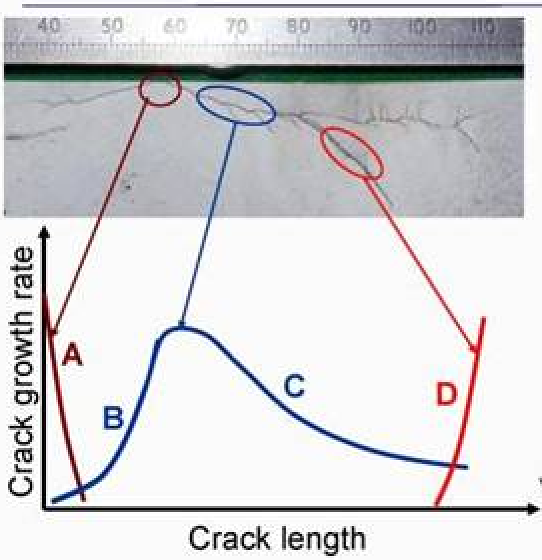
Whole-of-Life Rail Model



A: Crack initiation

B: As length increases, the crack propagation rate increases

C: However, long(ish) cracks move away from the contact stress field, and the rate of crack propagation drops

D: Finally the crack is driven by bending. Fast growth leading to rail break (TD).

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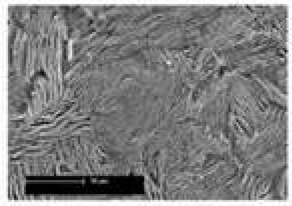
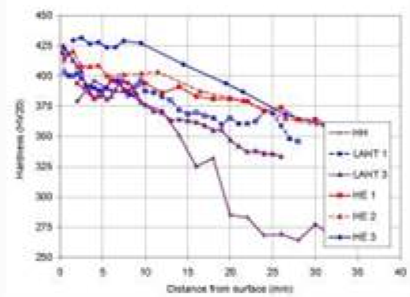
Assessment of heat treated rail grades

- Grades
  - Eutectoid
  - Low alloy
  - Hypereutectoid

Grade designation and nominal hardness	C	Mn	Si	Ni	Cr
HH (360HB)	0.75-0.80	0.80-1.00	0.25 max		
LAHT (350/380HB)	0.75-0.90	0.70-1.10	0.40-1.00	0.40-0.70	0.40-0.60
HE (400-420HB)	0.85-1.05	0.70-1.35	0.25-0.60	0.20-0.80	0.20-0.30



- Deformation behaviour
  - Hardness, strength and ductility measured throughout rail head



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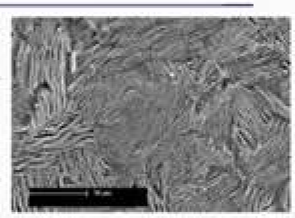
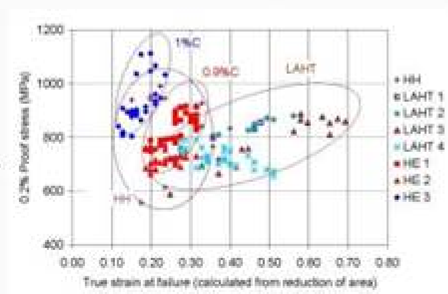
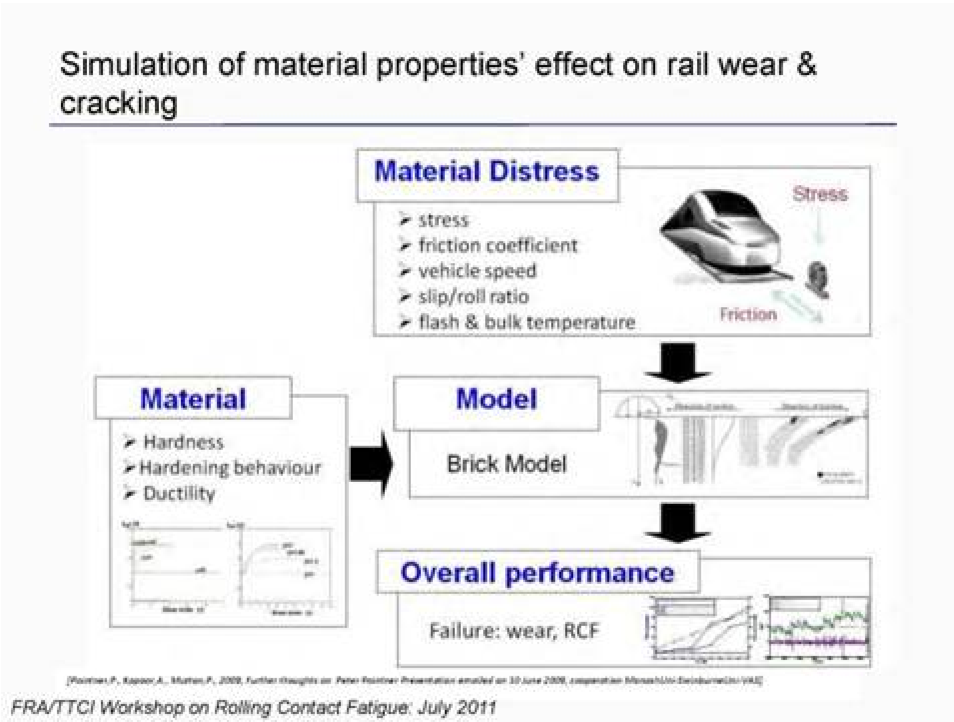


- Deformation behaviour
  - Hardness, strength and ductility measured throughout rail head
  - Relationship between proof stress/yield strength and ductility used to assess RCF tendency
  - Correlate with in-service behaviour





Simulation of material properties' effect on rail wear & cracking
Material Distress
stress
friction coefficient
vehicle speed
slip/roll ratio
flash & bulk temperature
Stress
Friction
Material
Hardness
Hardening behaviour
Ductility
Model
Brick Model
Overall performance
Failure: wear, RCF
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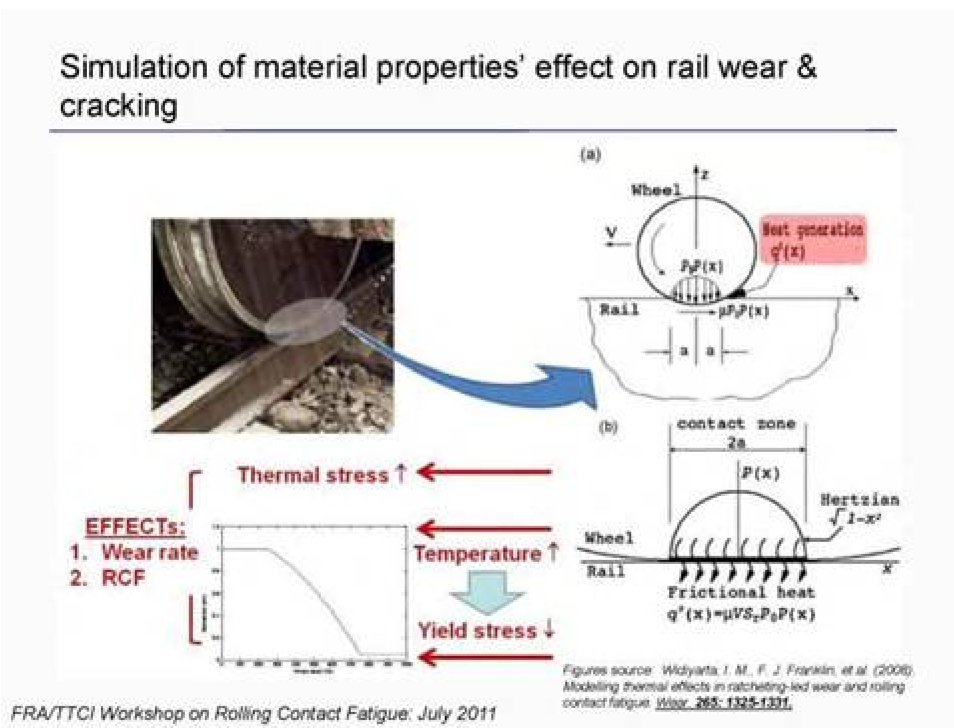

Simulation of material properties' effect on rail wear & cracking
(a)
Wheel
z
V
Heat generation
$q^f(x)$
$P_0P(x)$
Rail
$\mu P_0P(x)$
x
a
a
(b)
contact zone
2a
$P(x)$
Hertzian
$\sqrt{1-x^2}$
Wheel
Rail
x
Frictional heat
$q^f(x)=\mu VS_rP_0P(x)$
Thermal stress ↑
EFFECTs:
1. Wear rate
2. RCF
Temperature ↑
Yield stress ↓
Figures source: Widiyarta, I. M., F. J. Franklin, et al. (2008). Modelling thermal effects in ratcheting-led wear and rolling contact fatigue. Wear 265: 1325-1331.
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RCF/transverse defect development

- Aims
  - Predict conditions under which TD development occurs from RCF damage
  - Extend Whole-of-Life Rail Model approach to heavy haul conditions
  - Recommend rail wear limits for RCF-affected rail
- Activities to date
  - Measurement of rail stresses under service loading
  - Stress analysis to examine influence of wheel-rail contact conditions and rail head loss on bending stresses in rail head

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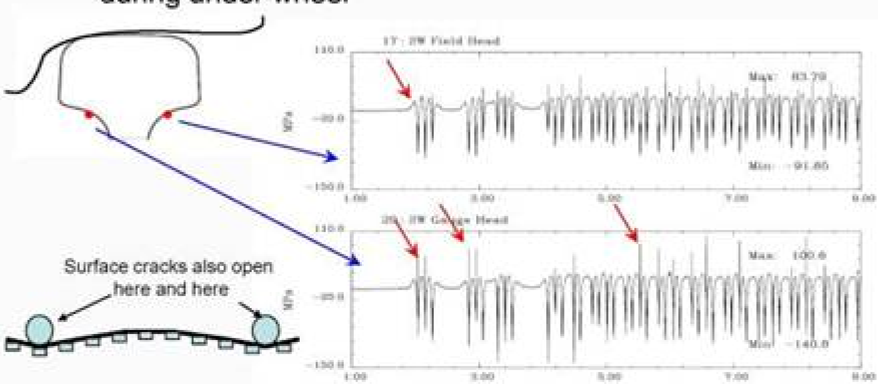
Rail head stresses under heavy haul conditions

- Longitudinal stresses, underhead radius
  - Small peak due to uplift ahead of/behind wheel passage
  - Increased tension associated with local response of head during under wheel



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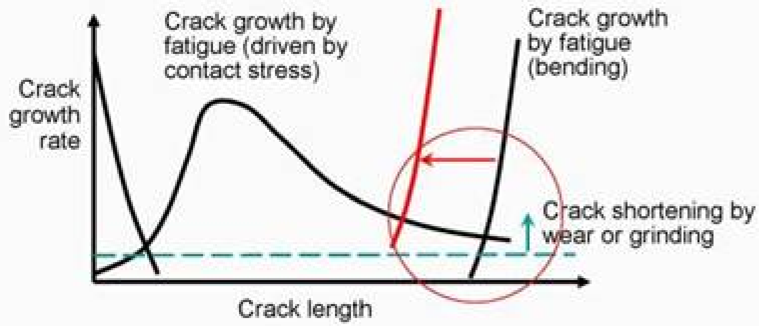
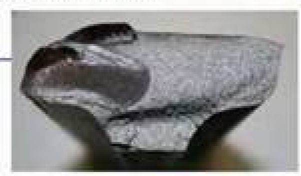
Effect of wear or grinding



Reduced wear rate moves the dotted line below the intersection and the crack does not get arrested

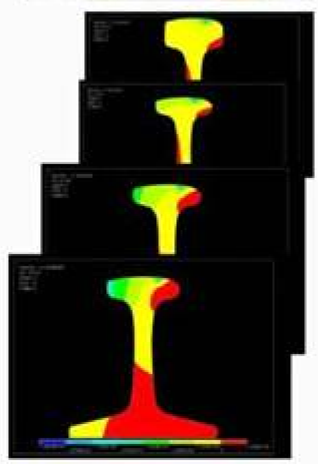
Increased bending stress in the railhead shifts the right hand curve to the left making it easier for the crack to turn down and grow by bending stresses.

Multi-axial fatigue analysis of worn rail under heavy haul conditions



Research approach

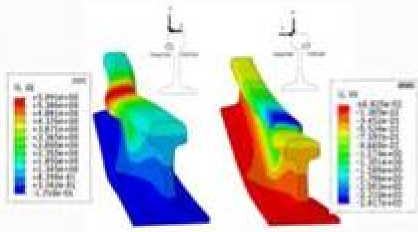
- FE modelling of gauge corner and underhead radius stresses in rail
- Investigate the effect of heavy haul operational parameters:
  - Magnitude and direction of loading
  - Position of contact patch.
  - Seasonal temperature variation
  - Worn rail profile
  - Foundation stiffness



Multi-axial fatigue analysis of worn rail under heavy haul conditions

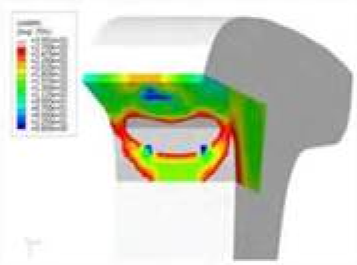
Results

- Mode I (tensile opening) behaviour due to local response of head has the potential to drive RCF (rolling contact fatigue) into TD's (transverse defects).
- Inward traction is more damaging.



Future work

- Multi-axial fatigue analysis and risk analysis for potential fatigue crack initiation at underhead radius based on predicted simulation results

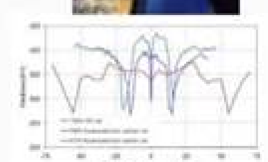


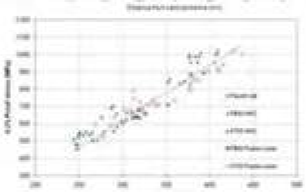
Behaviour of rail welds in wheel rail contact

(Proposed project)

Aims:

- To develop an improved methodology for predicting the behaviour of rail welds under the complex wheel-rail contact conditions that occur at welds
- Application of methodology to the design of improved rail welding procedures and weld maintenance strategies

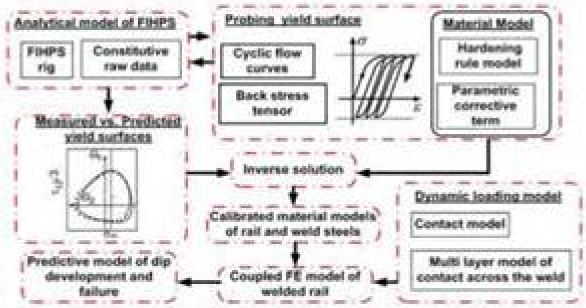




Behaviour of rail welds in wheel rail contact

Research approach

- *Experimentally generate data relevant to the deformation behaviour of the different regions of rail welds*
- *Employ the data in an experimental-analytical framework for predicting plastic deformation and surface fatigue in rail welds*
- *Sensitivity analysis for distribution of mechanical properties for the respective rail grades*
- *Calibrate parameters of the model for predicting accumulative strain in rail welds*
- *Develop a range of weld design guidelines to be adopted by the rail industry*



(FIHPS: Friction Induced High Pressure Shear)

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Acknowledgements

- Monash University
  - Darrien Welsby (IRT)
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  - Sagheer Ranjha
  - Iman Salehi

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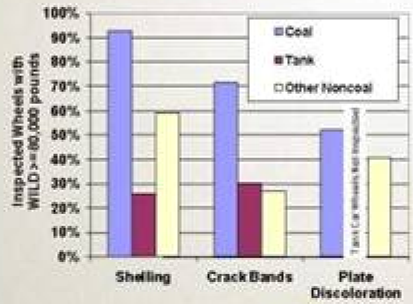
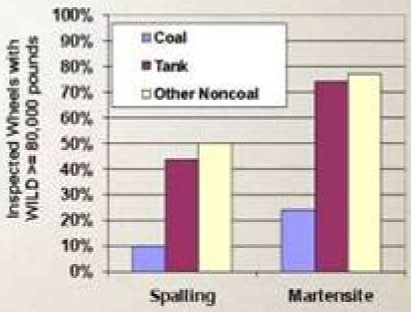
ASSOCIATION OF AMERICAN RAILROADS
U.S. Department of Transportation
Federal Railroad Administration
TTCI.
Transportation Technology Center, Inc.
Joint AAR/FRA Workshop
on Wheel & Rail Rolling Contact Fatigue in North America
Strategies to extend freight wheel life & eliminate failures in North America


Presentation Overview
♦ Wheel Shelling and Spalling
♦ Safety Issues
♦ Three Ways to Reduce Wheel Shelling
♦ Better Wheels
♦ Cooler Wheels
♦ Reduced Stress Environment
♦ Summary
♦ Way Forward
U.S. Department of Transportation
Federal Railroad Administration
TTCI.

