Bevan, Adam and Jaiswal, Jay

Rail steel metallurgy: why different elements are important and latest ‘mixes’

# Rail Steel Metallurgy: Why Different Elements are Important and Latest 'Mixes'

PWI London Technical Seminar: Rails – On Our Mettle

Jay Jaiswal & Adam Bevan

# Overview

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- Brief history of rails
- Past and present rail microstructures
- Rail steel grade selection for maximum benefit
  - Rail damage mechanisms
  - Route segmentation and damage susceptibility
  - Rail selection and attributes
  - Economic impact of optimised selection
- Discussion and recommendations

# Complexity of Design and Material Selection

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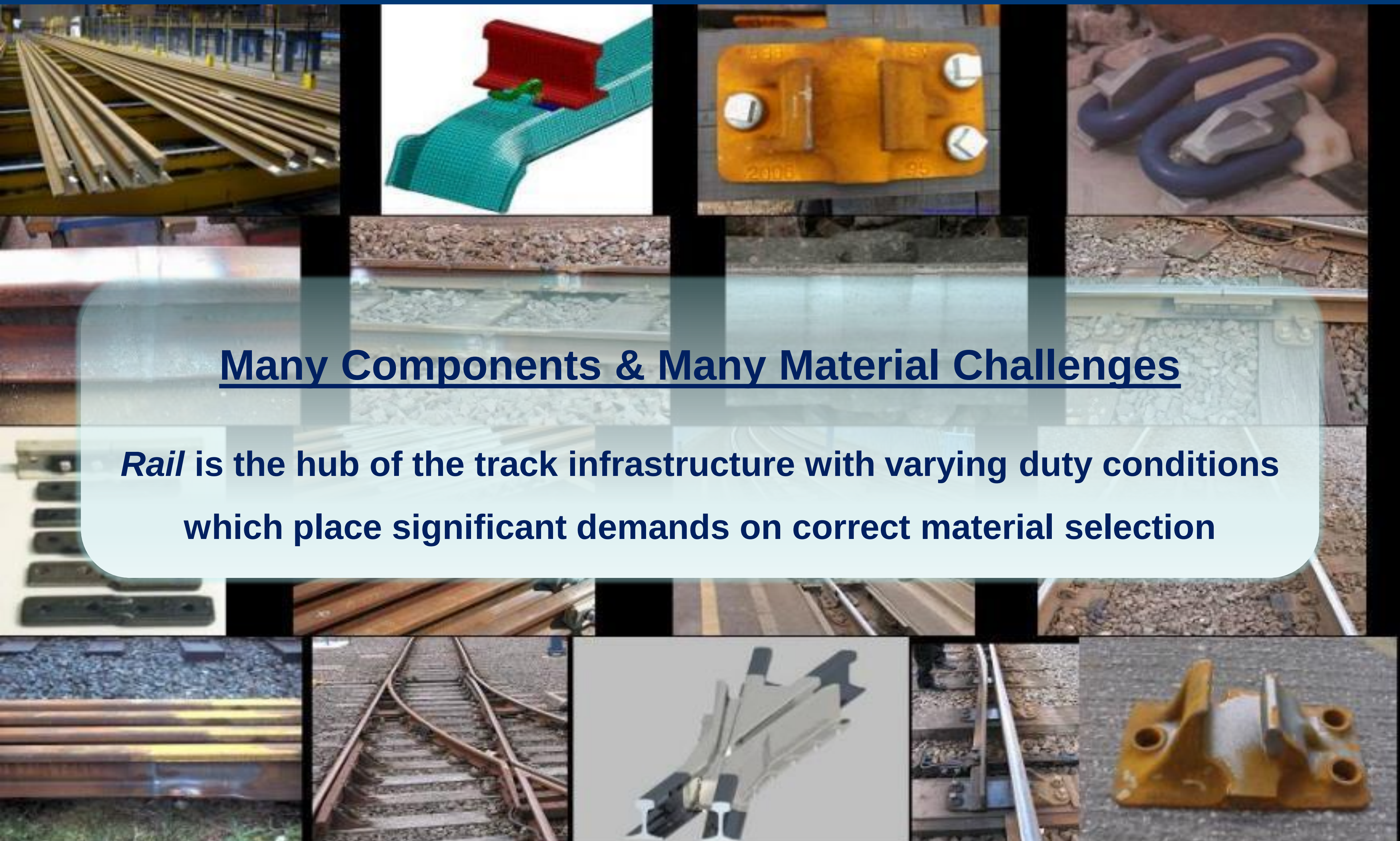

## Many Components & Many Material Challenges

***Rail*** **is the hub of the track infrastructure with varying duty conditions which place significant demands on correct material selection**

# Brief History of Rails – Life Before Steel

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- Early Railways and Wagonways (flange on wheel)
  - 600BC Ruts in Stone – Greece/Malta
  - 1540's – Wooden rails – Central Europe
  - 1603 – Wollaton, Nottingham
  - 1767 – Cast iron plates on wood rail - Coalbrookdale
- Cast Iron "Fish bellied" Edge Rails – Late 1780's
  - Short length (<6ft), brittle, many joints, uneven
- Tramway (flange on rail)
  - 1787 – "L" shaped Plates – Sheffield
- Trevithick's locomotive in 1804 broke the cast iron rails
- Wrought iron rails – 1808 – Tindale Fell, Brampton, Cumberland
- Up to 30ft, soft, delaminated

# Brief History of Rails – Introducing Steel

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Henry Bessemer

Robert Forester Mushet

**Wilson Cammell & Co, Dronfield - ~1860s**

**First Rail Rolled at Workington on 9th Oct 1883**

- 1857 – The first of Mushet's steel rails was delivered to Derby Midland Station
  - Heavily trafficked part of the line where the iron rails had to be renewed every six months, and occasionally every three
  - " Six years later, in 1863, the rail seemed as perfect as ever, although some 700 trains had passed over it daily. Life span achieved 16 years

# Past and Present Rail Microstructures

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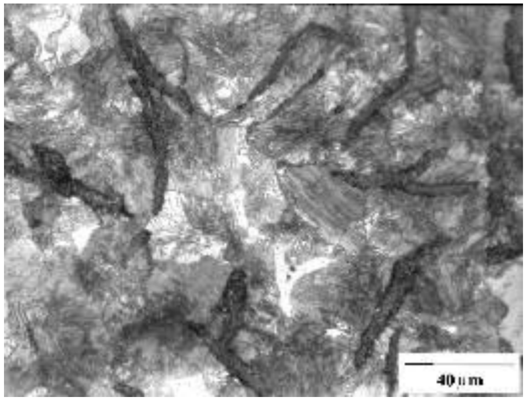
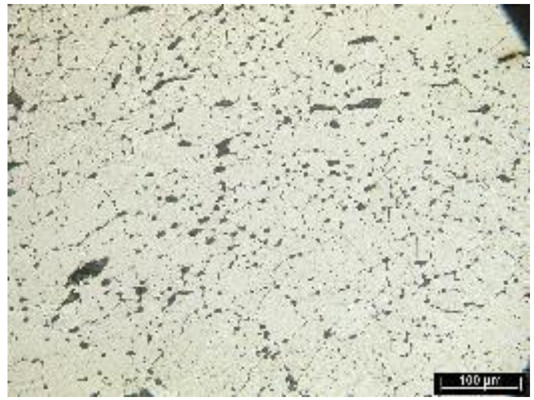
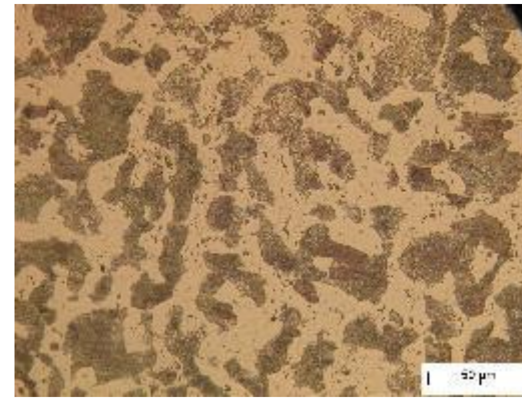