Wheel Shelling Vs. Spalling

- Shells – due to fatigue (RCF and TMS)
- Spalls – due to martensite from sliding
- The overall wheel tread damage problem in North American freight operations is split about evenly between shells and spalls
- The type of wheel tread damage is often tied to the type of car and service: unit trains tend to have more shelling (heavy axle loads, high mileage service)





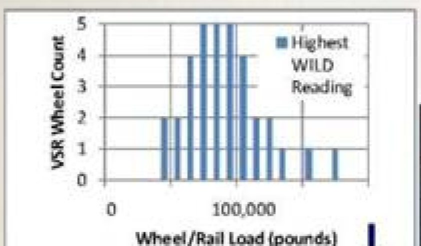
Shelling Progression Photos

- Photos show wheel shells developing as follows:
  1. Crack band appears outboard of tapeline
  2. Cracks join to form shells
  3. Shells grow inboard toward tapeline where contact with rail occurs on more regular basis

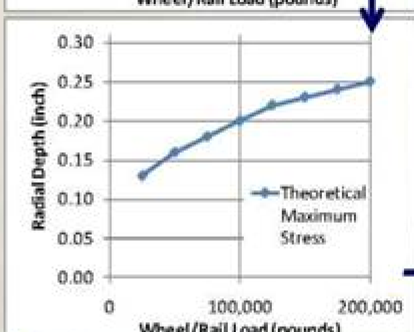
Safety Issues

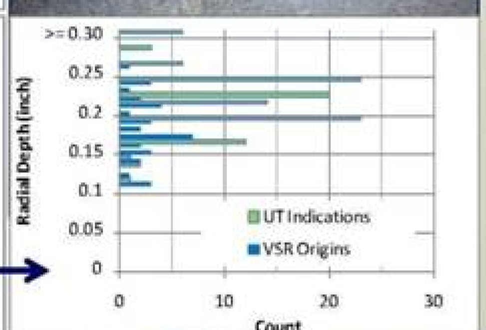
- Broken rim = 3rd in relation to all equipment accident causes
  - Shattered rim
  - Vertical split rim (VSR)
- Broken rim wheels frequently exhibit increased impact loads prior to failure

VSR Impact Loads



- Horizontal layer below tread surface
  - Depth of maximum stress dependent on wheel/rail load and contact conditions
  - Helps explain depth of UT indications and VSR origins





Ways to reduce wheel shelling:

1. **Improve wheel resistance to fatigue**
   - High performance wheel steels – yield strength, cleanliness, hardness, microstructure
2. **Control heat input, avoid TMS**
   - Improved brake performance – distribute brake heat load evenly to all wheels in the train
3. **Reduce wheel/rail tangential forces**
   - Improved trucks and truck/carbody interactions
   - Wheel/rail friction control
   - Wheel/rail profiles
   - Speed/curvature/superelevation relationship

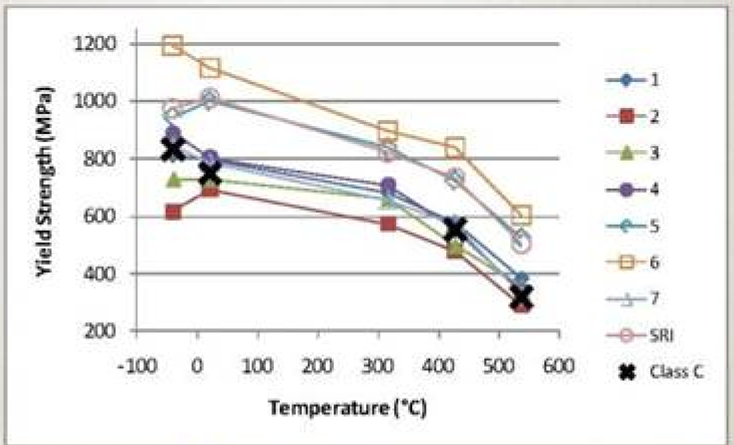
- **<u>This presentation to focus on first 2 issues</u>**

1. Improve Wheel Resistance to Fatigue

- **High performance wheel steels**
  - Improved alloys, stronger, cleaner, harder
- **Current testing of high performance wheel steels**
  - 8 types currently under test:
    - Griffin (USA)
    - OneSteel (Australia) x 2
    - Lucchini RS (Italy)
    - Sumitomo (Japan)
    - Standard Steel (USA)
    - SRI
    - Valdunes (France)
  - Lab testing completed in 2009
    - Wheel type 6 yield strength 40-50 ksi > Class C
    - Wheel type 5 and SRI wheel, YS 30 ksi > Class C
  - Durability test at FAST and in revenue service underway

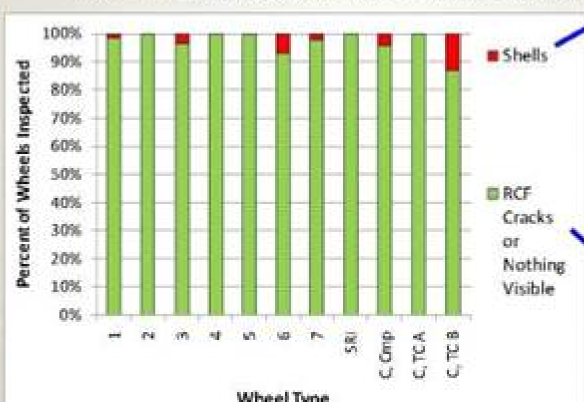
Laboratory Test Results

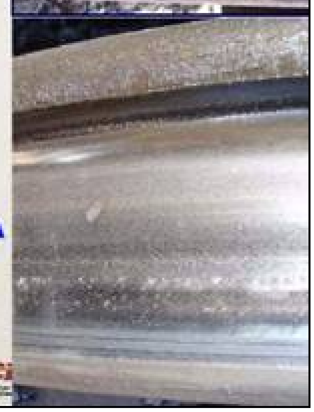
- Type 6 has bainitic microstructure; all others pearlitic
- Shakedown theory predicts that stronger steel can sustain higher traction loads without accumulating fatigue damage



High Performance Wheel Steels

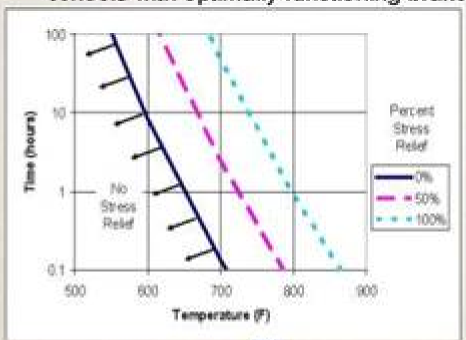
- **Preliminary Revenue Service Test Results (100,000 miles)**
  - Wheels performing fine so far
  - AAR Class C with tread conditioning brake shoe "B" showing more RCF cracks and shells

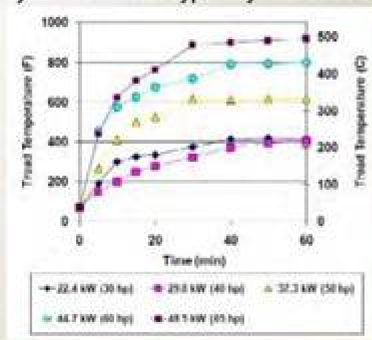




2. Control Heat Input, Avoid TMS

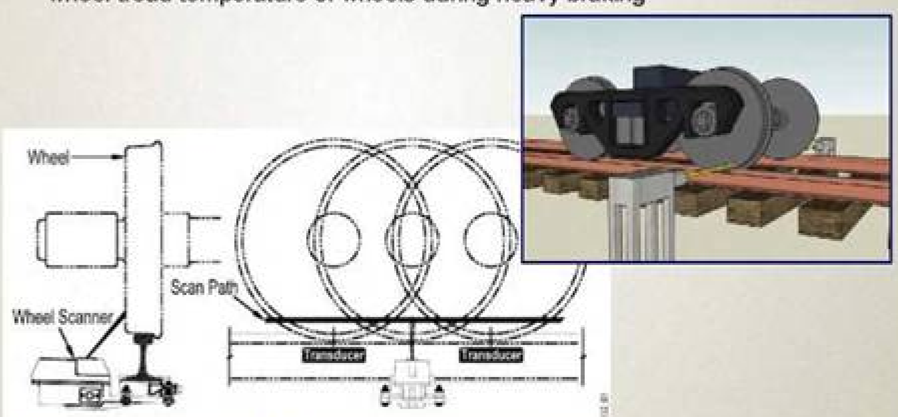
- **Maximum acceptable operating tread temperature to avoid TMS is approximately 600°F**
  - Steel properties degrade (yield strength)
  - Beneficial compressive residual hoop stresses are relieved
    - Sines fatigue calculation shows that wheels are far more prone to shelling in the absence of compressive residual stress
  - Wheels with optimally functioning brake systems do not typically reach 600°F





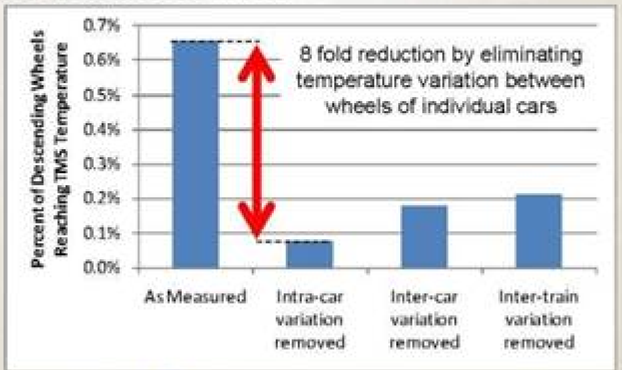
Wayside Wheel Temperature Measurement

- **WTD specifics**
  - Scanners are located perpendicular to the rail
  - Scanners view the field side of passing wheels, about 4 inches above top of rail
  - WTDs typically report values which are approx 100°F to 150°F cooler than the wheel tread temperature of wheels during heavy braking



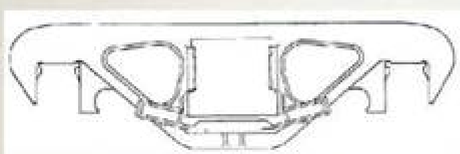
TMS Reduction Through Improved Braking

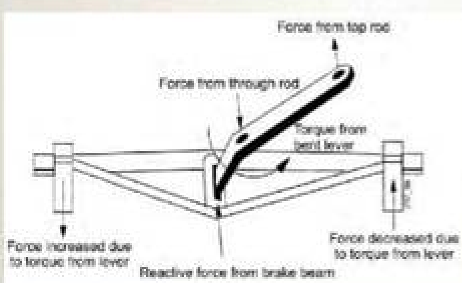
- Goal is similar brake work load at all wheels in the train
- Large variation currently exists between wheel temperatures in individual cars due to
  - Variation in brake shoe force
  - Variation in brake shoe friction

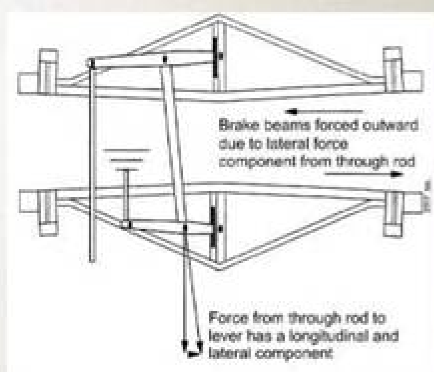


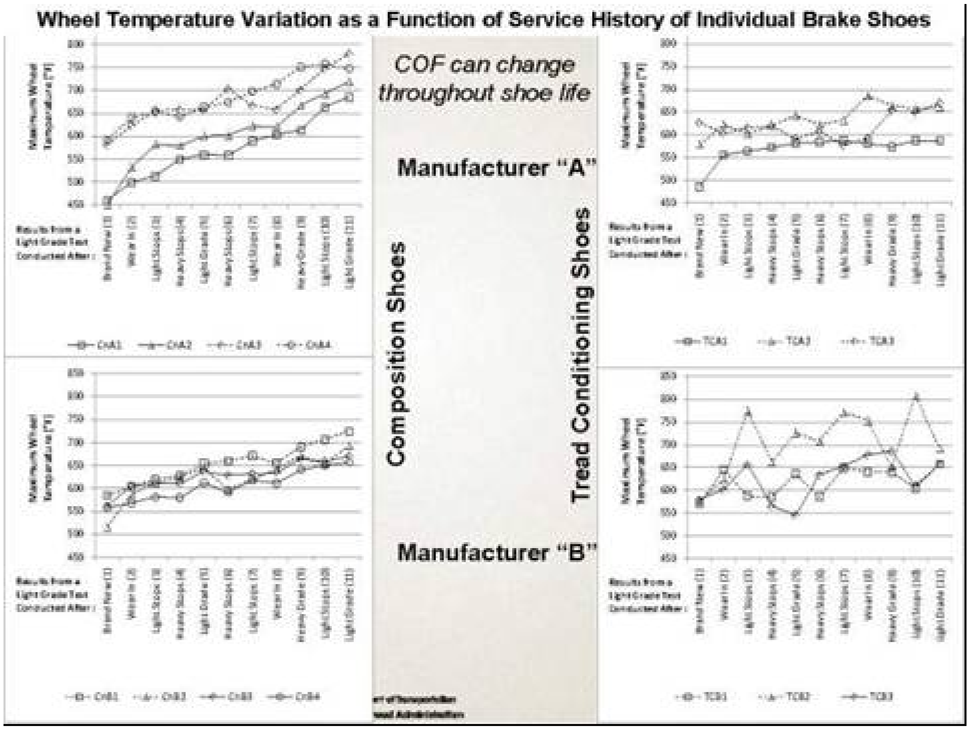
Sources of Brake Shoe Force Variation

- Typical brake shoe force variation between individual wheels of a car is 50 to 500 pounds under dynamic conditions



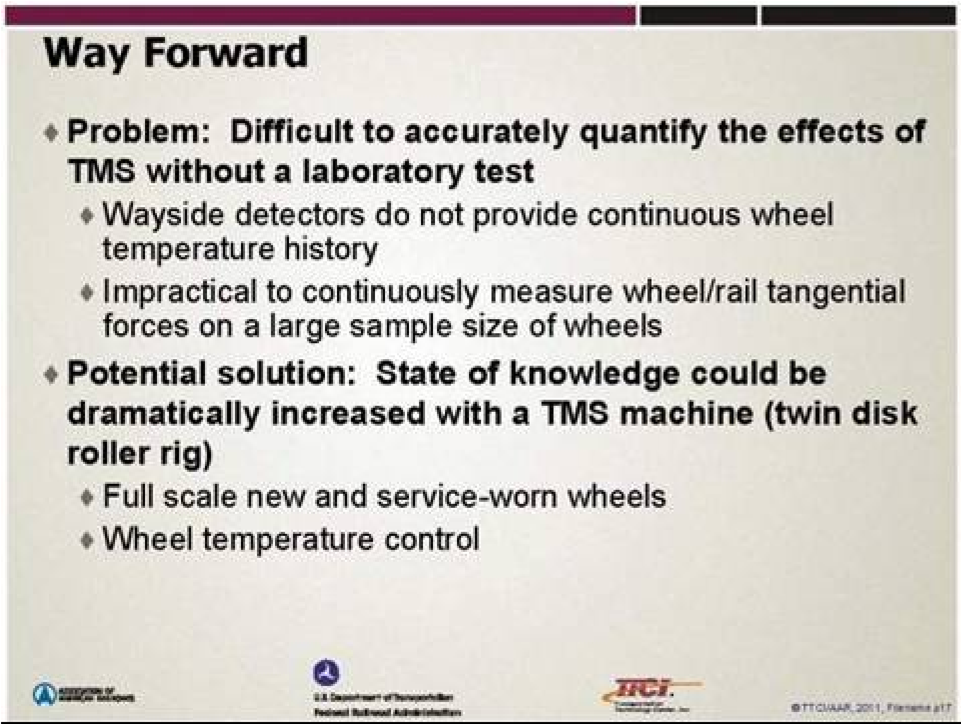






Summary

- Wheel shelling from RCF is a major issue in NA freight operations
- 8 types of high performance wheels are currently under test in revenue service and at FAST
  - Lab tests showed some wheels have substantially higher yield strength than AAR Class C wheels
  - All wheel types performing well at 100,000 miles
- Wheels > 600°F are subject to TMS
  - Relief of beneficial residual stress and reduction in yield strength
  - Variation in brake shoe force and brake shoe COF

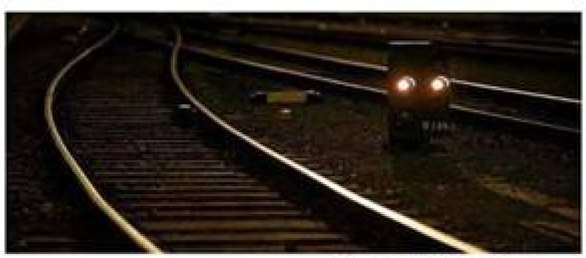

Way Forward
Problem: Difficult to accurately quantify the effects of TMS without a laboratory test
Wayside detectors do not provide continuous wheel temperature history
Impractical to continuously measure wheel/rail tangential forces on a large sample size of wheels
Potential solution: State of knowledge could be dramatically increased with a TMS machine (twin disk roller rig)
Full scale new and service-worn wheels
Wheel temperature control

Use of a rolling load machine to simulate & predict RCF

Richard Stock, Technical Customer Service
voestalpine Schienen GmbH, Austria

Outline

- voestalpine
- Damage mechanisms
- Rail-Wheel Test rig
- Tests with "dry" and "Friction Modifier" contact conditions
- Track Test results
- Differences Track vs. Rig
- Innotrack – European Rail Grade Selection
- Squats
- Outlook



In the heart of Austria (Europe)

voestalpine
ONE STEP AHEAD.

voestalpine Schienen GmbH in Leoben/Austria

- Europe´s leading rail manufacturer
- Variety of approx. 80 rail sections in length up to 120m (394ft)
- Special rail sections (grooved, tongue and guard rails)
- Complete product range available in HSH®-quality (Premium quality)
- JIT-Delivery of Ultra-long Rails (120m or 394ft)
- Staff: 530; Output: 500.000 t of rails

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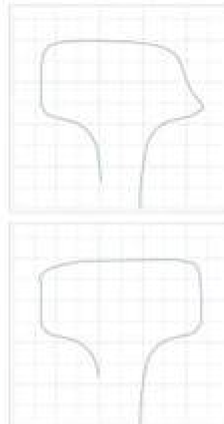
Damage Mechanism - Wear

Sharp curves | *Medium curves* | *Wide curves/ tangent*



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Damage Mechanism - Head Checks

Sharp curves | *Medium curves* | *Wide curves/ tangent*

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Damage Mechanism - Squats

Sharp curves | *Medium curves* | *Wide curves/ tangent*

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Rail - Wheel Test Rig

- Full Scale 1:1
- Real contact and load conditions
- Variation of friction conditions
- Simulation of surface defects
- Reproducibility
- Fast Test results
- Data recording

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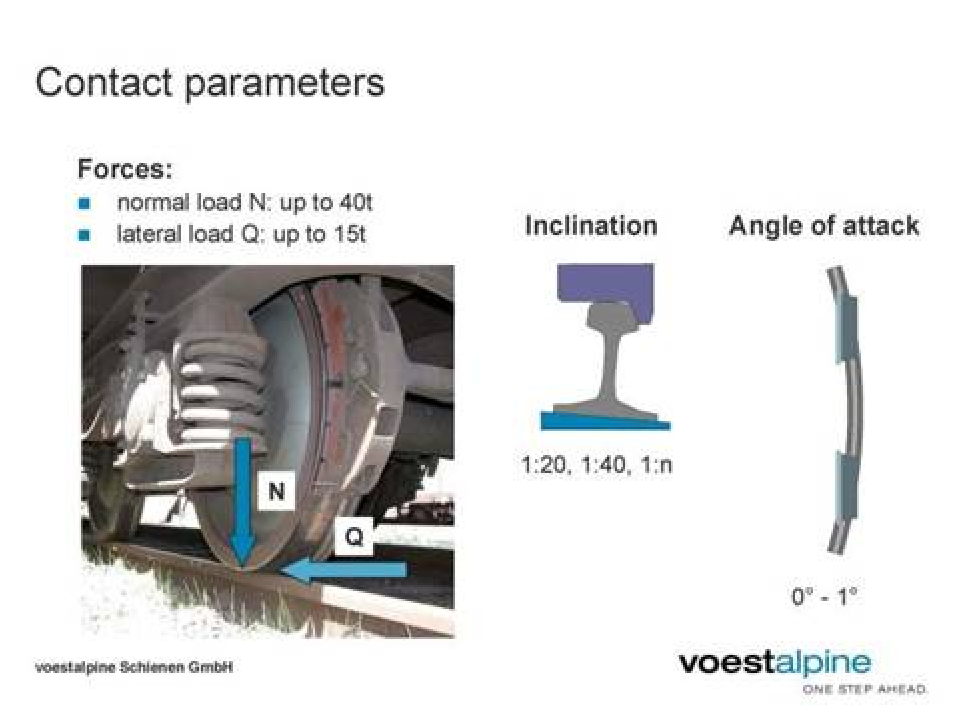
Contact parameters
Forces:
normal load N: up to 40t
lateral load Q: up to 15t
N
Q
Inclination
1:20, 1:40, 1:n
Angle of attack
0° - 1°
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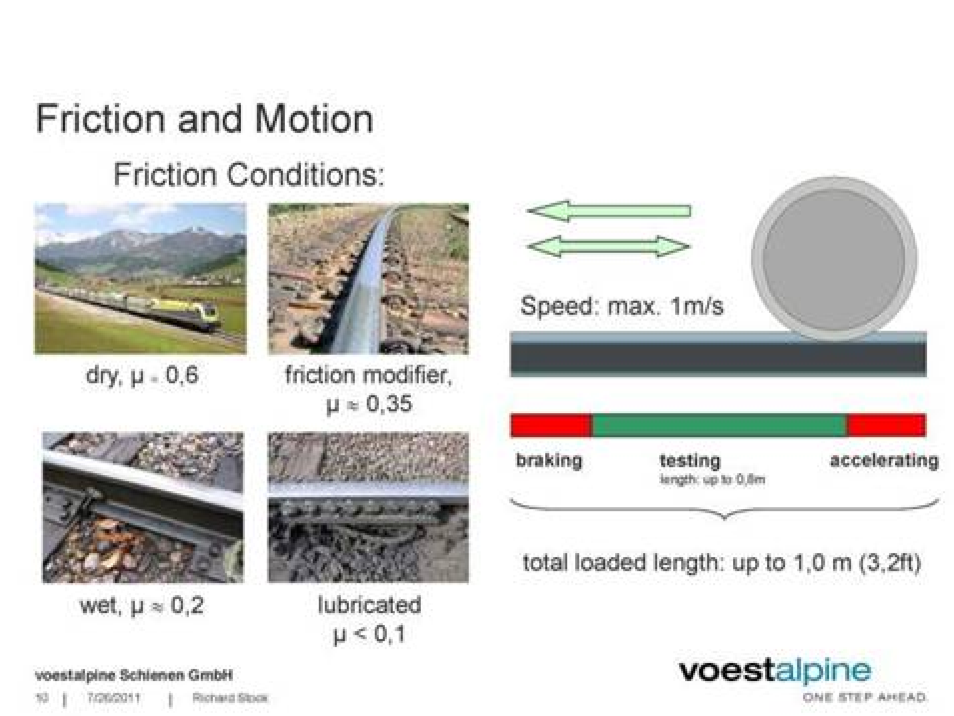
Friction and Motion
Friction Conditions:
dry, μ ≈ 0,6
friction modifier, μ ≈ 0,35
wet, μ ≈ 0,2
lubricated μ < 0,1
Speed: max. 1m/s
braking
testing
length: up to 0,8m
accelerating
total loaded length: up to 1,0 m (3,2ft)
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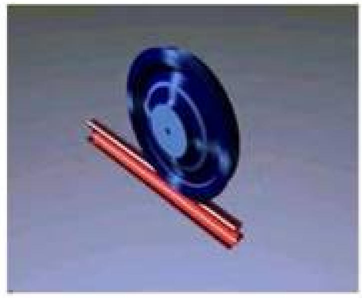
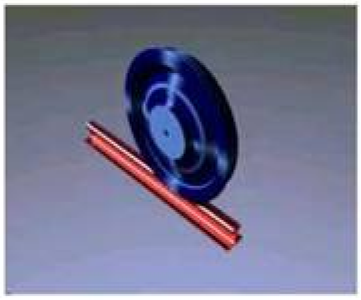
Motion types

V_{max} = 1.0 m/s

25k cycles/day

Bi-directional traffic





Uni-directional traffic

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Steel grade comparison

Steel grades according to prEN 13674-1 and AREMA									
	Chemical composition (%)						Mechanical data		
grade	C	Si	Mn	P_{max}	S	Cr	R_m [Ksi] min	Ellong. [%] min	Hardness [HB]
R260	0.62-0.80	0.15-0.58	0.70-1.20	0.025	0.08-0.025		127	11	260-300
SS	0.74-0.84	0.10-0.60	0.75-1.25	0.020	0.020	0.25	120	10	300
LA	0.71-0.82	0.10-0.50	0.80-1.10	0.020	0.020	0.25-0.40	142	10	300
IH	0.71-0.82	0.10-1.00	0.70-1.25	0.020	0.020	0.40-0.70	147	8	325
R350HT	0.72-0.80	0.15-0.58	0.70-1.20	0.020	0.025		170	10	350-390
R350LHT	0.72-0.80	0.15-0.58	0.70-1.20	0.020	0.025	<0.30	170	10	350-390
HH	0.74-0.84	0.10-0.60	0.75-1.25	0.020	0.020	0.25	171	10	370
LH	0.71-0.82	0.10-1.00	0.70-1.25	0.020	0.020	0.40-0.70	171	10	370
R370CrHT	0.70-0.82	0.40-1.00	0.70-1-10	0.020	0.020	0.40-0.60	185	10	370-410
R400HT	0.90-1.00	0.20-0.40	1.20-1.30	0.020	0.020	<0.30	185	10	400-440

Several hypereutektoid grades and Bainitic grades

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General Test Parameters

- Rail: 60E1 profile (132lb); R260, R350HT, R400HT and bainitic grade
- Wheel: Freight disc wheel, 920mm (3ft) diameter, UIC/ORE S1002 profile, R7
- Uni-directional running
- Vertical Load: 23t , Lateral Load: 4t, Longitudinal Load: 0t
- Angle of Attack: 0°
- Rail Cant: 0 → single point contact
- Dry and Friction Modifier (FM) friction conditions
  - FM tests in collaboration with LB Foster Friction Management (Kelsan)
  - FM Coverage: TOR, Gauge Corner and upper Gauge Face
  - FM Application: Spray application every 250 cycles
- Contact conditions selected from previous results to ensure formation of RCF defects within 100k wheel passes

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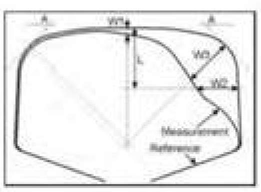
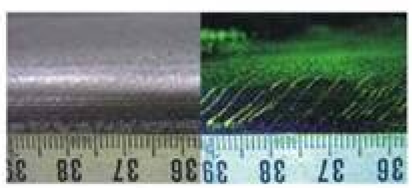
Test examinations





- Wear measurements with MiniProf
- Photo documentation
- Metallographic examinations

- Magnetic particle inspection
- Image analysis (cracks, plast. deformation)

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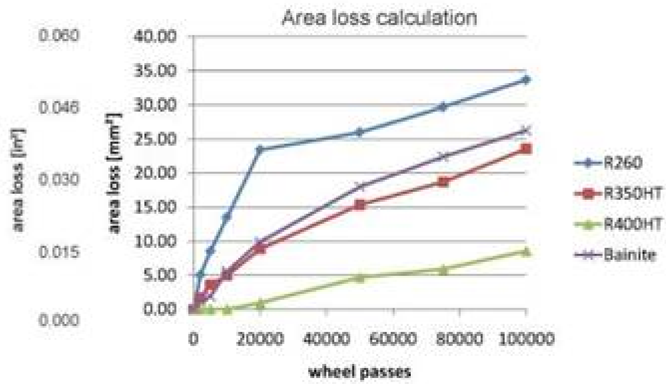
Wear Results

- Decreasing rail wear with increasing hardness
- Bainite located between R260 and R350HT



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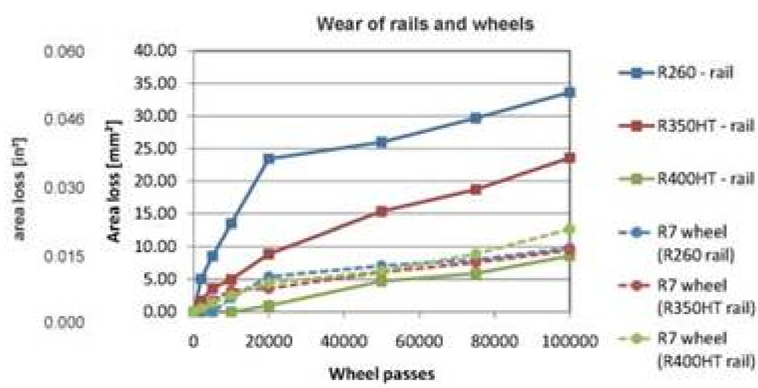
Wear results for wheels (R7 grade)



- Wheel wear stays on the same level despite increasing rail hardness (wheel represents the softer partner)

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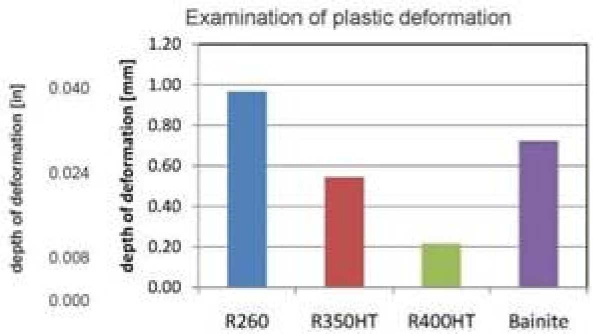
Plastic deformation

- Decreasing plastic deformation with increasing hardness (pearlite)
- Bainite located between R260 and R350HT



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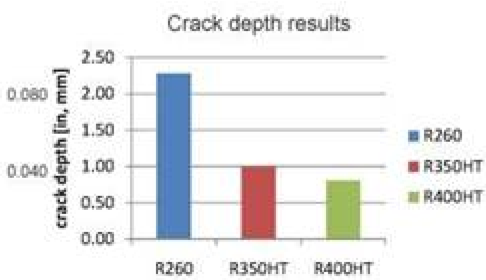
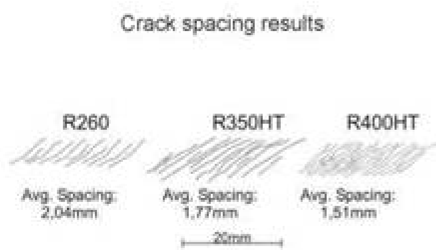
RCF results

- Decreasing crack depth and surface crack spacing with increasing pearlitic rail strength
- Bainite developed no cracks





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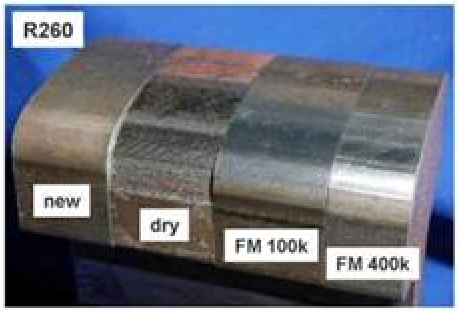
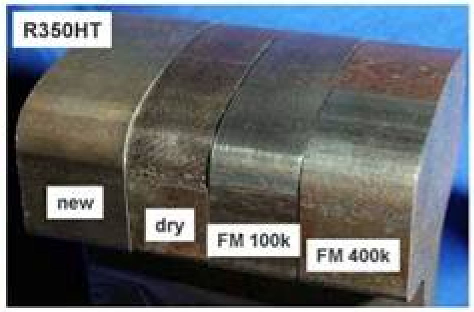
Tests with Friction Modifier





- Reduced wear due to FM application
- No Formation of Cracks under test rig conditions
- Reduced surface roughness

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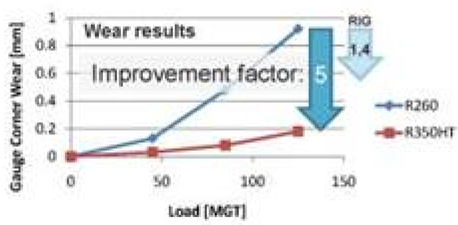
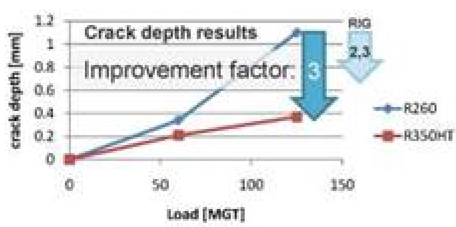
Track Test Results – Wear and RCF

- Mixed traffic conditions
- R = 1400m (1,25°)
- Rail grades R260 and R350HT
- Wear Results
  - Gauge Corner Wear
- Crack results
  - Measured by EC





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Differences Track vs. Test Rig

- Test rig:
  - Constant loading conditions – no dynamics, low speed (no dynamic defects)
  - Only one wheel – no wheelset
  - Same piece of rail in contact with same wheel
  - Closed environment – no environmental influences
  - Results in short time
- Track Test
  - Real Conditions (Vehicles, Profiles, Loads, Environment, etc…)
  - High degree of unknown parameters
  - Limited measurement / analysis possibilities during and at the end of the test
  - Test duration months / years

Track vs. Rig Results:
Absolute values differ but trends are comparable

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Innotrack – LCC based solution concepts

36 project partners…

- 11 infrastructure owners
- 11 railway industry companies
- 3 construction companies
- 8 universities

… from 11 countries

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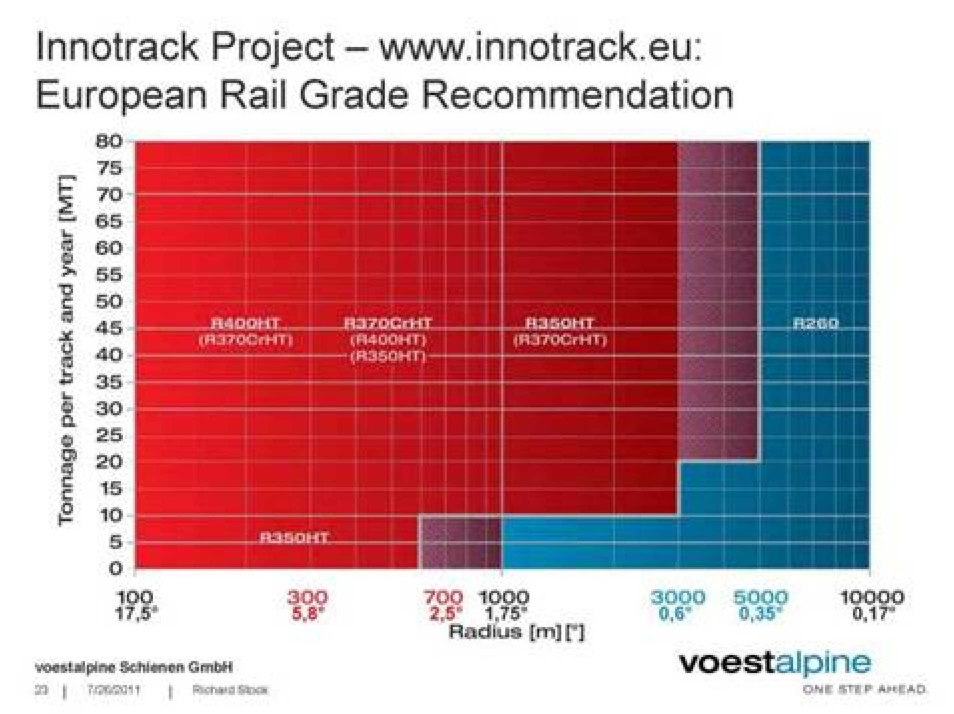