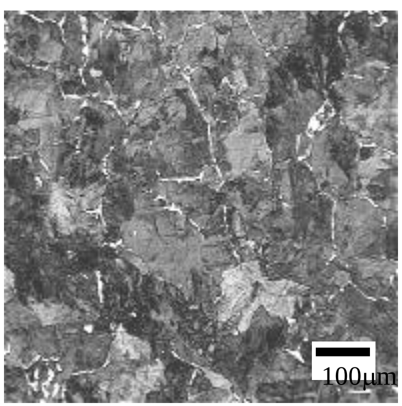

1767 Cast Iron ~ 3%C; 200HB



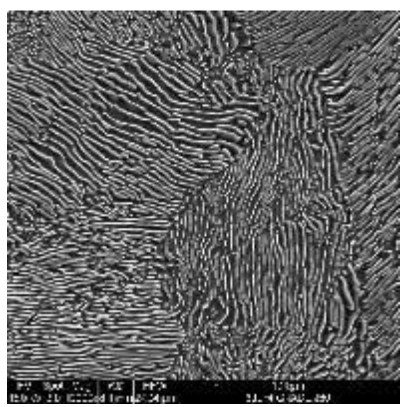
1808 Wrought Iron 0.05%C; 174HB



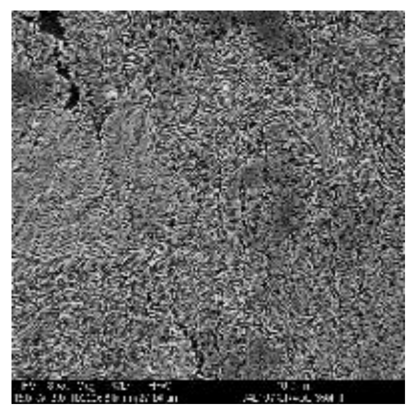
1857 Bessemer Steel ~ 0.25%C; 182HB



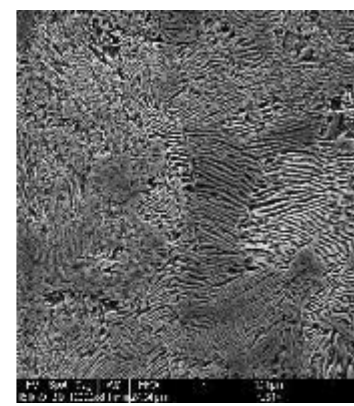

1950 BS11 Normal (R220); ~0.55%C, 230HB



1970 Grade A (R260) ~ 0.8%C, 280HB



1985 MHT (R350HT) 0.8%C, 350HB



Current HE Grades (R400HT) ~0.9%C; >400HB

# Drivers for Developments in Rail Metallurgy

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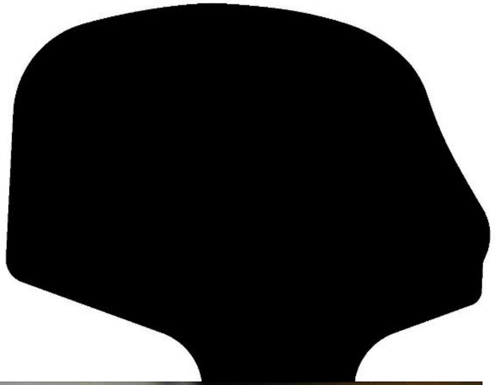

- Reduce rail breaks and defects
  - Improved steel cleanness
  - Increased section and stiffness
- Reduce rail joints
  - Increased hot rolled length
  - Improved welding technologies
- Reduce wear, RCF and plastic deformation
  - Increase carbon and alloy content
  - Heat treatment to refine microstructure and increase hardness


# Rail Degradation Mechanisms: Wear

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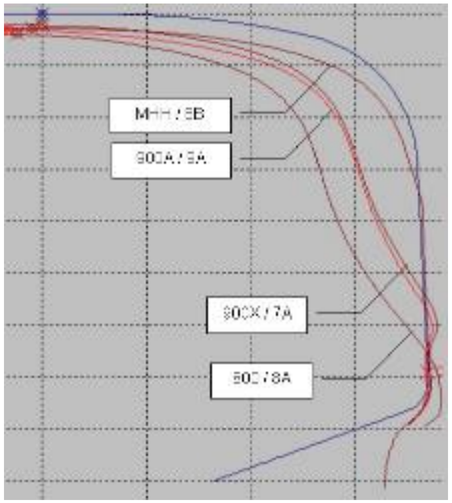

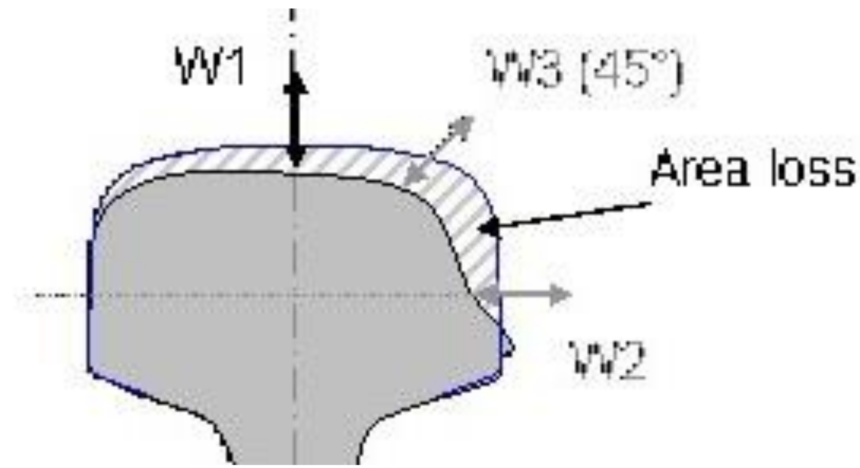


- Rail Wear – remains a significant key cost driver in European Railways
  - Only 20-30% of rail section weight is available for consumption through wear – therefore need to MAXIMISE the life of the ≈20% of rail weight
  - Increase in rail life requires a reduction in rate of wear
  - Increasing traffic density makes reduction in wear rate even more desirable to increase track availability

# Rail Degradation Mechanisms: RCF

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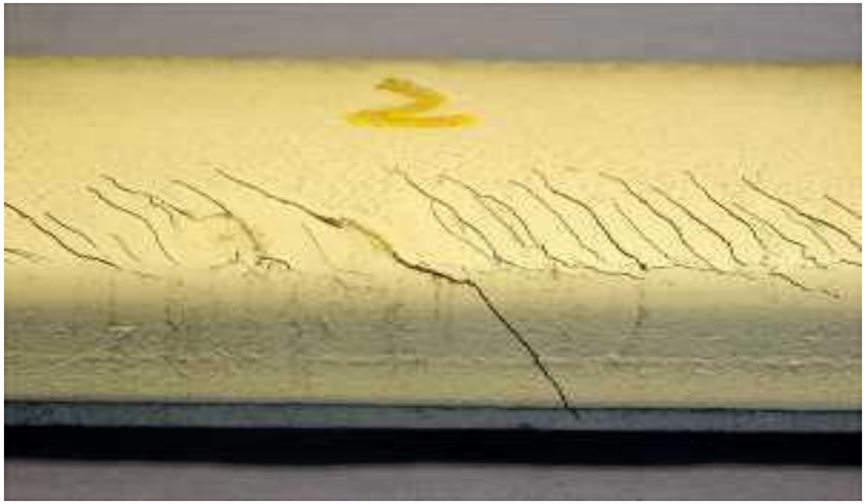


- Rolling Contact Fatigue:
  - A key cost driver in most railways
    - Increased grinding costs
    - Increased inspection costs
    - Premature rail replacement well before wear limit is reached

# Rail Degradation Mechanisms: Squats

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- Squat Defects – growing cause of increased track maintenance
  - No universal consensus on cause
  - Can rail metallurgy contribute towards eliminating Squats?
    - Can a softer grade promote wear of initial cracks & better rail wheel contact?