Innotrack Project – www.innotrack.eu:
European Rail Grade Recommendation
Tonnage per track and year [MT]
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
R400HT
(R370CrHT)
R370CrHT
(R400HT)
(R350HT)
R350HT
(R370CrHT)
R260
R350HT
100
17,5°
300
5,8°
700
2,5°
1000
1,75°
3000
0,6°
5000
0,35°
10000
0,17°
Radius [m] [°]
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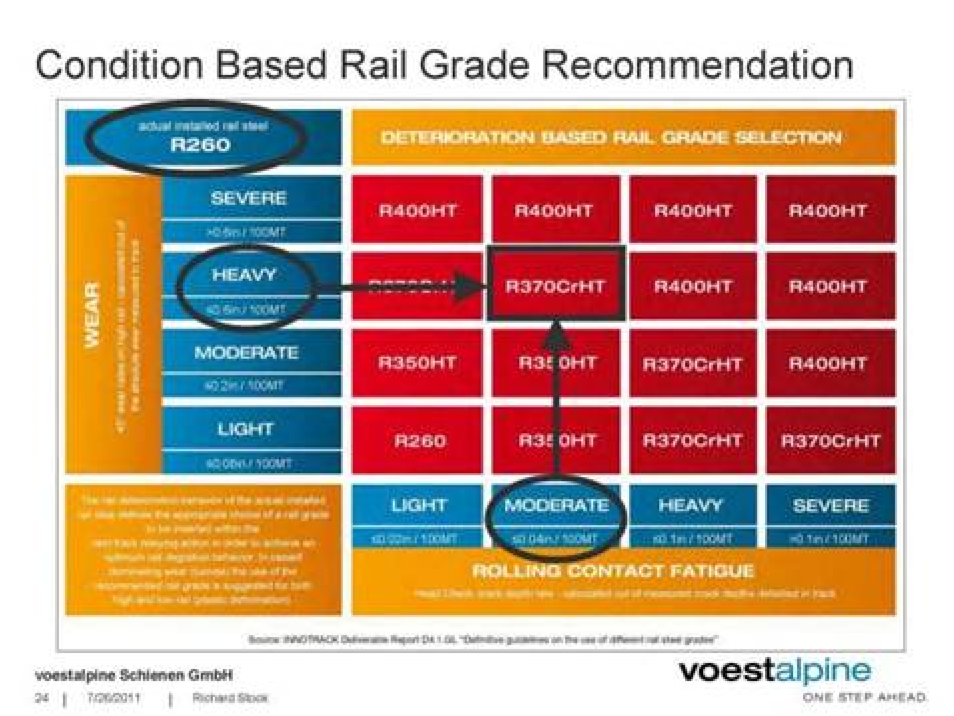

Condition Based Rail Grade Recommendation
actual installed rail steel
R260
DETERIORATION BASED RAIL GRADE SELECTION
WEAR
SEVERE
HEAVY
MODERATE
LIGHT
R400HT
R400HT
R400HT
R400HT
R370CrHT
R400HT
R400HT
R350HT
R370CrHT
R400HT
R260
R370CrHT
R370CrHT
LIGHT
MODERATE
HEAVY
SEVERE
ROLLING CONTACT FATIGUE
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Specific Defect: Squat

- Shallow surface impression
- Typical kidney shape
- Crack network below
- Can lead to rail break
- Appears randomly – singular or epidemic
- Early stage difficult to identify by automated track inspection
- Classification according to size/stage

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Squat Activities

- Squat defects represent a huge problem in Europe and Australia
- Associated with:
  - Low wear conditions (mixed traffic, passenger traffic)
  - Tractive forces – traction systems
  - Stiffness of track and vehicles – dynamic behavior
  - Material Transformation – White Etching layers
- Mechanism not yet fully understood
- Differences: Squats in 1980s and Squats nowadays?
- Controllable by preventive maintenance
- Extensive research activities in Europe and Australia

Question: Can this be a future problem in the US?

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Outlook – Rail Wheel Test Rig II (RSP II)

- head checks in shorter time
- generation and analysis of SQUATS
- Automated rail inspection
- coming summer 2011

Conclusion

- Full scale test rig concept allows testing of rails and wheel concerning
  - Wear
  - Plastic flow
  - RCF
- Reproducible results obtained within very short time intervals
- Absolute values differ compared to track conditions (due to specific differences and limitations) but the trends are the same.

ASSOCIATION OF AMERICAN RAILROADS

U.S. Department of Transportation
Federal Railroad Administration

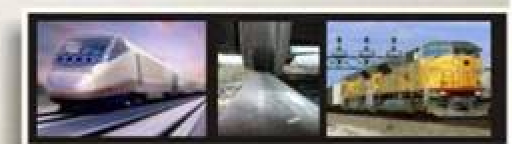
Transportation Technology Center, Inc

Joint AAR / FRA Workshop

on Wheel & Rail Rolling Contact Fatigue in North America

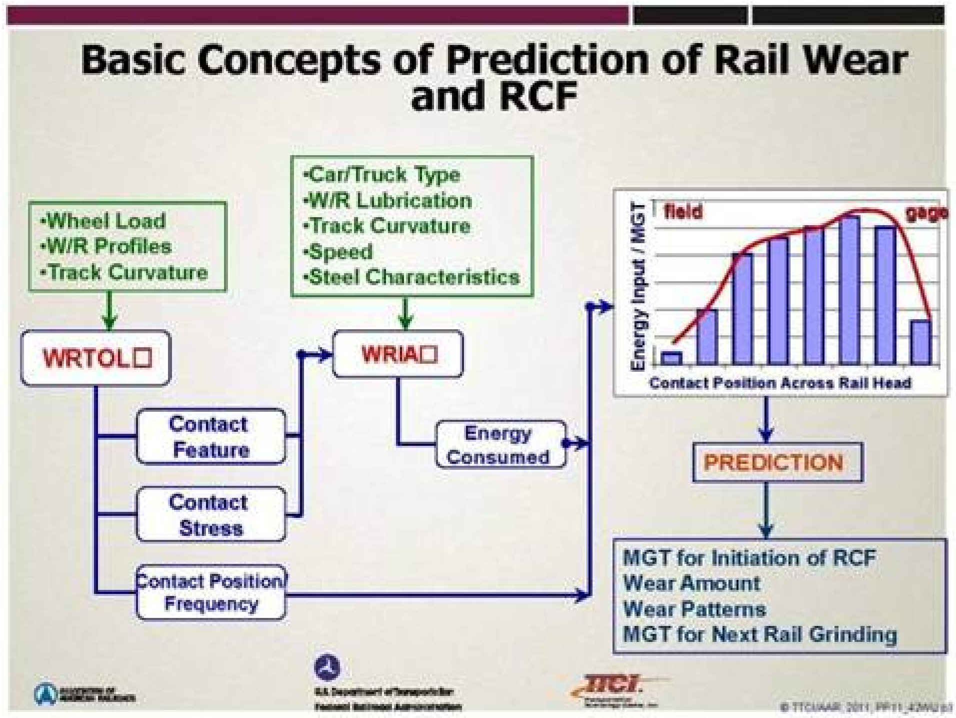
Wear and RCF Prediction Algorithms for North American Railway Service

Huimin Wu



Development of WRIM Model

- **Wheel/Rail Interface Management (WRIM) Model**
  - Rail Maintenance Planning Tool
  - Develop WRIM model further for evaluation and prediction of the shared tracks with mixed high-speed passenger and lower speed freight operations


Basic Concepts of Prediction of Rail Wear and RCF
•Wheel Load
•W/R Profiles
•Track Curvature
WRTOL□
•Car/Truck Type
•W/R Lubrication
•Track Curvature
•Speed
•Steel Characteristics
WRIA□
Contact Feature
Contact Stress
Contact Position/ Frequency
Energy Consumed
Energy Input / MGT
field
gage
Contact Position Across Rail Head
PREDICTION
MGT for Initiation of RCF
Wear Amount
Wear Patterns
MGT for Next Rail Grinding
TTCI


Special Features of North American Freight Operational Condition
◆Special Features include
• Axle loads commonly from 29.8 tons to 32.4 tons with some reaching 35.7 tons
• Use of three-piece bogies
• Track curves with small radii in many territories
• Worn wheel and rail profiles with considerable variability
▲ Contact positions on rails
▲ Contact area
▲ Rolling radius difference on straight and curved track
◆Vehicle/track interaction conditions will be even more complex for shared tracks with mixed high-speed passenger and lower speed freight operations
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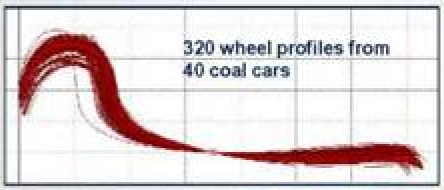
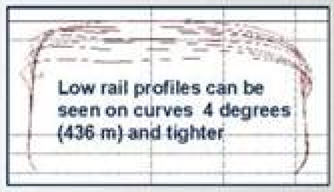
Wheel and Rail Profile Variations

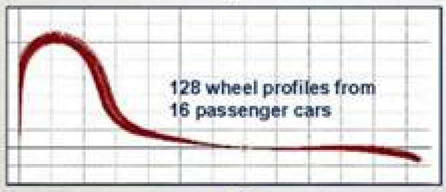
- **Examples of measured wheel and rail profiles**

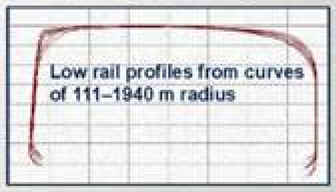
Examples of wheel and rail profiles measured in North American freight service





Examples of wheel & rail profiles measured in UK (mainly passenger service)





Wheel/Rail Contact Computation Method

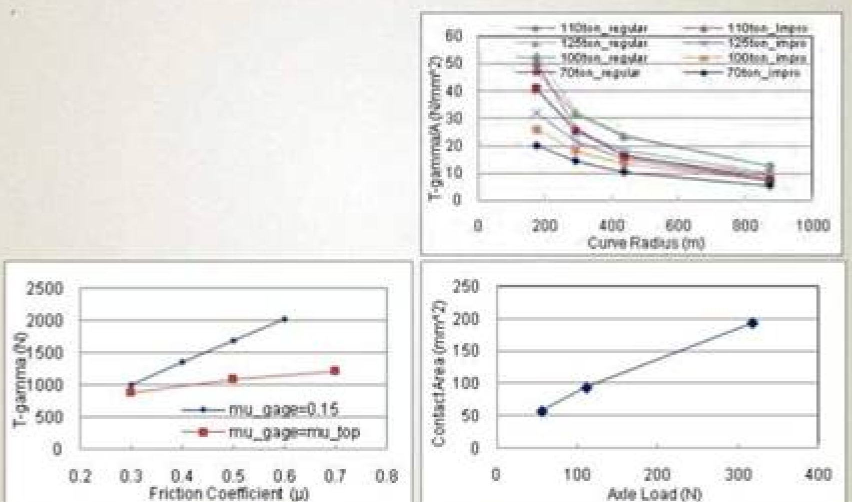
- **Method used in WRIM to handle the large variations in wheel/rail profiles**
  - Precomputing the wheel/rail contact parameters
    - Contact position
    - Contact area
    - *ΔRRD2 and ΔRRD3*
  - Using a large representative group of wheel pairs contacting a pair of measured rail profiles (with measured track gauge)
  - For each wheel/rail combination, *Ty* values of all contact points are determined based on the simulation results
  - Then the associated wear and RCF damage are distributed and accumulated for all contact positions

NUCARS®* Simulation Matrix

Parameters	Descriptions
Car types	8 types of cars with axle loads from 25 tons to 35.7 tons
Track curve radius (m)	873, 436, 291, 175 (2, 4, 6, 10 degrees)
Cant deficiency (mm)	-12.5, 0, 25.4, 50.8, 76.2
Lubrication - μ (t-rail top, g-rail gauge)	0.5t, 0.5g; 0.5t, 0.15g; 0.3t, 0.3g
ΔRRD2 (mm)	12, 8, 4, 0
ΔRRD3 (mm)	-1, 0, (1, 2, 3)

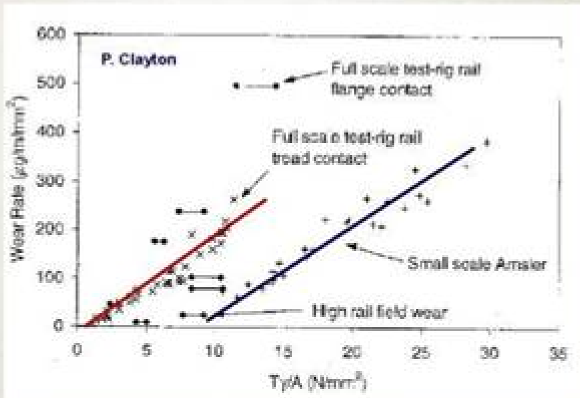
*NUCARS is a registered trademark of Transportation Technology Center, Inc.

Relations of Contact Parameters and *Tλ*



General Wear Rate Equation

$$Wear\,Rate\,(\mu g/m/mm^2) = k\frac{T\lambda}{A}$$



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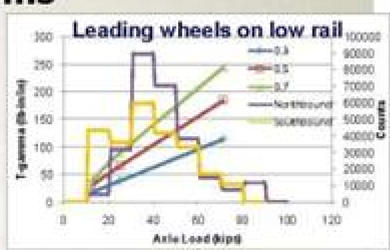
Preliminary Rail Wear and RCF Prediction Algorithms

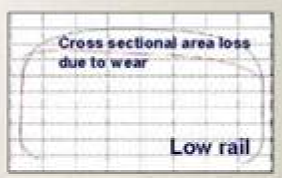
- **Preliminary low rail wear prediction algorithm**



$$MGT = \sum_{1}^{n} Axle\ Load_i * E_i$$

$$Wear_{mgt}(\frac{\mu g}{m}) = k_s \sum_{1}^{n} k_{ci} (\sum_{1}^{m} T\lambda_j * L_j)_i$$

k_s – rail steel related coefficient
k_c – calibration coefficient



$$Wear^{mgt}_{cross\,area}(mm^2) = \frac{Wear_{mgt}}{Steel\ density}$$

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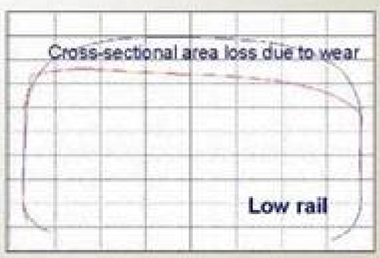
Federal Railroad Administration

Rail Wear Prediction Results

	Service Site A (GL)	Service Site B (TOR+GL)	Service Site C (TOR+GL)	Service Site D (GL)	FAST-2004 (Dry)
Curve Radius (m)	175	175	166	291	339
MGT	184.3	339.07	230	100	203
Wear (mm^2/MGT)	4.149	2.814	0.5049	1.2456	0.1478
Comparison Ratio *Measured/Prediction*	1.05	0.96	1.17	0.98	**3.07**
Rail Steel *Ke-BHN*	≈80ksi-400BHN	≈80ksi-400BHN	≈75.6-80.8ksi/387-420BHN	≈69ksi/370BHN	≈80ksi-400BHN

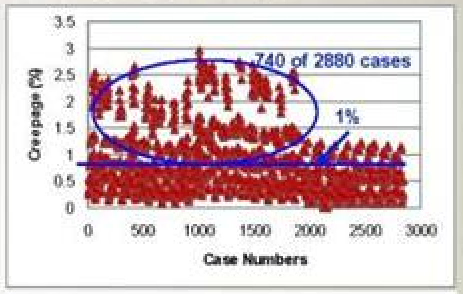
Observations

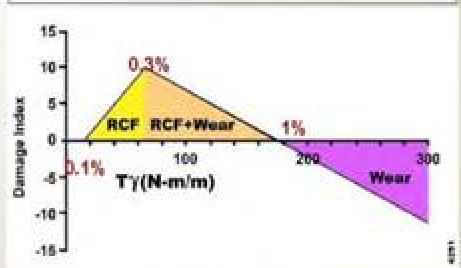
- **According to the observations in many freight revenue service curves**
  - Rail sections that experience only RCF without wear are rare
  - Also, on many curves where the creepages were above 1% based on the simulations, both wear and RCF are present



Wear and RCF Creepage Regime

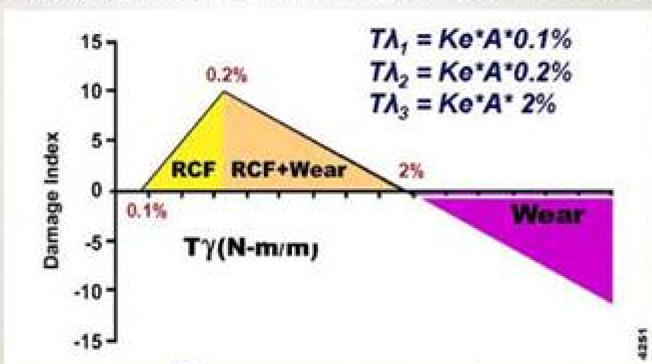
- 740 of 2,880 simulated cases have creepage values higher than 1%
  - Generally on 6- and 10-degree curves
  - 8 types of cars
  - Mixed wheel/rail contact patterns
  - 3 types of rail lubrication
- Did not include the cases of poor wheel/rail combinations such as asymmetrically and hollow worn wheels that can cause reverse rolling radius difference





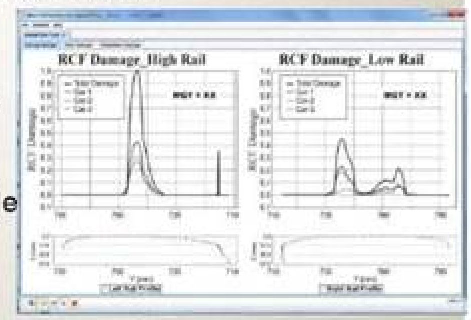
Modification of Regime Boundary

- A modification of regime boundary is being validated using the field data
  - 0.1%, 0.2% and 2%
- The boundaries are computed based on critical yield stress (*Ke*) and the contact area of each contact point



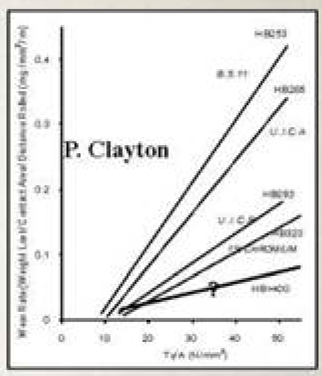
RCF Prediction Issues

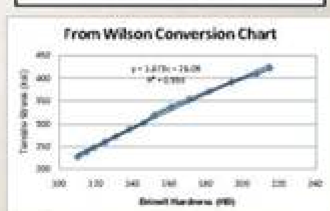
- **How should the RCF damage values be distributed and accumulated in the contact patch(s) to predict the initiation of RCF in terms of MGT?**
- **Distribution methods**
  - No distribution
  - Half space parabolic distribution (WRIM)
  - Other methods?
- **Accumulation methods**
  - Accumulate at same position
  - Accumulate based on the contact positions and associated bins that rail profile was divided into (WRIM)
  - Other methods?

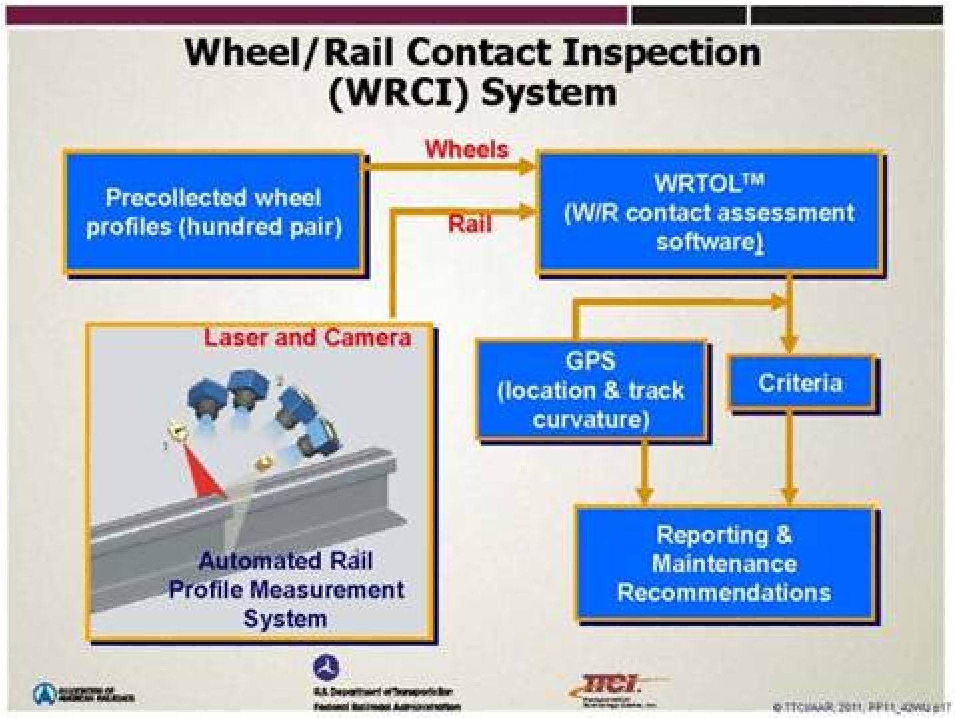


Issues Related to Rail Steel Characteristics

- **Issues**
  - Wear rate and RCF
    - Not only related to *Ke* and hardness of the rail steels
    - Other components and characteristics also have influences
  - Proper scale controlled laboratory tests are required
    - Calibrate with the field measurements
  - RCF development and propagation are difficult to measure and predict

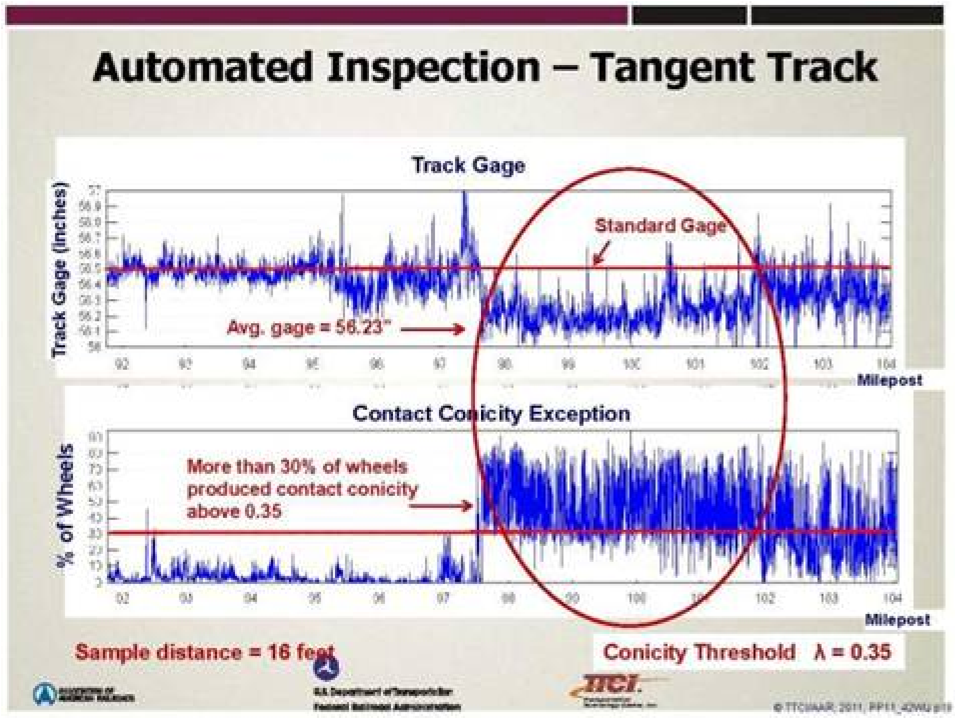


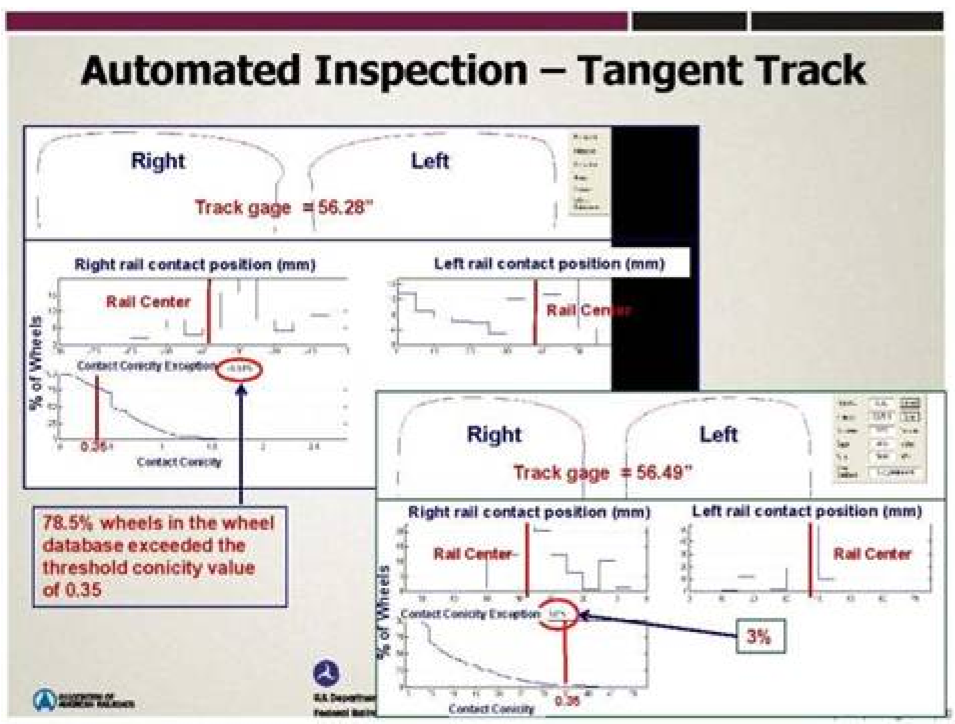




WRCI Outputs

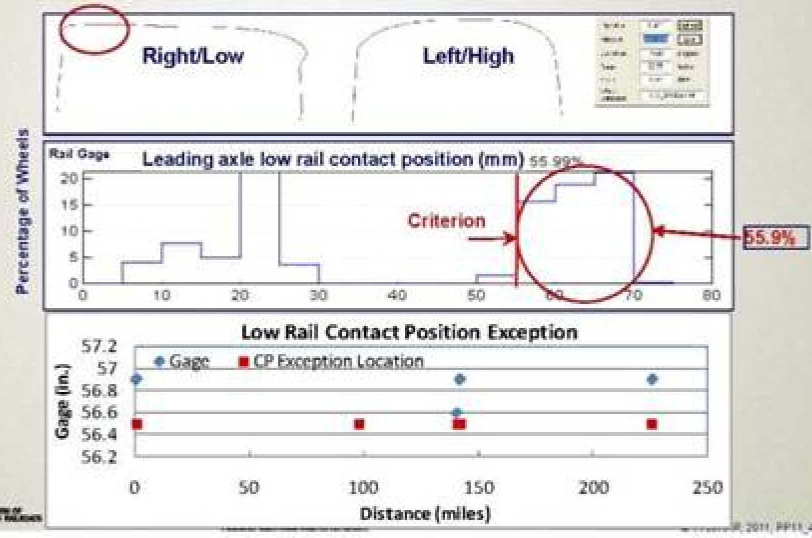
- **WRCI System Output Parameters**
  - Location information (Milepost, GPS coordinates)
  - Track curvature
  - Track gage
  - Contact conformity
  - Contact positions
  - Contact stresses
  - Rolling radius difference of both leading and trailing wheelsets on curves
  - Effective conicity on tangent track


Automated Inspection – Tangent Track
Track Gage
Track Gage (inches)
Standard Gage
Avg. gage = 56.23"
Milepost
Contact Conicity Exception
% of Wheels
More than 30% of wheels produced contact conicity above 0.35
Milepost
Sample distance = 16 feet
Conicity Threshold λ = 0.35


Automated Inspection – Tangent Track
Right
Left
Track gage = 56.28"
Right rail contact position (mm)
Left rail contact position (mm)
Rail Center
% of Wheels
Contact Conicity Exception
0.35
Contact Conicity
78.5% wheels in the wheel database exceeded the threshold conicity value of 0.35
Right
Left
Track gage = 56.49"
Right rail contact position (mm)
Left rail contact position (mm)
Rail Center
% of Wheels
Contact Conicity Exception
3%
0.35
Contact Conicity

Automated Inspection – Curves

- Low rail contact position toward the field side increases the risk of rail rollover



Way Forward

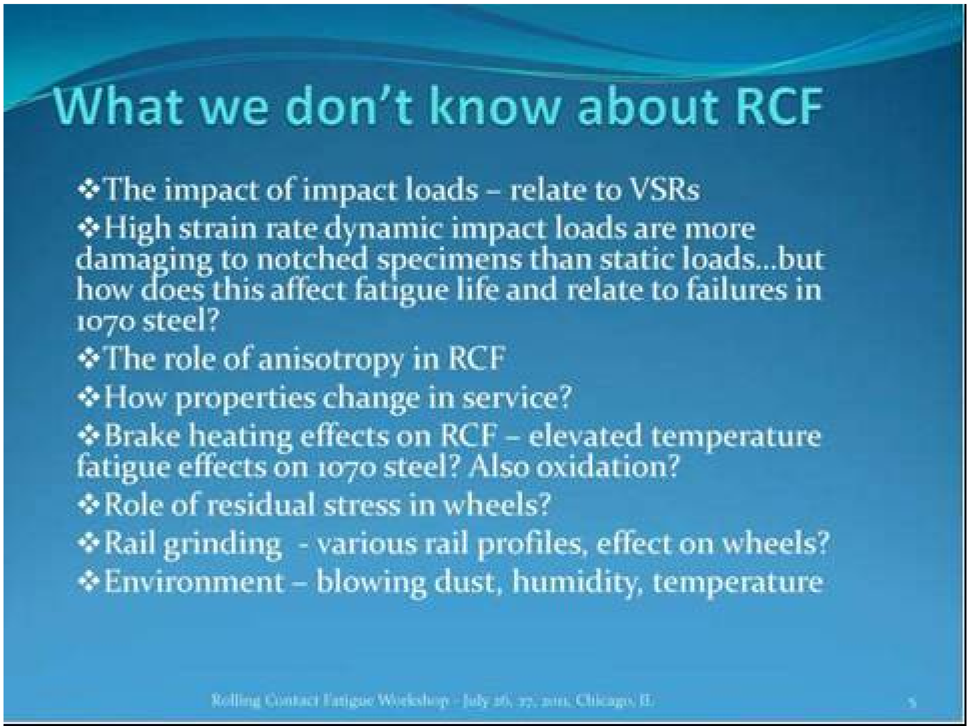
- Further verify proposed wear and RCF prediction algorithms using measured field data of vertical and lateral forces to account for variations in curving performance of three-piece bogies due to alignment problem
- Conduct more complex predictions for high rail using one-point, two-point, and conformal contact conditions
- Conduct laboratory tests to determine k_s in the wear prediction and material characteristics in addition to *Ke* for the RCF prediction

Rolling Contact Fatigue – Workshop Presentation for FRA/AAR

Cameron Lonsdale - Amsted Rail
Steven Dedmon – Standard Steel, LLC

What we know about RCF

- ❖Must exceed Elastic Limit
- ❖Thermal mechanical shelling more common in unit train service than mixed freight service
- ❖Initial material strength and work hardening are important
- ❖Lateral and longitudinal creepage plays a role but how important in N. American freight service?...


What we don't know about RCF
❖The impact of impact loads – relate to VSRs
❖High strain rate dynamic impact loads are more damaging to notched specimens than static loads…but how does this affect fatigue life and relate to failures in 1070 steel?
❖The role of anisotropy in RCF
❖How properties change in service?
❖Brake heating effects on RCF – elevated temperature fatigue effects on 1070 steel? Also oxidation?
❖Role of residual stress in wheels?
❖Rail grinding - various rail profiles, effect on wheels?
❖Environment – blowing dust, humidity, temperature
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5


Strategic Research Initiative
❖Griffin Microalloyed
❖Lucchini Alloyed
❖One Steel (Class B Microalloyed)
❖One Steel (Class C Microalloyed)
❖Standard Steel Microalloyed
❖Sumitomo Microalloyed
❖TTCI Microalloyed
❖Valdunes Microalloyed
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Patents on Improved Performance Wheels
Amsted 6783610
Standard Steel 2041635
Sumitomo 6372057, 6663727, 5899516
TTCI 2009-0051182, 6387191
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Development of a Class D Wheel
❖Pearlitic wheel steels are microalloyed with Chromium, Molybdenum, Vanadium, Niobium, Boron, Tungsten or some combination of these alloying elements.
❖Increasing strength is accomplished by Ferrite strengthening, grain refinement and by increasing hardenability.
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Development of a Class D Wheel

❖Bainitic wheel steels, with different microstructure, are alloyed primarily with Manganese, Nickel, Chromium, Molybdenum, Vanadium, Niobium, Boron, or some combination of these elements.

❖Increasing strength is accomplished by increasing hardenability.

❖However at comparable hardness levels, Bainitic steels wear worse than Pearlitic steels.

Development of a Class D Wheel

Simply increasing the hardness of a Class C wheel does not produce a Class D wheel.