# Rail Degradation Mechanisms: Plastic Deformation

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- Plastic Deformation – a further cause of premature rail replacement
  - Highly canted track – higher forces on low rail
  - Increased freight traffic resulting in high forces on low rail

# Rail Degradation Mechanisms: Corrugation

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- Corrugation – a further rail degradation mechanism & a cost driver
  - Increased dynamic forces leading to degradation of rail & support
  - Increased noise & vibration
  - Increased maintenance costs from remedial grinding
- Harder grades are considered to be more resistant to corrugation development & growth

# Rail Damage Susceptibility

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- Rate of rail degradation (and life) is not uniform throughout any railway network
  - Governed by a combination of *track*, *traffic* and *operating characteristics* in addition to the *metallurgical* attributes of the steel
- A network is made up of individual segments with varying track characteristics, degradation rates and expected life
- Selection of rail steel grade to maximise life needs to combine knowledge of the metallurgical attributes of the available rail steels with the conditions of wheel-rail and vehicle-track interfaces

# Route Segmentation

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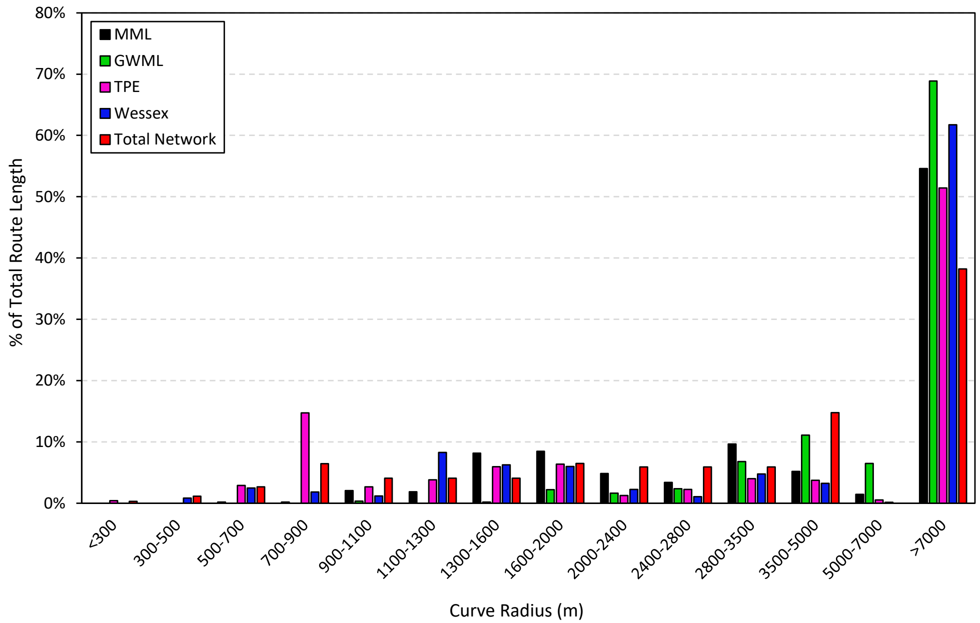
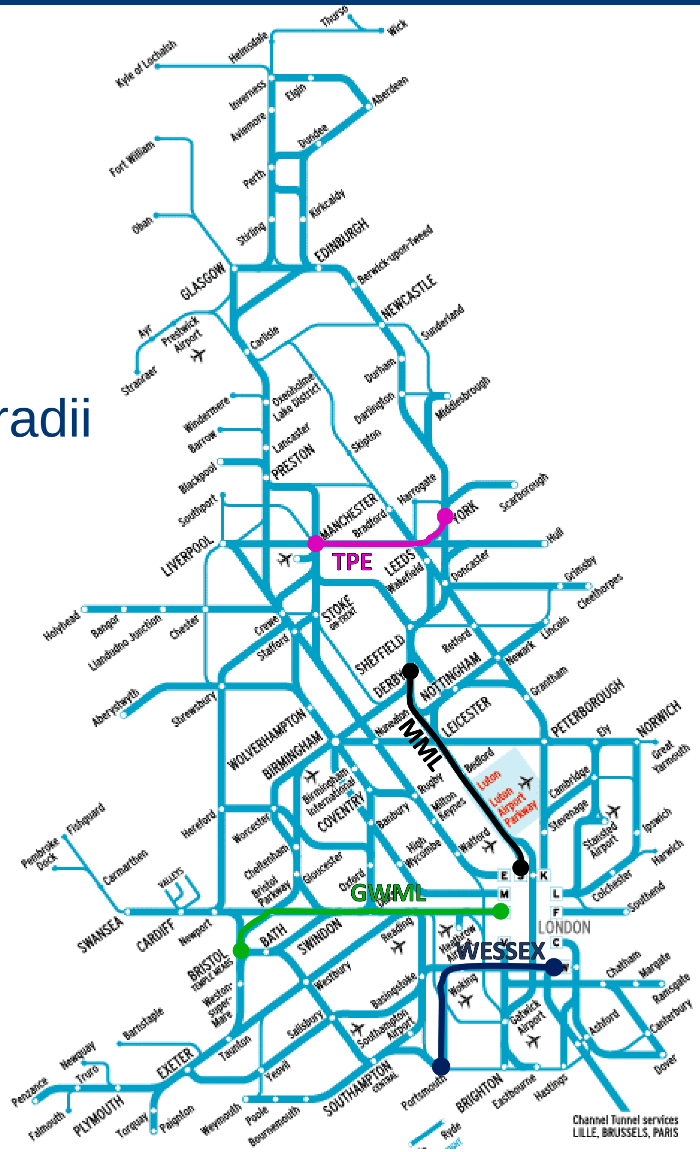
- Routes segmented into sub-assets based on curve radius
- Susceptibility to the known degradation mechanisms determined for each segment
- Additional simulation cases undertaken using generic model running over a range of curve radii and cant deficiencies



# Modelling Methodology

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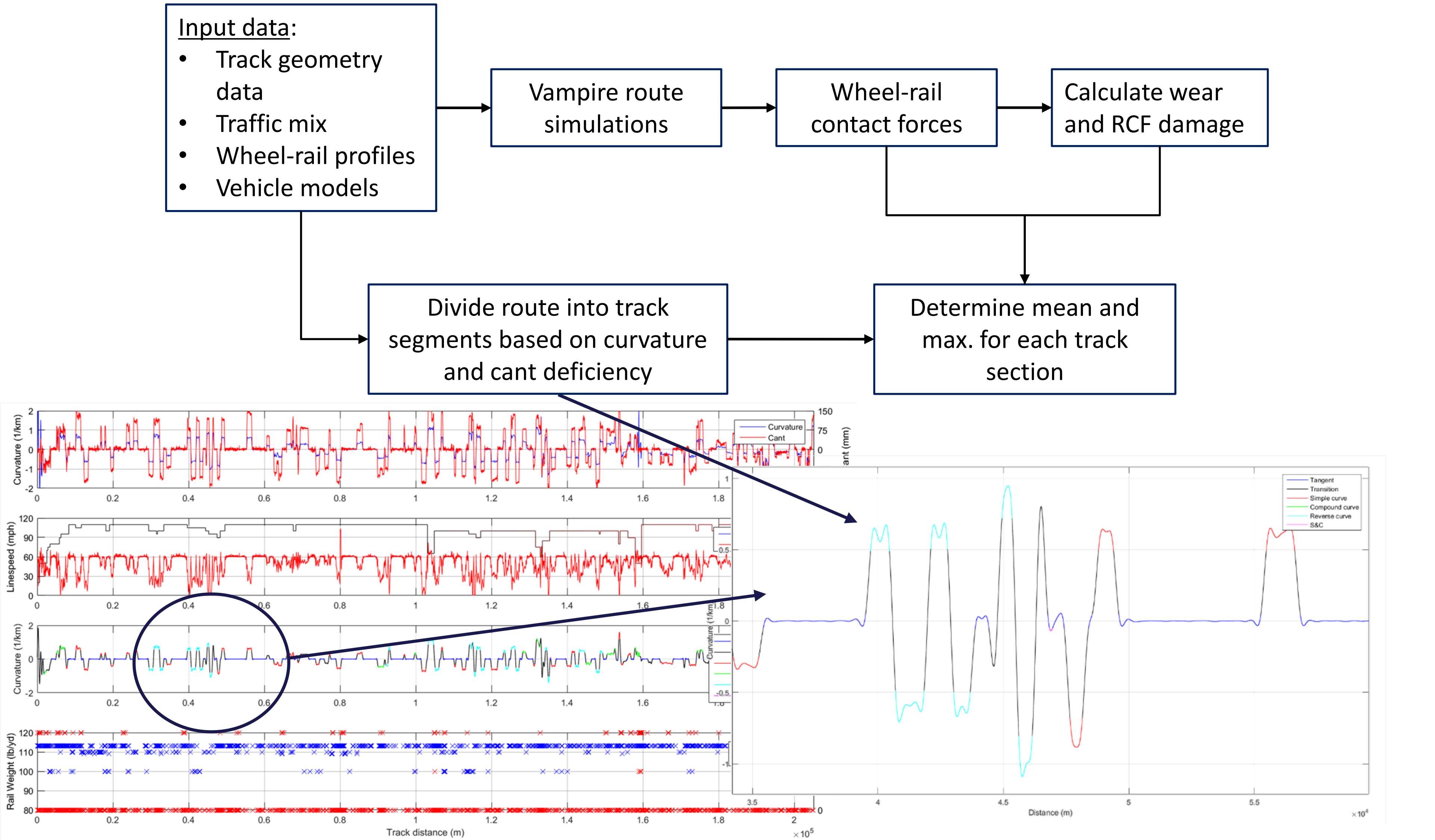
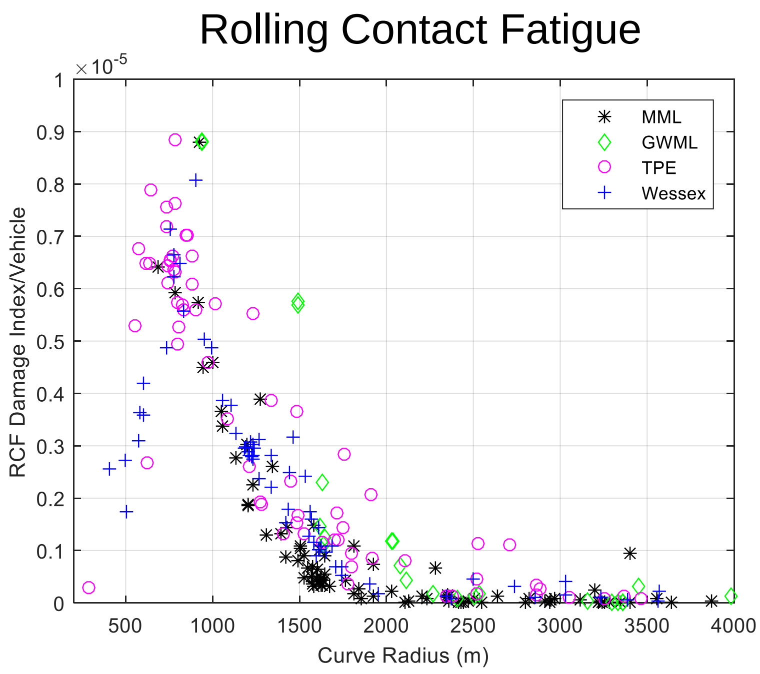
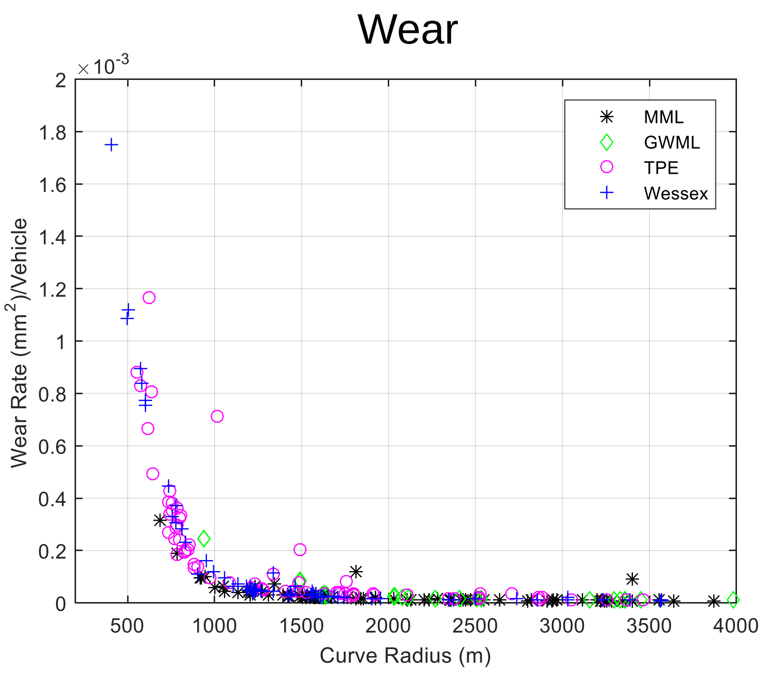


# Damage Susceptibility Map



# Damage Susceptibility Map

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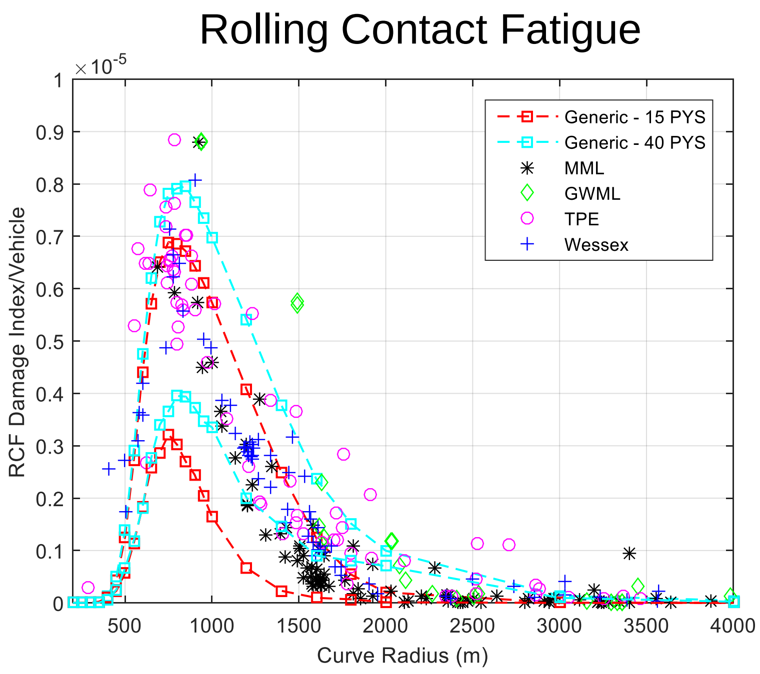


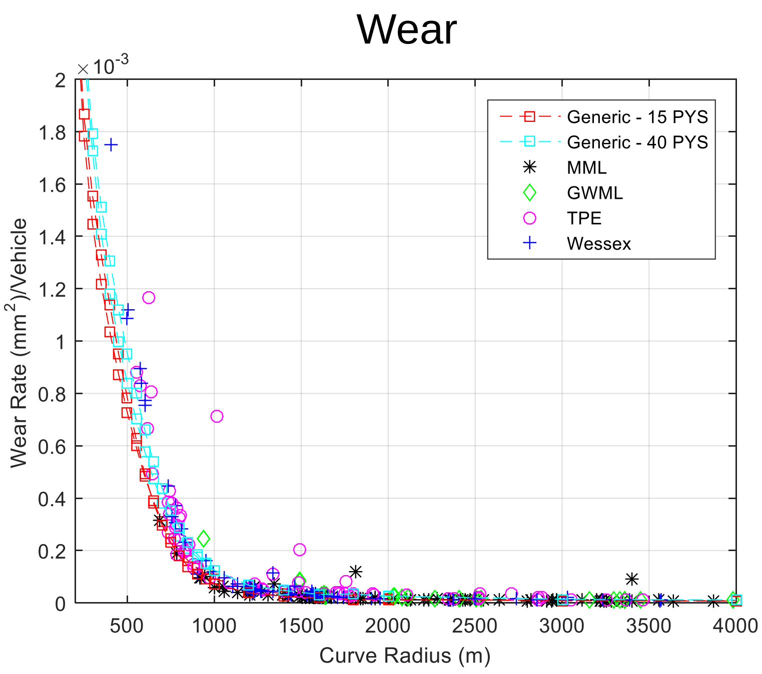

# Damage Susceptibility Criteria

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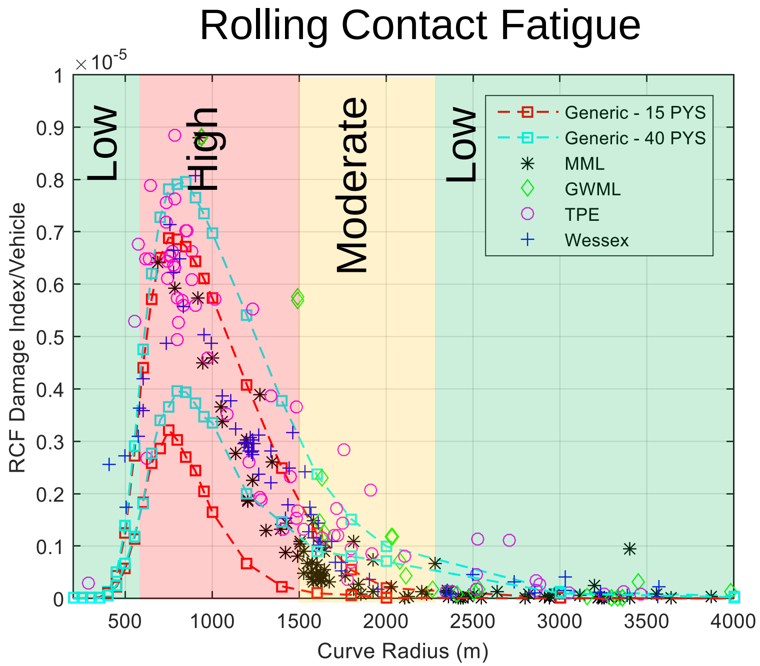