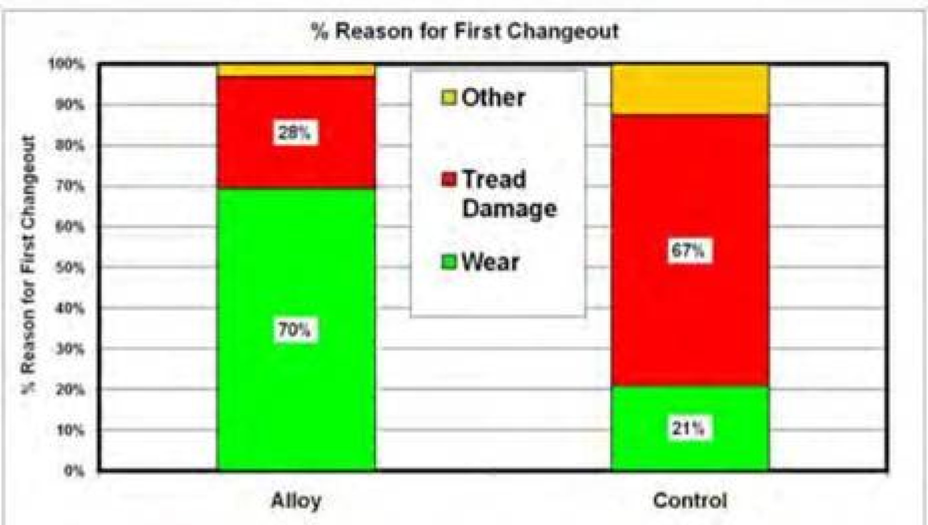
Increasing hardness will almost always be accompanied by decreasing ductility:

- **❖Depth of Hardening of Class C steel is limited.**
- **❖Elevated Temperature properties do not change.**
- **❖Impact and fracture toughness properties decrease.**
- **❖Structure does not change (pearlitic)**
- **❖If spalling is a problem, Class D steels won't help.**

Example of D steel improvements

- ❖Canadian National Railway, Quebec Cartier Mining, etc.
- ❖930 wheels total in all field tests
- ❖CN Tests – Griffin Class C and 400 Griffin Microalloy wheels under 2 sets of 100 new aluminum coal cars
- ❖Average mileage to first reprofile:
  - ❖Class C = 213,600 miles
  - ❖Microalloy = 368,150 miles
  - ❖72% improvement in wheel life
- ❖QCM Tests – 198 wheels tested, 40-50% improvement in wheel life due to decrease in thermal-mechanical shelling

CN Microalloy Wheel Field Test



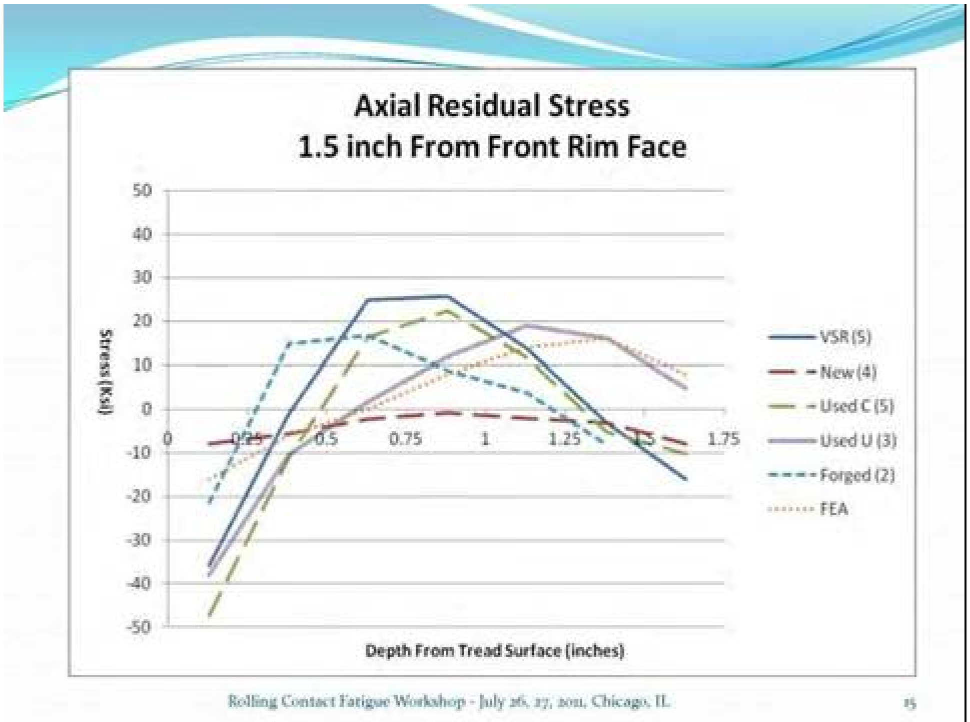
Example of D steel improvements

- ❖Quebec North Shore & Labrador, Canadian Pacific, Union Pacific
- ❖Average life to condemning Class C was 5.5 years
- ❖Average life to condemning Microalloy was over 7 years, or over 30% higher, without increasing hardness.

- ❖Average wear of Class C is about 1/16" per 35,000 miles.
- ❖Average wear on UP/TTCI revenue service test was 0.054" per 100,000 miles or an improvement of 70%, with a range of 56% to 92% better life.

Axial Residual Stress

- Measured on radial slices removed from wheels
- VSR, Used C, Used U, New
- Differences noted
- Paper to be presented at ASME Fall RTD Conference, Minneapolis, September 2011.



What is needed?

- Wheel/rail dynamometer like the one in South Korea (ref. IHHA 2011, Calgary)
- Practical approach to address industry issues

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TTCI Transportation Technology Center, Inc.

Joint AAR / FRA Workshop

on Wheel & Rail Rolling Contact Fatigue in North America

July 26-27, Chicago

Workshop Review: Freight Operation

Semih Kalay, TTCI

Workshop Review

- **Freight Operations in North America**
  - **RCF Control Measures**
  - Lessons Learned
  - Gaps in Current knowledge
  - Future strategies, requirements and standards

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RCF Control Measures

- Improved rail materials (Next gen rail steels)
- Improved rail maintenance (corrective/preventive grinding)
- Wheel / rail interface treatment (lube & TOR friction control and conformal wheel/rail profile design)
- Improved trucks (M976 & integrated truck designs)
- Improved wheel materials (AAR Class D and high performance wheel steels)
- Improved braking and brake rigging
- Wheel impact and wheel temperature detectors

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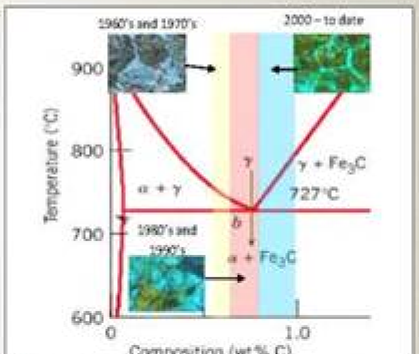
Metallurgy

- **Background:**
  - Metallurgical improvements result in better performance
    - In the past 50 years hardness increased from ≈250 to ≈400HB (mainly through carbon content increase)
    - Microstructure changed from hypoeutectoid to hypereutectoid
  - RCF is still a problem
  - Rail cleanliness influences RCF development



Decade (generation)	C Content (wt.%)	Average Hardness (HB)	Failure Mode
1960's	0.7	248	RCF and Wear Present
1980's	0.8	360	Mostly Wear Present
2000's	1.0	400	Mostly RCF Present

Evolution of the rail steels in the last 50 years

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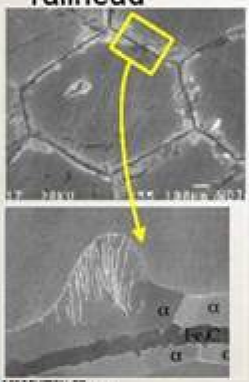
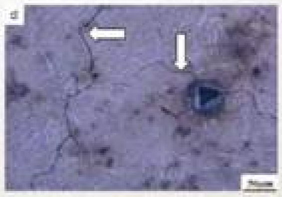
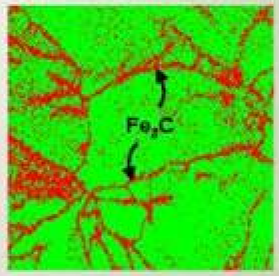
Metallurgy

- **Study Findings:**
  - TTCI/University of Pittsburgh research into metallurgical factors affecting rail performance
  - Pro-eutectoid cementite (Fe_3C) at the prior-austenite grain boundaries contributes to RCF development in the railhead





Phase	Total Fraction
Iron Carbide	0.235
Iron - Alpha	0.765



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Premium Rail Test at FAST

ERMSM	CORUS	NSC-HEX	JFE-A	JFE-B	MITTAL	SUMIT.	NSC-HEX	VAS-2	VAS-1	ERMSM	NSC-HEX

- **Conditions**
  - 5° curve
  - 4-inch superelevation
  - No direct lubrication
- **Rails**
  - 136-8 RE rail
  - 412 HB average
  - Evraz RMSM
  - Corus
  - JFE
  - ArcelorMittal
  - NSC
  - voestalpine
  - Panzhihua
  - voestalpine 400NEXT

Rail ID	YS (ksi)	UTS (ksi)	El. %	HB
AREMA	120	171	10	370
1	138	207	12.0	427
2	136	205	10.2	416
3	129	194	13.7	406
4	142	204	14.5	444
5	125	193	10.0	395
6	133	206	10.0	396
7	139	205	10.9	415
8	138	204	10.7	425
9	147	203	11.0	397
10	139	205	10.0	402
Avg	137	203	11.3	412

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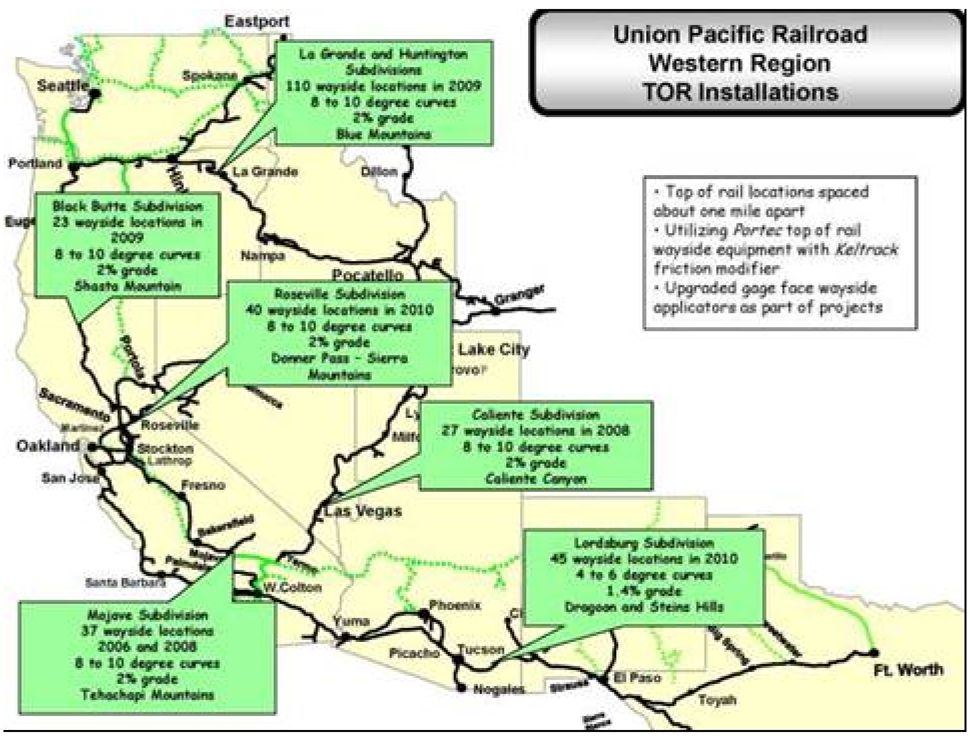
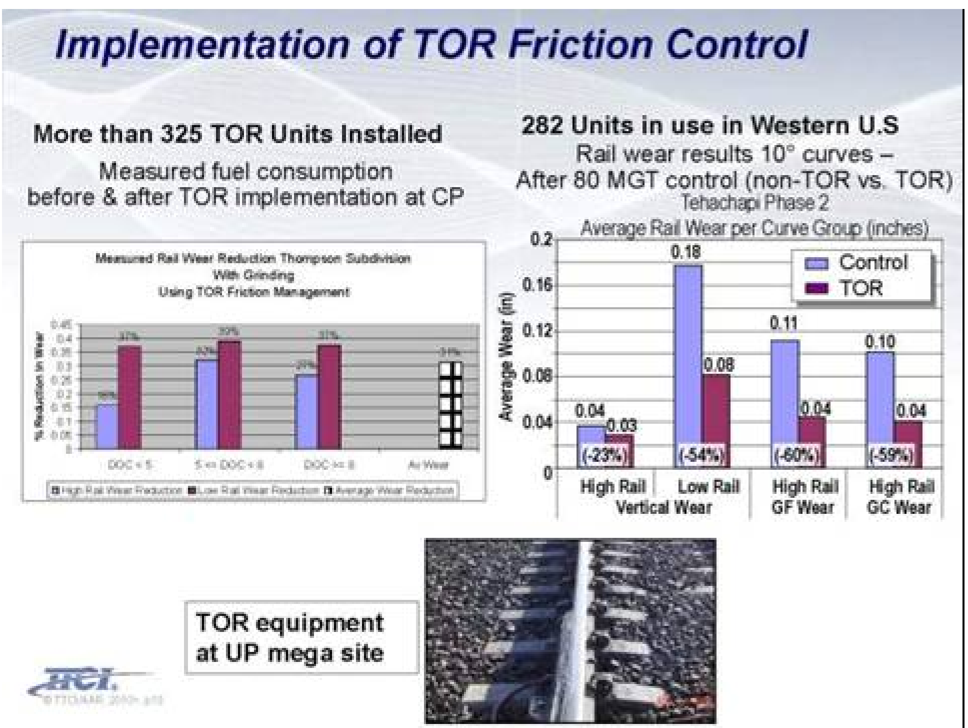
Friction Control vs. Lubrication Fundamental Concept Differences

- **Lubrication**
  - Applied to gage and wheel flanges
  - Lubricant reduces friction to < 0.25µ
  - Migration of product to top of rail is generally not controlled
    - Can lead to problems
  - Primarily addresses wear and energy
- **Friction control**
  - Applied to top of rail (variety of methods)
  - Product controls friction to 0.30 µ-0.34 µ
  - Little migration to gage face
    - General rule - gage lubrication still required
  - Primary interest is in reduced curving forces
    - Secondary benefits to wear and energy, depending on deployment method




Canadian Pacific in British Columbia
Ruling grades:
Westward 1.2%
Eastward 2.4%
Several hundred systems installed
British Columbia
Friction Management Pilot Test Zone
Vancouver
Roberts Bank


Implementation of TOR Friction Control
More than 325 TOR Units Installed
Measured fuel consumption
before & after TOR implementation at CP
Measured Rail Wear Reduction Thompson Subdivision
With Grinding
Using TOR Friction Management
282 Units in use in Western U.S
Rail wear results 10° curves –
After 80 MGT control (non-TOR vs. TOR)
Tehachapi Phase 2
Average Rail Wear per Curve Group (inches)
Control
TOR
Average Wear (in)
High Rail
Low Rail
Vertical Wear
High Rail
GF Wear
High Rail
GC Wear
(-23%)
(-54%)
(-60%)
(-59%)
TOR equipment
at UP mega site

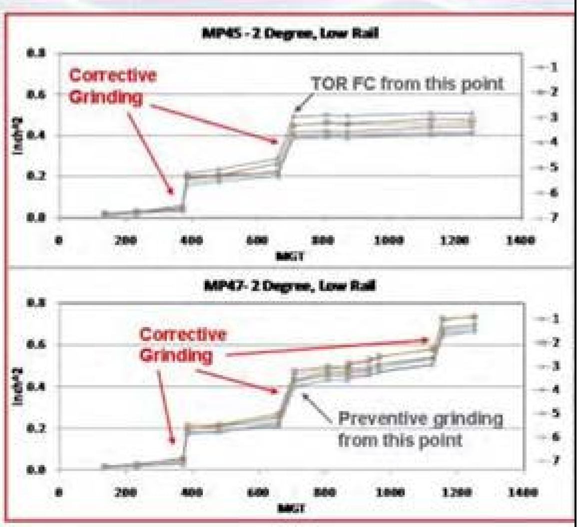
HAL Revenue Service Testing

Key Findings – Rail Tests

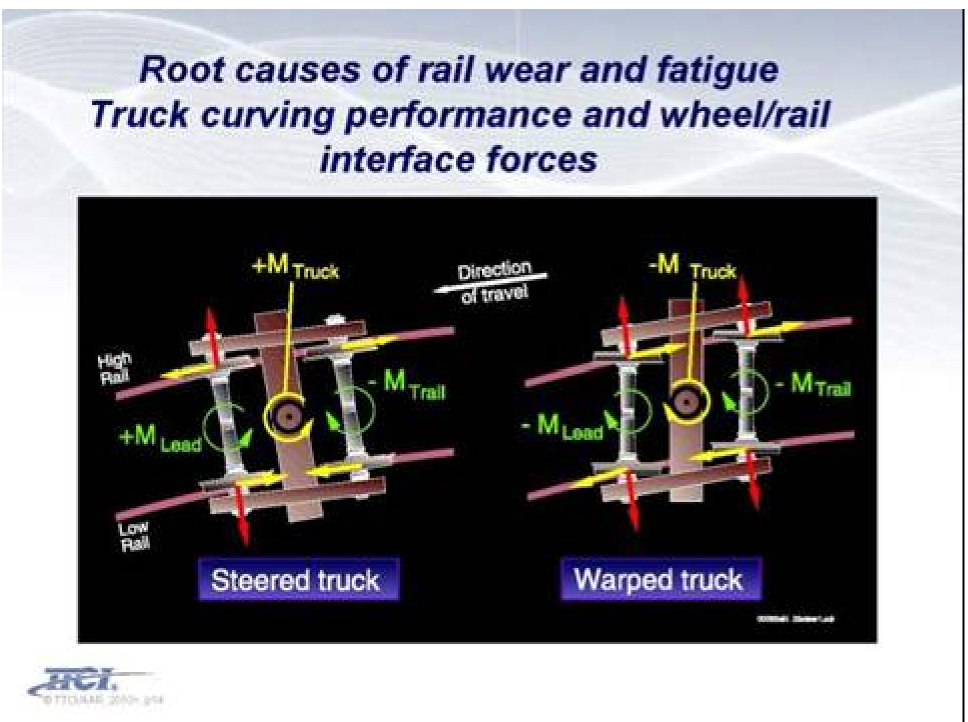
- **Premium rails continue to show excellent performance in resisting wear from traffic and internal fatigue growth**
  - 300 MGT at the eastern mega site
  - 1,400 MGT at the western mega site
- **RCF occurrence can be significant**
- **TOR friction control can greatly reduce occurrence of RCF and also wear from traffic**
- **Grinding can control and prevent RCF, but planning of grinding should be based on**
  - Tonnage, curvature, superelevation, balanced speed, friction control, etc