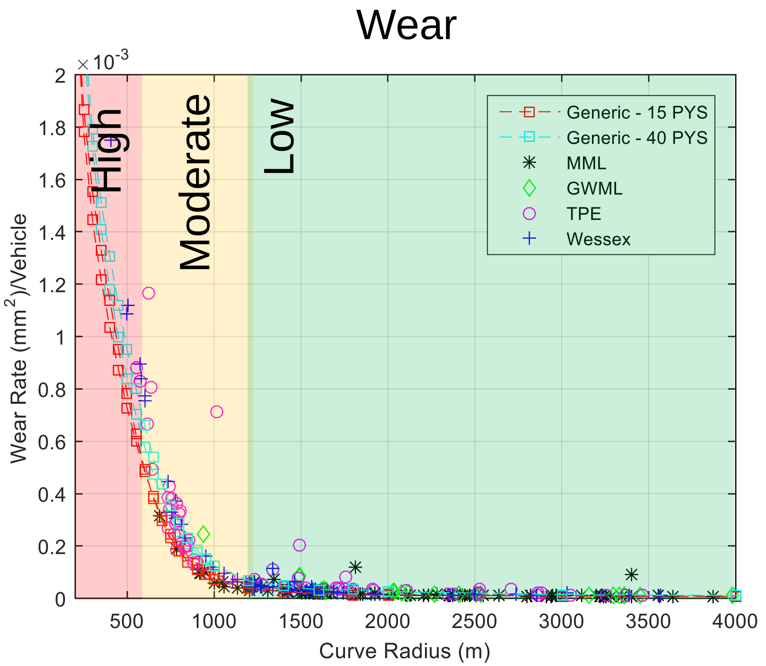

# Damage Susceptibility Criteria

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| **Curve Radius (m)** | **Damage Susceptibility** | | **Rail Degradation Mechanisms** |
|---|---|---|---|
| | **RCF** | **Wear** | |
| < 600 | Low | High | High rail – side wear<br>Low rail – plastic deformation |
| 600 – 1500 | High | Moderate | High rail – RCF and side wear |
| 1500 – 2500 | Moderate | Low | High rail – RCF |
| > 2500 | Low | Low | Vertical wear, squats and corrugation |

# Damage Susceptibility Criteria

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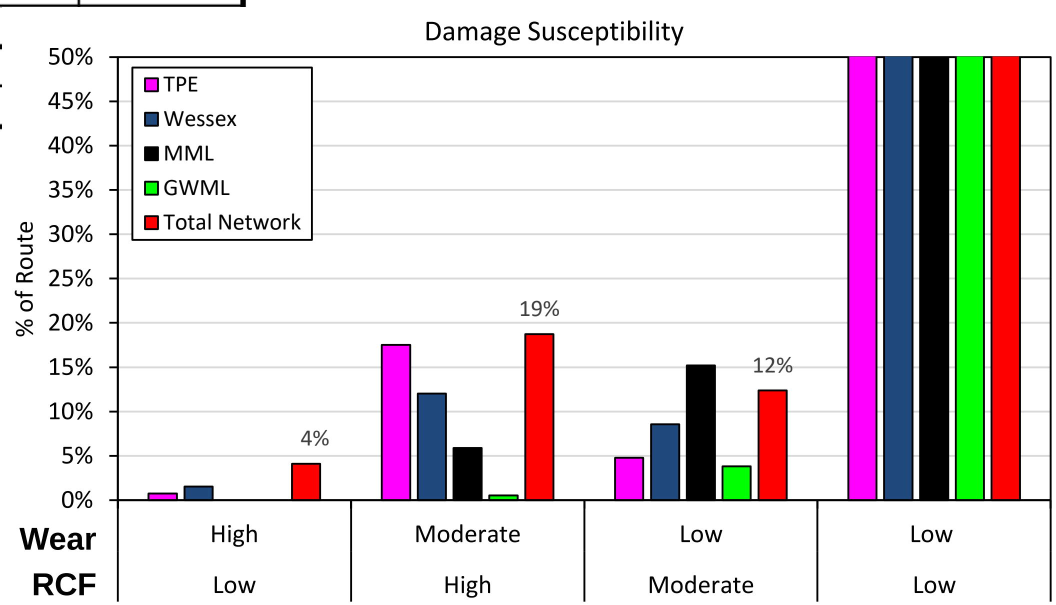
| | | Damage Susceptibility | | | |
|---|---|---|---|---|---|
| **Route** | **Curve Radius (m)** | **< 600** | **600 - 1500** | **1500 - 2500** | **> 2500** |
| | **RCF** | **Low** | **High** | **Moderate** | **Low** |
| | **Wear** | **High** | **Moderate** | **Low** | **Low** |
| **TPE** | No. segments | 3 | 38 | 15 | 74 |
| | Route miles | 0.5 | 11.7 | 3.2 | 25.0 |
| **Wessex** | No. segments | 5 | 32 | 18 | 87 |
| | Route miles | 1.1 | 8.9 | 6.3 | 39.9 |
| **MML** | No. segments | 0 | 20 | 43 | 111 |
| | Route miles | 0.0 | 7.5 | 19.4 | 69.3 |
| **GWML** | No. segments | 0 | 4 | 10 | 147 |
| | Route miles | 0.0 | 0.6 | 4.3 | 95.8 |
| **Routes Total** | No. segments | 8 | 94 | 86 | 419 |
| | Total Route miles | 1.6 | 28.7 | 33.2 | |
| **Total Network** | **No. segments*** | **152** | **1031** | **862** | |
| | **Track miles** | **740** | **3376** | **2230** | |



# Available Rail Steels



| Steel Grade Category | Steel Grade | Composition (Liquid), % by mass | | | | | | | | TS, min. | Elongation, min, % | Hardness Range (HBW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Si | Mn | P max | S, Max | Cr, max | V, max | N, max | Mpa | | |
| "Soft" | R200 | 0.40-0.60 | 0.15-0.58 | 0.70-1.20 | 0.035 | 0.035 | 0.15 | 0.03 | 0.009 | 680 | 14 | 200 to 240 |
| | R220 | 0.50-0.60 | 0.20-0.60 | 1.00-1.25 | 0.025 | 0.025 | 0.15 | 0.03 | 0.009 | 770 | 12 | 220 to 260 |
| Standard | R260 | 0.62-0.80 | 0.15-0.58 | 0.70-1.20 | 0.025 | 0.025 | 0.15 | 0.03 | 0.009 | 880 | 10 | 260 to 300 |
| | R260Mn | 0.55-0.75 | 0.15-0.60 | 1.30-1.70 | 0.025 | 0.025 | 0.15 | 0.03 | 0.009 | 880 | 10 | 260 to 300 |
| Intermediate Non Heat Treated | R320Cr | 0.60-0.80 | 0.50-1.10 | 0.80-1.20 | 0.02 | 0.025 | 0.80 - 1.20 | 0.03 | 0.009 | 1080 | 9 | 320 to 360 |
| Hard Heat Treated | R350HT | 0.72-0.80 | 0.15-0.58 | 0.70-1.20 | 0.02 | 0.025 | 0.15 | 0.03 | 0.009 | 1175 | 9 | 350 to 390 |
| | R350LHT | 0.72-0.80 | 0.15-0.58 | 0.70-1.20 | 0.02 | 0.025 | 0.3 | 0.03 | 0.009 | 1175 | 9 | 350 to 390 |
| Hardest Heat Treated | R370CrHT | 0.70-0.82 | 0.40-1.00 | 0.70-1.10 | 0.02 | 0.02 | 0.40 - 0.60 | 0.03 | 0.009 | 1280 | 9 | 370 to 410 |
| | R400HT | 0.90-1.05 | 0.20-0.60 | 1.00-1.30 | 0.02 | 0.02 | 0.30 | 0.03 | 0.009 | 1280 | 9 | 400 to 440 |
| New Steel Grades not yet with EN Specifications | | | | | | | | | | | | |
| Tata Steel As-Rolled Hypereutectoid Steel | HP335 | 0.87-0.97 | 0.75-1.00 | 0.75 – 1.00 | ≤0.02 | 0.008 – 0.025 | ≤ 0.10 | 0.09 - 0.13 | ≤ 0.006 | 1150 | 7 | 335 minimum |
| Tata Steel As-Rolled Carbide-Free Bainitic Steel | B320 Contains 0.10-0.20% Mo | 0.15-0.25 | 1.00-1.50 | 1.40-1.70 | - | - | 0.30 - 0.70 | 0.10 - 0.20 | - | 1100 – 1200 | 14 - 17 | 320 to 340 |
| | B360 Contains 0.10-0.20% Mo | 0.25-0.35 | 1.00-1.50 | 1.40-1.70 | - | - | 0.30 - 0.70 | < 0.03 | - | 1200 – 1300 | 13 - 16 | 360 to 390 |
| Voestalpine Heat Treated Bainitic Steel | DOBAIN | 0.76-0.84 | 0.20-0.35 | 0.80-0.90 | - | - | 0.40 - 0.55 | - | - | 1400 | 9 | >430 |

# Available Rail Steels – Attributes

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| Steel Grade | Fracture Toughness [MPa m1/2] | | Max. Fatigue crack growth rate, [m/Gc] | | Fatigue strength | Residual stress | Hardness | Tensile Strength | Elongation |
|---|---|---|---|---|---|---|---|---|---|
| | Min. single value | Min. mean value | Delta K= 10, [MPam1/2] | Delta K= 13, [Mpam1/2] | | [MPa] | [HBW] | [MPa] | [%] |
| R200 | 30 | 35 | Not specified | | 5X106 Cycles for total strain amplitude of 0.00135 | <250 | 200-240 | 680 | 14 |
| R220 | 30 | 35 | 17 | 55 | | <250 | 220-260 | 770 | 12 |
| R260 | 26 | 29 | 17 | 55 | | <250 | 260-300 | 880 | 10 |
| R260Mn | 26 | 29 | 17 | 55 | | <250 | 260-300 | 880 | 10 |
| R320Cr | 24 | 26 | Not specified | | | <250 | 320-360 | 1080 | 9 |
| R350HT | 30 | 32 | 17 | 55 | | <250 | 350-390 | 1175 | 9 |
| R350LHT | 26 | 29 | 17 | 55 | | <250 | 350-390 | 1175 | 9 |
| R370CrHT | 26 | 29 | 17 | 55 | | <250 | 370-410 | 1280 | 9 |
| R400HT | 26 | 29 | 17 | 55 | | <250 | 400-440 | 1280 | 9 |
| HP335 | 27 | 31 | <12 | <34 | Compliant | <250 | 335-380 | 1150 | 7 |
| B320 | Data not available but believed to be compliant with current specifications | | | | | <250 | 320-340 | 1100 | 14 |
| B360 | | | | | | <250 | 360-390 | 1200 | 13 |
| DOBAIN380 | | | | | | <250 | 380-420 | 1250 | 10 |
| DOBAIN430 | | | | | | <250 | >430 | 1400 | 9 |

- **Key properties specified in EN13674-1: 2011**
- **How are they related to in-service performance**
- **How should they be used for the selection of rail grades**

# Response of Rail Microstructures

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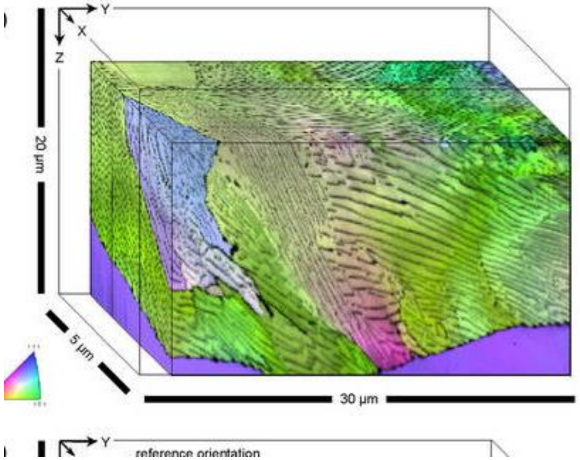


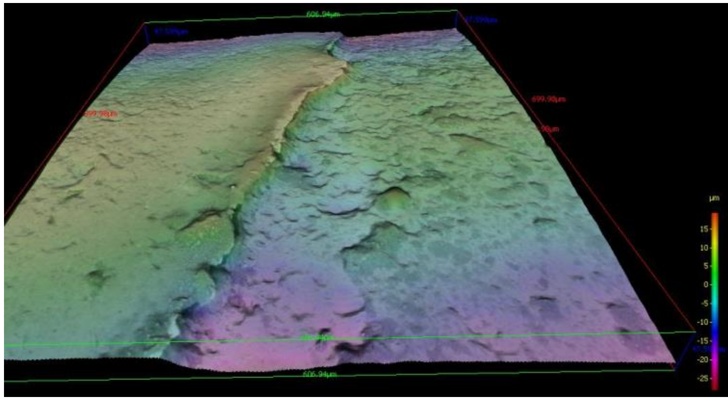

- Virtually all rail steels in use today have a pearlitic microstructure comprising a lamellar of “soft ferrite” and “hard cementite”
- Pearlite is a 3-dimensional entity and the wheel encounters both the ferrite & cementite laths at a wide range of orientations
- How does this composite microstructure react to ratchetting?

# Comparing Wear Resistance

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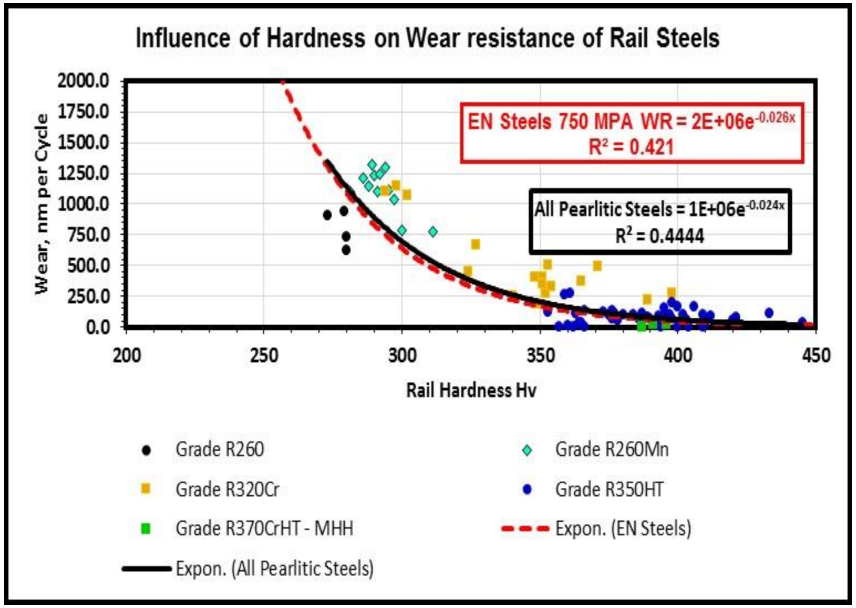


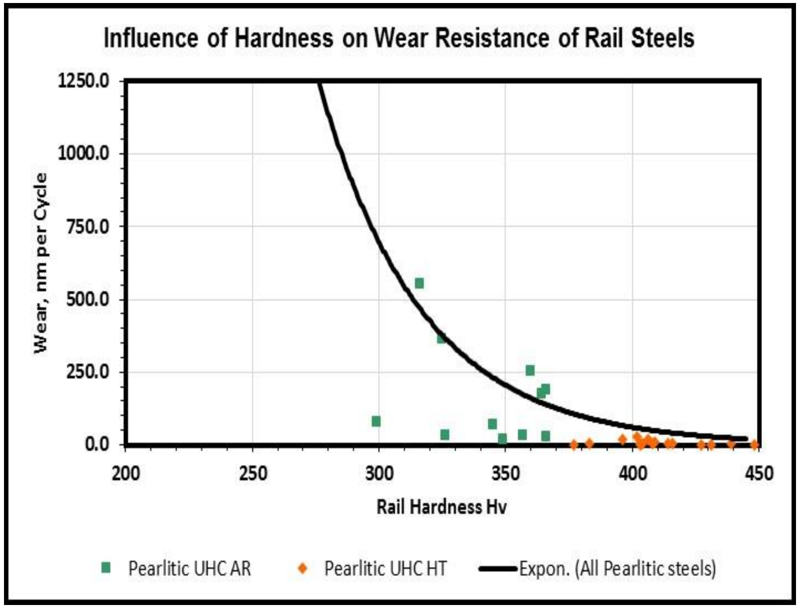


- Hardness is a very good indication of resistance to wear for both as-rolled and heat treated grades in EN
- Ultra high carbon steels provide very good resistance to wear - both as-rolled & heat treated conditions
- Optimised HP335 composition has wear resistance equivalent to much harder grades – What microstructural features impart this attribute?
- Can laboratory twin disc test results represent side wear?