Rail Life Extension at Western Mega Site

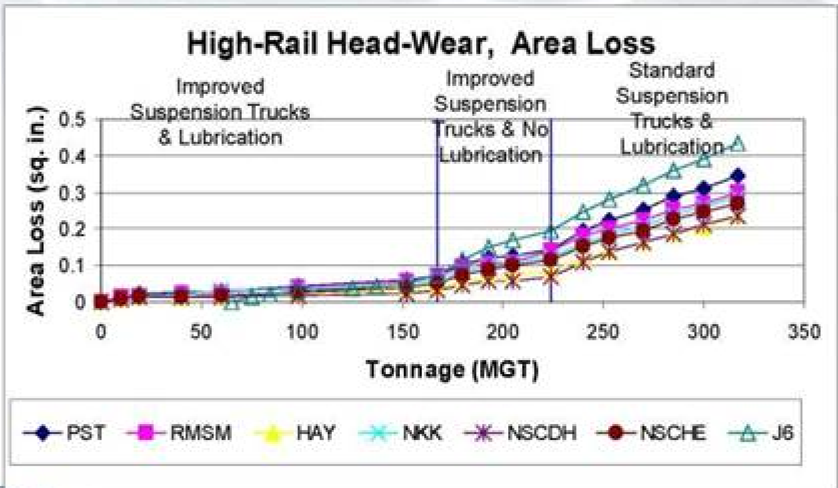
- **Wear from traffic was insignificant compared to that from corrective grinding**
- **To control RCF, wear was much less from preventive grinding or TOR FC than from corrective grinding**
- **Projected wear life is over 4,000 MGT for the curve with TOR FC**
- **Projected wear life is over 2,200 MGT for the curve with preventive grinding**




Effects of TOR FC and Preventive Grinding
Rail surface after 250 MGT without TOR FC or preventive grinding
Rail surface after 250 MGT with TOR FC or preventive grinding
TOR FC
Preventive Grinding
9/05
Corrective Grinding 375 MGT
Corrective Grinding 690 MGT
4/11, 1340 MGT Good rail surface condition

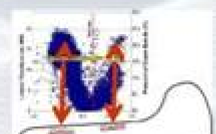

Root causes of rail wear and fatigue
Truck curving performance and wheel/rail interface forces
+M Truck
Direction of travel
-M Truck
High Rail
Low Rail
+M Lead
- M Trail
- M Lead
- M Trail
Steered truck
Warped truck

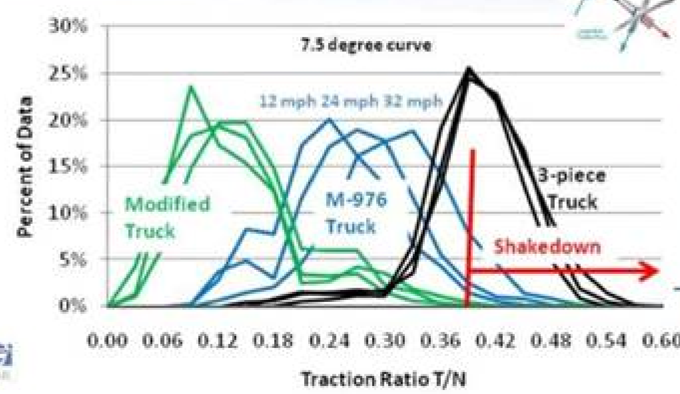
Standard 3-pice trucks increase the stress state by significantly increasing rail wear under heavy axle loads

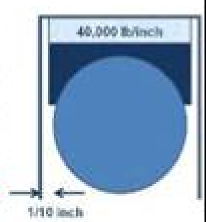


SRI 2A: Improved Truck & Car Performance

- **Key Findings (IFCT)**
  - **Low Rail Tractions (A root cause for HIW):**
    - **Reduce with the use of M-976 trucks**
    - **Further reduce with increased longitudinal clearance between adapter & pedestal**







SRI 2A: Improved Truck & Car Performance

- Test alternative truck designs offered by suppliers
  - 4 suppliers have shown interest with an offer of possibly 6 truck types
  - Delivery: June –Sep 2011
  - Tests:
    - IWS through curves & determination of cycles above shakedown
    - Loaded & empty car hunting using BNSF grain cars
    - An assessment of vertical load reduction through use of vertical primary suspension stiffness

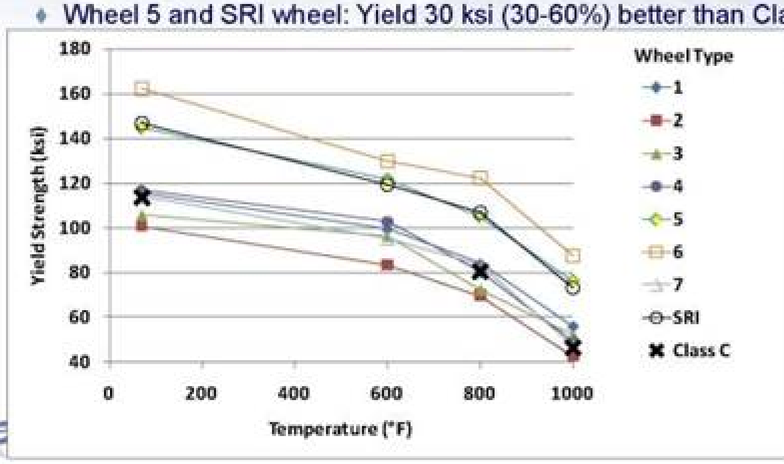
Strategies to Prevent HAL Wheel Failures

- Laboratory testing of wheel steels
  - High performance wheels meet or exceed all Class C criteria
  - Most high performance wheels cleaner than a typical Class C wheel
  - SRI wheel meets all proposed criteria for next generation wheel steels
    - Room temperature yield strength > 130 ksi
    - Room temperature fracture toughness > Class C
    - Hardness 380 to 420 HB

	Wheel	1	2	3	4	5	6	7	SRI
Meets Proposed Spec?	Yield Strength	No	No	No	No	Yes	Yes	No	Yes
	Fracture Toughness	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Hardness	Yes	No	No	Yes	Yes	No	Yes	Yes
	Cleanliness	Yes	Yes	No	No	No	Yes	Yes	Yes

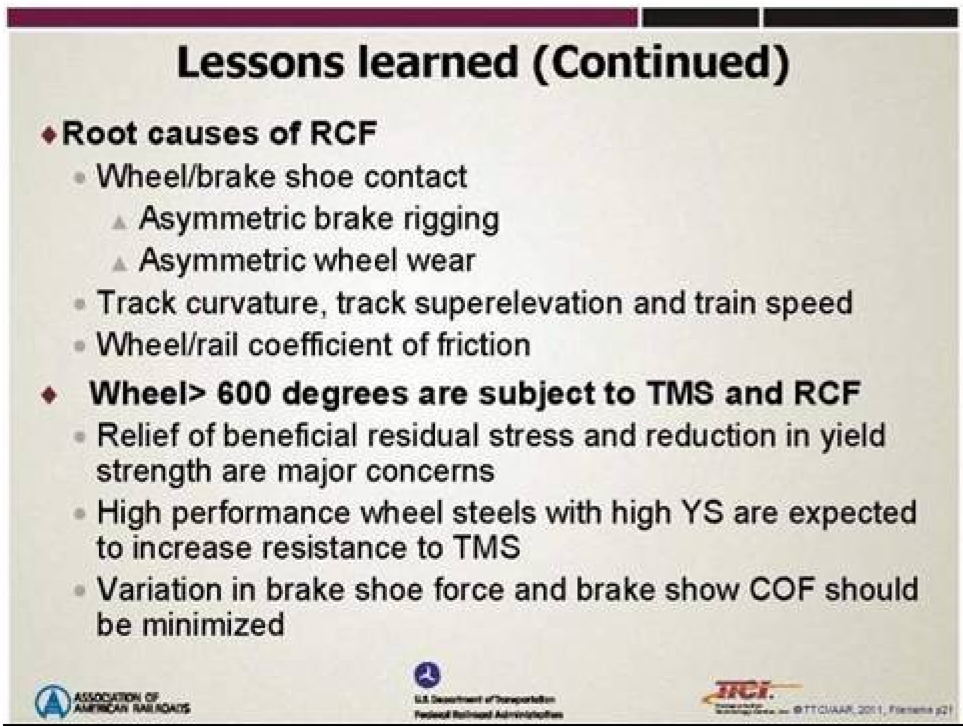
Strategies to Prevent HAL Wheel Failures

- **Laboratory testing of wheel steels**
  - High temperature tensile testing
    - Wheel 6 (bainitic): Yield 40-50 ksi (40-90%) better than Class C
    - Wheel 5 and SRI wheel: Yield 30 ksi (30-60%) better than Class C

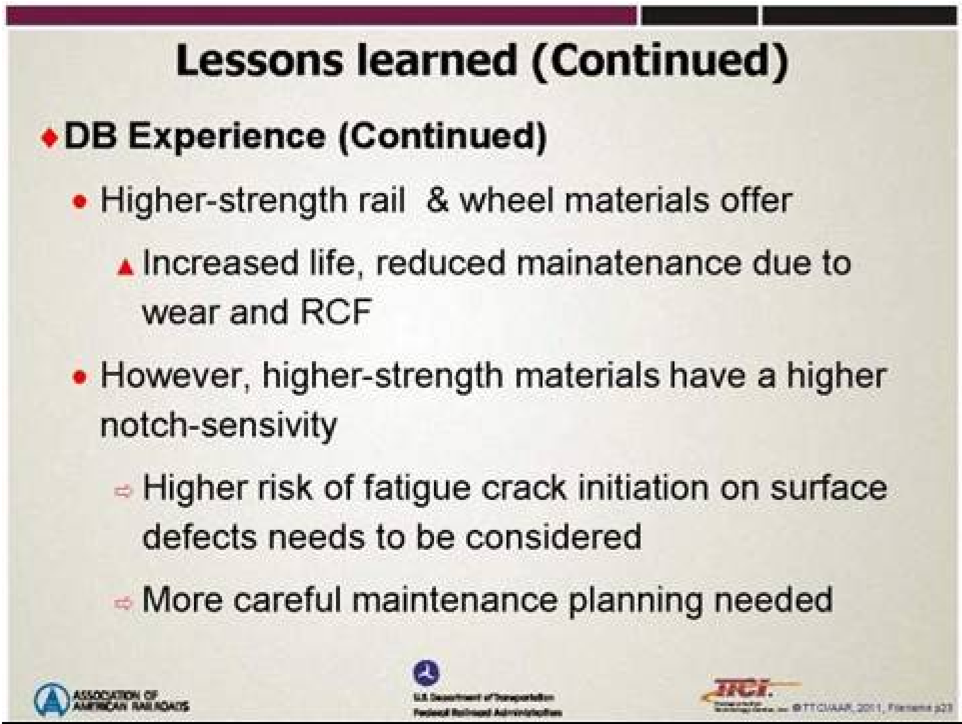


Lessons learned

- **Root causes of RCF**
  - Winter conditions greatly affect RCF
    - Cold temperatures, snow and ice, humidity
    - Cold temps induce tensile stresses in welded rail
    - Tensile stresses promote crack growth and fracture
    - Melting snow promotes crack growth
    - Ice on trains and switches
    - Ice coating on rails
    - Frozen track bed – increased vertical loads
  - Rail steel properties affect RCF
    - Hardness, tensile strength, ductility, toughness
  - Increased friction promotes wear and RCF
  - Decreased suspension capabilities


Lessons learned (Continued)
Root causes of RCF
Wheel/brake shoe contact
Asymmetric brake rigging
Asymmetric wheel wear
Track curvature, track superelevation and train speed
Wheel/rail coefficient of friction
Wheel> 600 degrees are subject to TMS and RCF
Relief of beneficial residual stress and reduction in yield strength are major concerns
High performance wheel steels with high YS are expected to increase resistance to TMS
Variation in brake shoe force and brake show COF should be minimized


Lessons learned (Continued)
DB experience
RCF – Surface cracks
Enormous increase in last 10 years
Modern electrical and diesel traction units especially concerned
RCF - Sub-surface cracks
Sub-surface cracks and total tread collapses are slightly increasing
Wheel material grade has a strong influence on RCF damages of wheels