# Comparing RCF Resistance

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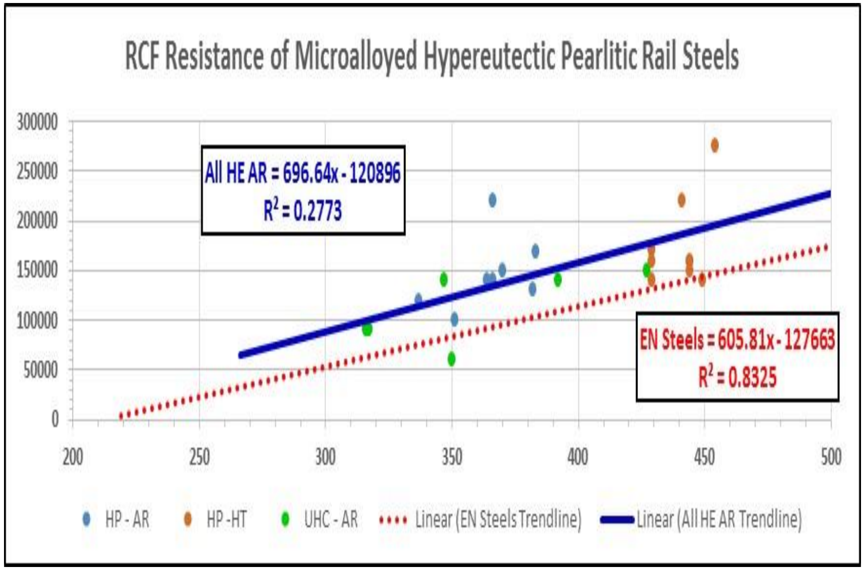


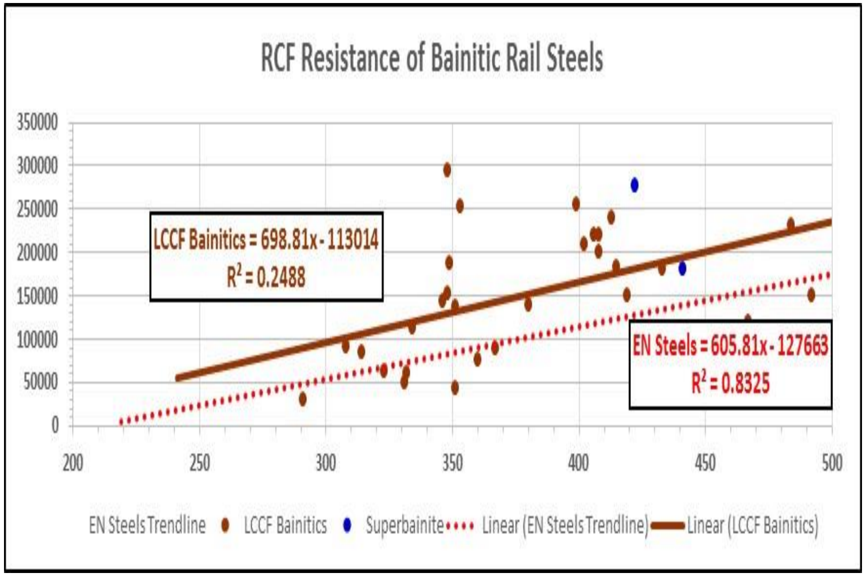


- Resistance to RCF also increases linearly with hardness for the full range of steels in EN 13674-1:2011
- Resistance to RCF of UHC steels optimally alloyed with Si, V, N (HP335) also increases linearly with hardness but is displaced to great resistance than other pearlitic steels within EN
- Hypothesis exists for this improved performance but more systematic investigation needed for validation

# Comparing Resistance to Plastic Deformation

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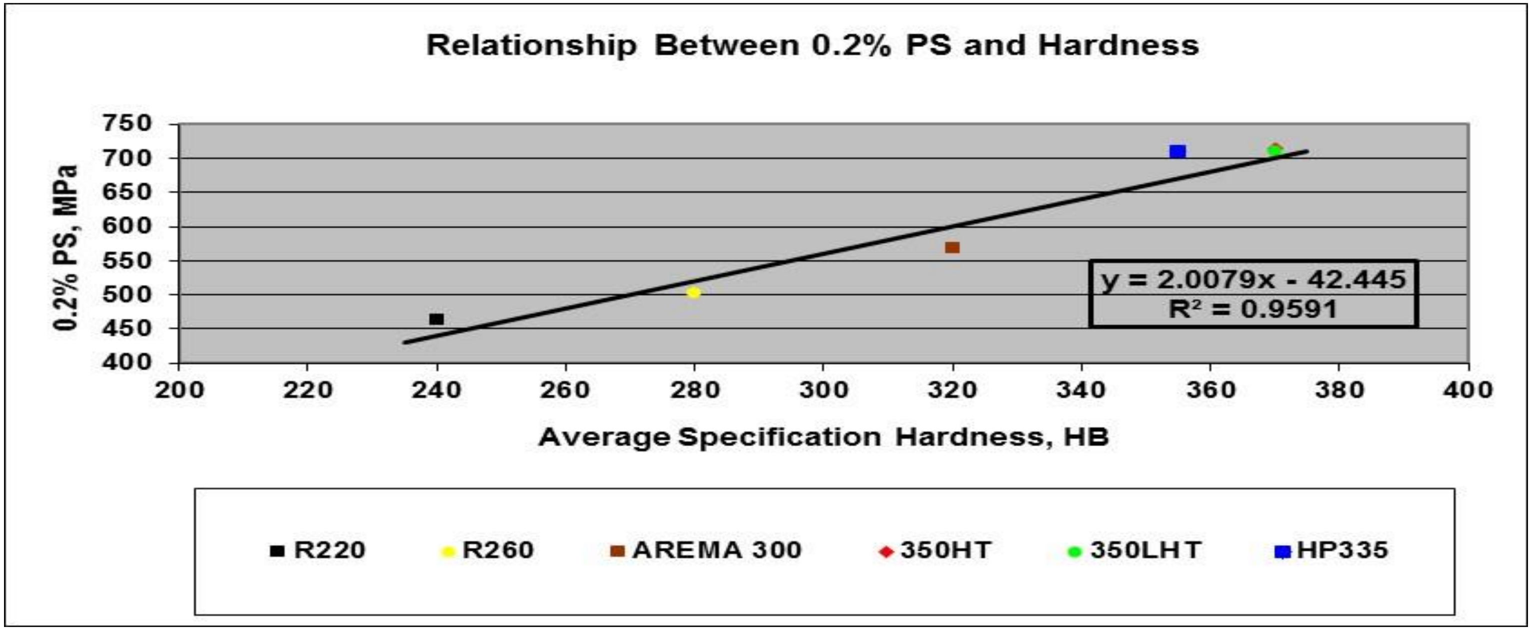


- 0.2% PS shows a linear dependence on hardness
- Is resistance to plastic deformation just governed by 0.2% PS?
- Samples of low rail of different grades need to be analysed to establish material flow patterns