Lessons learned (Continued)
DB Experience (Continued)
Higher-strength rail & wheel materials offer
Increased life, reduced mainatenance due to wear and RCF
However, higher-strength materials have a higher notch-sensivity
Higher risk of fatigue crack initiation on surface defects needs to be considered
More careful maintenance planning needed
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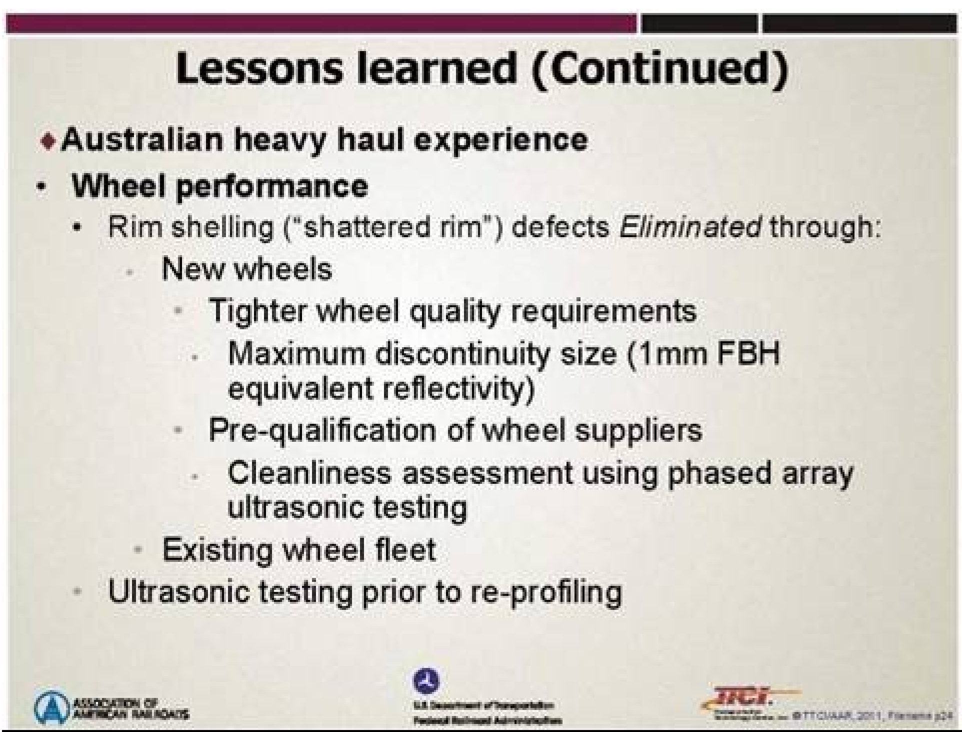
Lessons learned (Continued)
Australian heavy haul experience
Wheel performance
Rim shelling ("shattered rim") defects Eliminated through:
New wheels
Tighter wheel quality requirements
Maximum discontinuity size (1mm FBH equivalent reflectivity)
Pre-qualification of wheel suppliers
Cleanliness assessment using phased array ultrasonic testing
Existing wheel fleet
Ultrasonic testing prior to re-profiling
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Lessons learned (Continued)
Australian heavy haul experience (Continued)
Wheel performance
RCF develops in high mileage wheels due for reprofiling
Defect initiation due to plastic deformation and ratcheting failure at tread surface
Addressed through:
Implementation of micro-alloyed wheel grades
Wheel maintenance
Reprofiling at ~200,000-250,000km
Limit tread hollowing to 3-4mm
Minimize metal removal during machining
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Lessons learned (Continued)
Australian heavy haul experience (Continued)
Reduced rail wear rates resulting from profile optimization and use of higher strength rail steels
Rail RCF
Damage initiation due to plastic deformation and ratcheting failure at rail surface
Currently main rail damage mode in high traction locations:
Addressed through:
Preventative rail grinding strategies
Grinding intervals based on track alignment (curves/grades)
Minimum metal removal rates to control extent of cracking
Monitoring of rail surface condition
Increasing use of non-contact measurement systems
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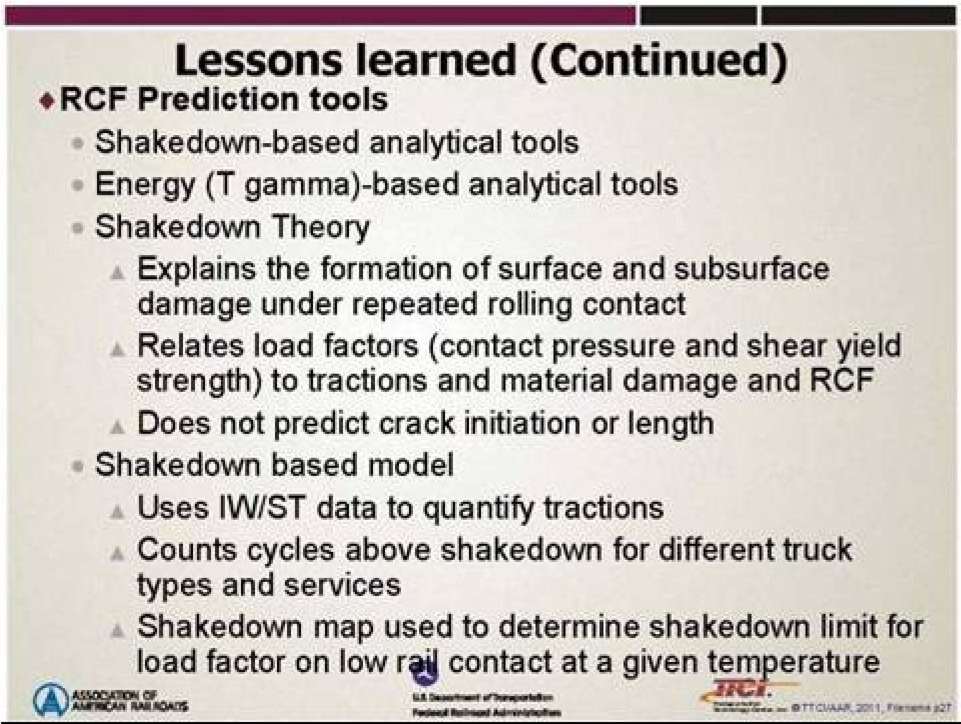
Lessons learned (Continued)
RCF Prediction tools
Shakedown-based analytical tools
Energy (T gamma)-based analytical tools
Shakedown Theory
Explains the formation of surface and subsurface damage under repeated rolling contact
Relates load factors (contact pressure and shear yield strength) to tractions and material damage and RCF
Does not predict crack initiation or length
Shakedown based model
Uses IW/ST data to quantify tractions
Counts cycles above shakedown for different truck types and services
Shakedown map used to determine shakedown limit for load factor on low rail contact at a given temperature
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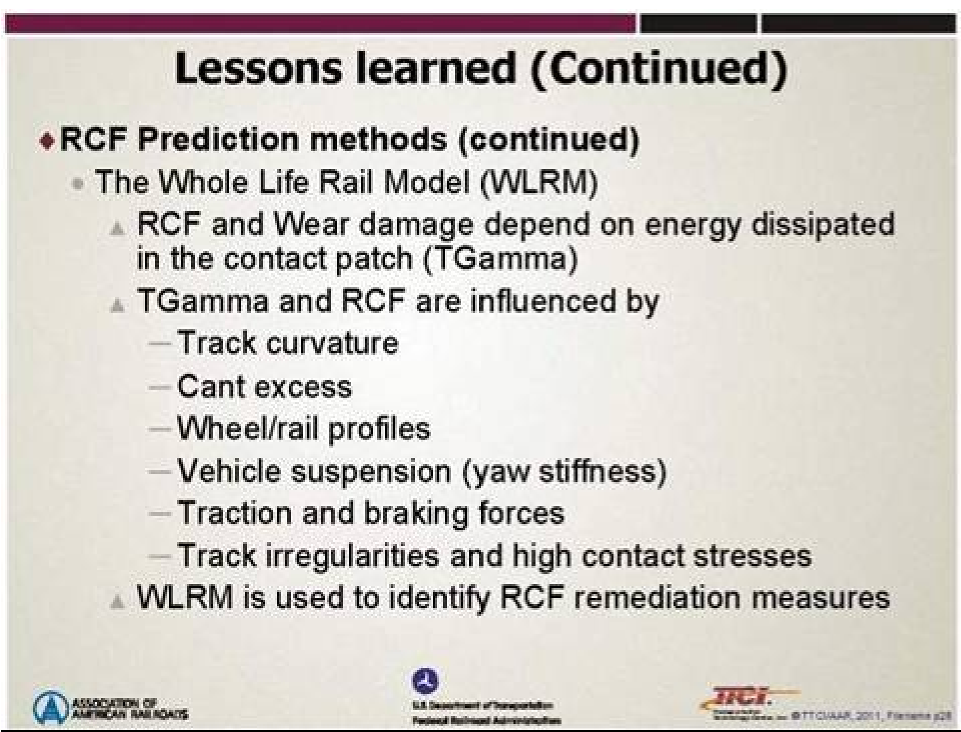
Lessons learned (Continued)
RCF Prediction methods (continued)
The Whole Life Rail Model (WLRM)
RCF and Wear damage depend on energy dissipated in the contact patch (TGamma)
TGamma and RCF are influenced by
Track curvature
Cant excess
Wheel/rail profiles
Vehicle suspension (yaw stiffness)
Traction and braking forces
Track irregularities and high contact stresses
WLRM is used to identify RCF remediation measures
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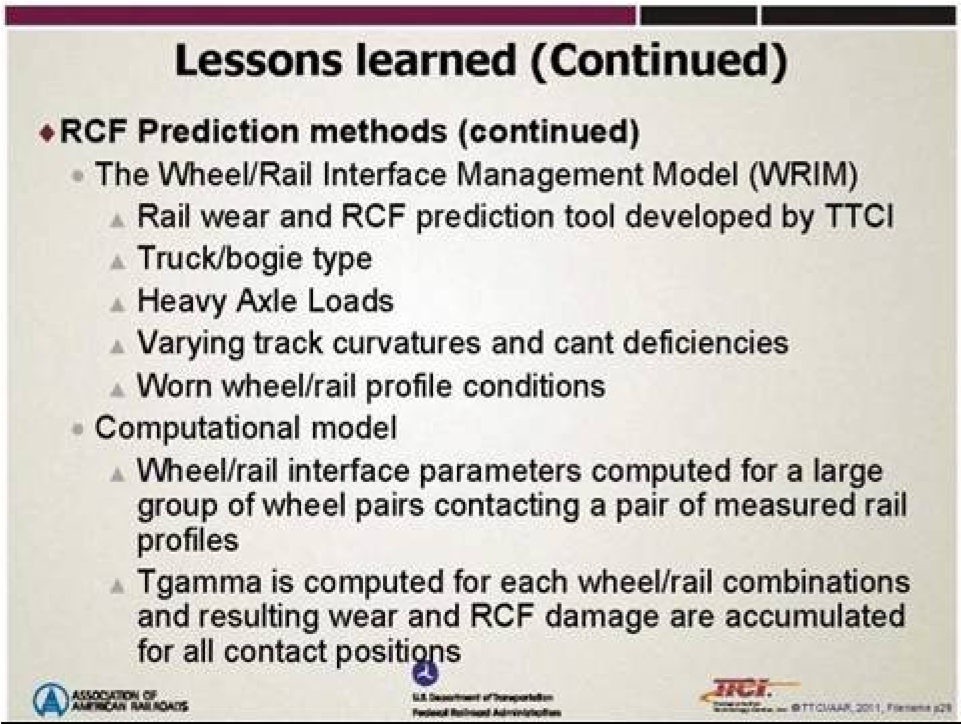
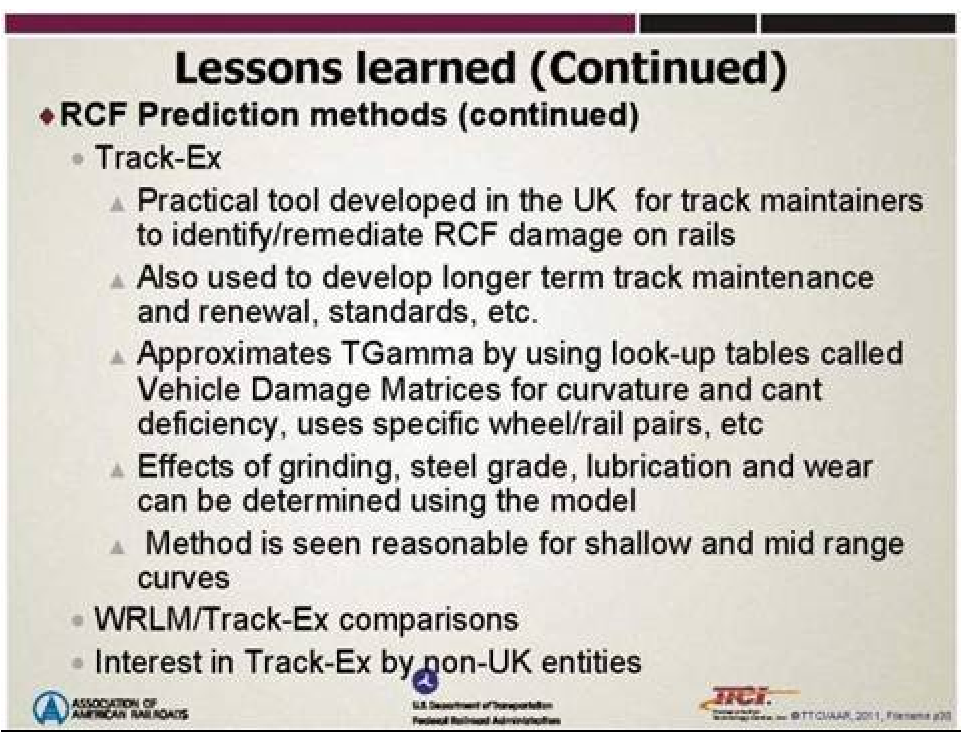

Lessons learned (Continued)
◆RCF Prediction methods (continued)
• The Wheel/Rail Interface Management Model (WRIM)
▲ Rail wear and RCF prediction tool developed by TTCI
▲ Truck/bogie type
▲ Heavy Axle Loads
▲ Varying track curvatures and cant deficiencies
▲ Worn wheel/rail profile conditions
• Computational model
▲ Wheel/rail interface parameters computed for a large group of wheel pairs contacting a pair of measured rail profiles
▲ Tgamma is computed for each wheel/rail combinations and resulting wear and RCF damage are accumulated for all contact positions

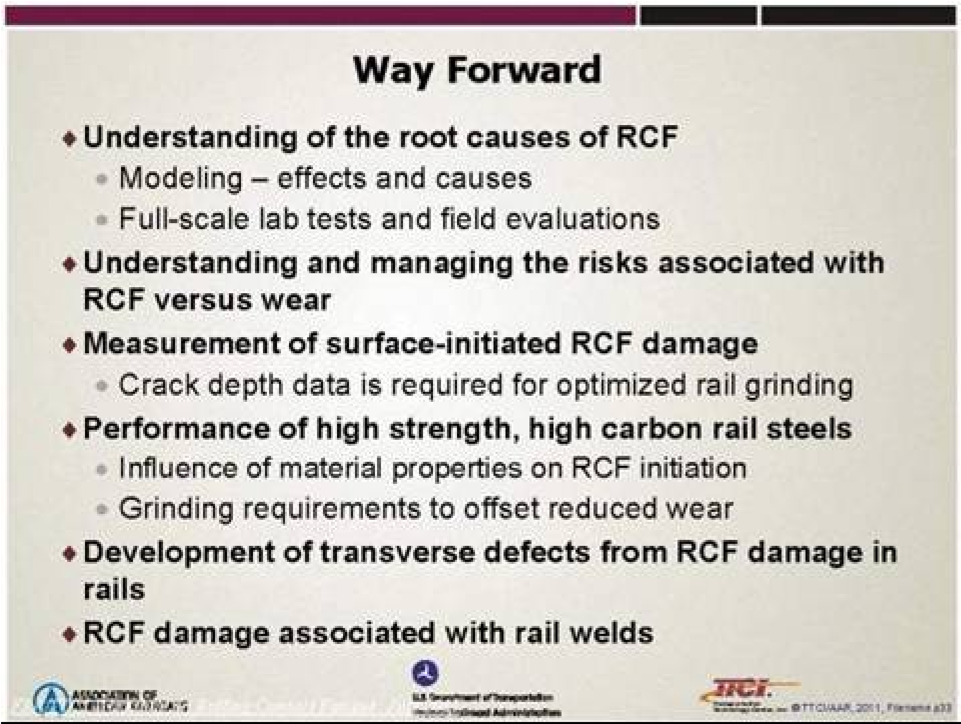

Lessons learned (Continued)
◆RCF Prediction methods (continued)
• Track-Ex
▲ Practical tool developed in the UK for track maintainers to identify/remediate RCF damage on rails
▲ Also used to develop longer term track maintenance and renewal, standards, etc.
▲ Approximates TGamma by using look-up tables called Vehicle Damage Matrices for curvature and cant deficiency, uses specific wheel/rail pairs, etc
▲ Effects of grinding, steel grade, lubrication and wear can be determined using the model
▲ Method is seen reasonable for shallow and mid range curves
• WRLM/Track-Ex comparisons
• Interest in Track-Ex by non-UK entities

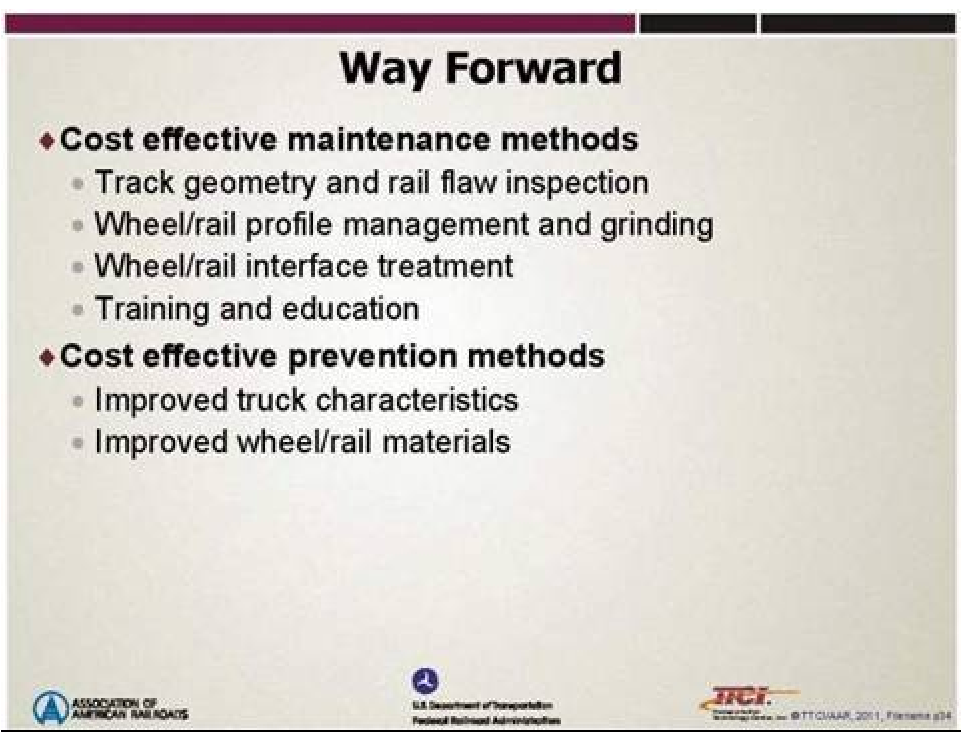
Future Research Needs

- **Need for more fundamental understanding of RCF**
  - Need lab test facilities to quantify the effects of TMS
    - State of knowledge can be dramatically increased with a TMS machine (i.e., twin disc roller rig, S. Korean rig)
    - Full scale new and service-worn wheels
    - Wheel temperature control
    - Friction control
- **Need to validate existing models for all axle loads and mixed freight/passenger operations**
- **Need to manage RCF: Ops vs. infrastructure owners**
- **Need to quantify the costs and benefits of remedial procedures**
  - Friction control, improved wheel/rail steels, controlled wheel/rail profiles, improved steering trucks, controlled wheel temperatures

Future Research Needs

- **Improved prediction of RCF damage for premium rail grades**
  - Extend WLRM to heavy haul conditions
  - Validate WRIM, Track-Ex, and other models
- **Conduct lab tests to determine shear yield strength and other material parameters used in prediction models**
- **Measurement systems**
  - Implementation of WRCI at NS
  - RCF measurement systems for HH conditions needed urgently
    - European systems (Spino and others)
    - Australian system (Loram/Rio Tinto)
    - Some tested at TTC with varying degrees of success


Way Forward
Understanding of the root causes of RCF
Modeling – effects and causes
Full-scale lab tests and field evaluations
Understanding and managing the risks associated with RCF versus wear
Measurement of surface-initiated RCF damage
Crack depth data is required for optimized rail grinding
Performance of high strength, high carbon rail steels
Influence of material properties on RCF initiation
Grinding requirements to offset reduced wear
Development of transverse defects from RCF damage in rails
RCF damage associated with rail welds


Way Forward
Cost effective maintenance methods
Track geometry and rail flaw inspection
Wheel/rail profile management and grinding
Wheel/rail interface treatment
Training and education
Cost effective prevention methods
Improved truck characteristics
Improved wheel/rail materials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Wheeling & Lake Erie Railway
G&W
CANADIAN PACIFIC RAILWAY
CSX TRANSPORTATION
ANACOSTIA & PACIFIC
Federal Railroad Administration

Abbreviations and Acronyms

AAR	Association of American Railroads
CHARMEC	Chalmers Railway Mechanics
FRA	Federal Railroad Administration
HAL	heavy axle load
IWS	instrumented wheelset
MGT	million gross tons
Monash-IRT	Monash University Institute of Railway Technology
NEC	Northeast Corridor
NRC	National Research Council Canada
RCF	rolling contact fatigue
RTRI	Railway Technical Research Institute
TMS	thermal mechanical fatigue (shelling)
TTC	Transportation Technology Center (the site)
TTCI	Transportation Technology Center, Inc. (the company)
UK	United Kingdom
Volpe	Volpe National Transportation Systems Center
VTI	vehicle track interaction
WLRM	Whole Life Rail Model
WRCI	wheel/rail contact inspection
WRIM	wheel/rail interface management