# Economic Modelling

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- Aims to quantify the costs and benefits from using new rail steel grades
- Workshop held with NR to help understand and quantify costs and benefits of using premium rail steel grades
  - Additional benefits not captured in current cost models (e.g. VTISM) identified (e.g. availability, reliability, safety, environmental)
- Initial VTISM modelling undertaken (on 4 selected routes) to identify potential costs savings from deployment of premium rail on entire routes
  - Further benefits may be obtained from optimum deployment of steel in correct locations
- Further work on-going to improve the cost benefit analysis in collaboration with NR

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# RCF and Wear Costs

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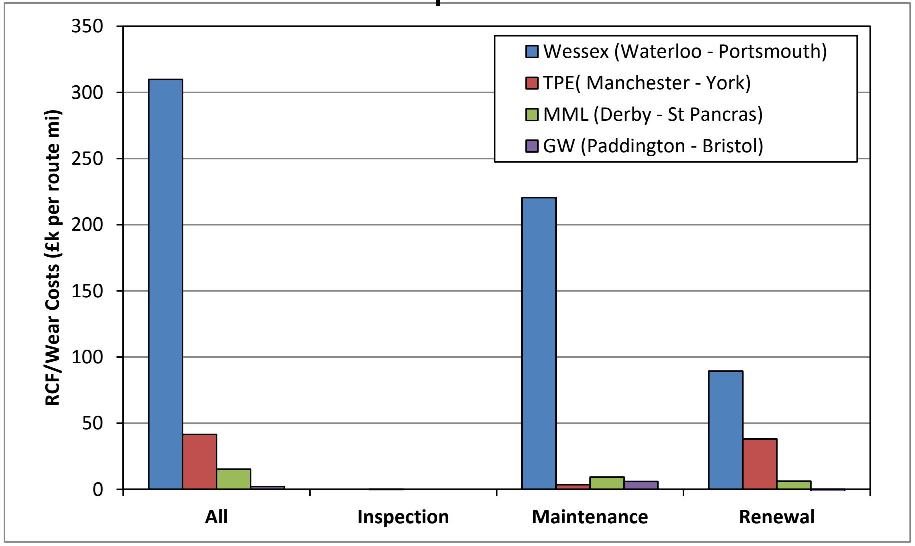
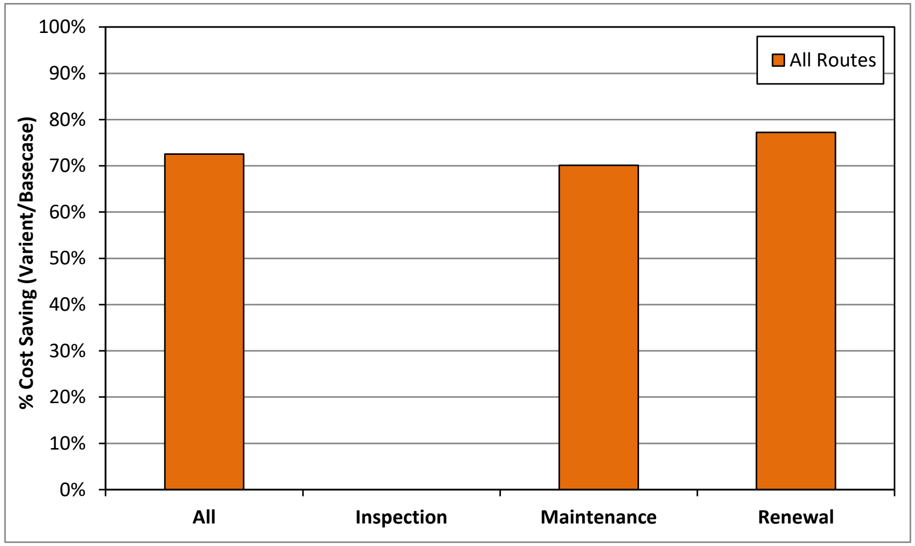
- RCF and wear damage rates reduced based on observations from previous HP335 trial sites
- Grinding interval for all track sections = 45MGT
  - Lower damage depth ≈ less metal removal required during grinding

Total costs per route mile




% cost savings from premium rail



# Discussion and Recommendations

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- A number of GB routes segmented based on track characteristics
- Susceptibility of these segments to RCF and wear damage quantified to support selection of optimum rail steel grade to maximise life
- Experimental data for a range of steel grades have been compared to quantify resistance to key damage mechanisms
  - Further controlled testing and microstructural assessment of the full matrix of rail steels is on-going – a singularly **unique** database for the industry
- Research has helped to quantify the benefits of current NR strategy for rail steel grade selection

# Application of Premium Rail Steels

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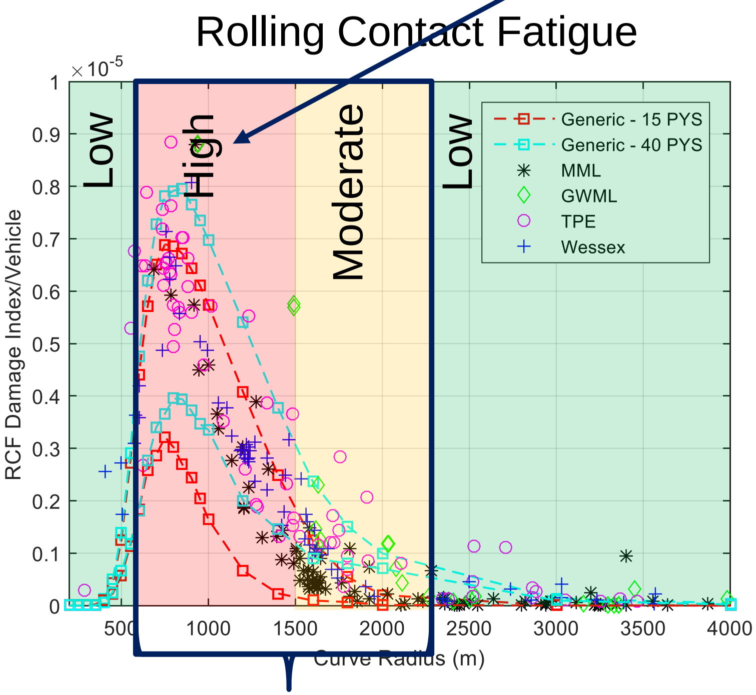
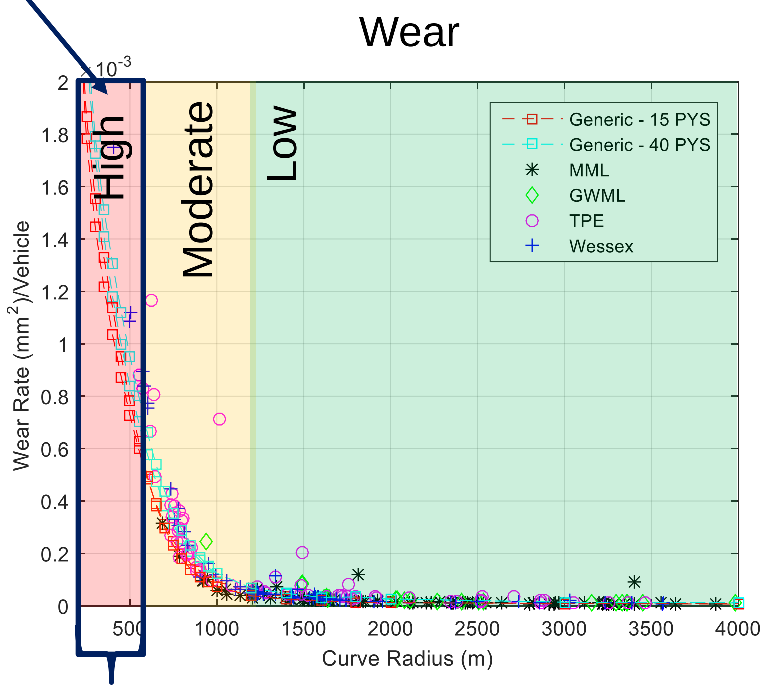
To reduce whole life costs, *premium rail steels* should be *considered* for use in critical curves where *RCF* or *wear* causes the premature replacement of the rail




Used in moderate curves to preserve the ground rail profile and increase the *resistance to RCF*

Used in in tight radius curves with a *high wear rate*

# Acknowledgements

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- This research was financed under EPSRC grant EP/M023303/1 “Designing steel composition and microstructure to better resist degradation during wheel-rail contact"
- In collaboration with:
  - Rail Safety and Standards Board (RSSB)
  - Department of Transport
  - University of Cambridge
  - University of Leeds
  - Cranfield University