Judicious Selection of Available Rail Steels to Reduce Life Cycle Costs

Dr Adam Bevan[1*], Dr Jay Jaiswal[1], Prof Andrew Smith[2],
Dr Manuel Ojeda Cabral[2]

[1] Institute of Railway Research, University of Huddersfield, Huddersfield, Queensgate, HD1 3DH (*a.j.bevan@hud.ac.uk)

[2] Institute of Transport Studies (ITS), University of Leeds, Leeds

Abstract

The rate of rail degradation and hence its expected life is not uniform throughout any railway network and is governed by a combination of track, traffic and operating characteristics in addition to the metallurgical attributes of the rail steel. Consequently, it is suggested that any route or network is not a single linear asset but is a compilation of individual segments with different track characteristics, degradation rates and expected life spans. Thus, the choice of rail steel grade to maximise life (and minimise life cycle costs) needs to combine knowledge of the metallurgical attributes of the available rail steels with the conditions prevailing at the wheel-rail and vehicle-track interfaces; whilst also considering the economic costs and benefits of the different options. This paper focuses on the classification of the susceptibility to rail degradation in various parts of a mixed-traffic network using vehicle dynamics simulation. The metallurgical attributes of the currently available rail steels are summarised along with an assessment of the life cycle costs and wider economic implications associated with selection of a rail steel which provides improved resistance to the key degradation mechanisms of rolling contact fatigue and wear. Overall the proposed methodology, which incorporates engineering, metallurgical and economic assessments, provides guidance on the circumstances in which the introduction of alternative rail steels make sense (or not) from an economic perspective.

1. Introduction

Optimum selection of materials is a key requirement to achieve reductions in whole-life costs of the railway system through increased asset life and reduced maintenance while realising performance improvements through increased service availability and reliability. Selecting the optimum materials for wheels and rails is a complex task with many conflicting requirements, including: a range of failure mechanisms, operating conditions and the associated economic and financial implications.

Recent research has focused on investigating changes to vehicle-track characteristics (e.g. wheel profile design, lower vehicle primary yaw stiffness, increases in cant deficiency) to reduce the forces and damage generated at the wheel-rail interface [1, 2], whereas less effort has been spent on increasing the resistance of the materials to the imposed forces.

Historically the industry has relied upon testing of properties such as hardness and tensile strength and to a limited extent comparative assessment of wear resistance under simplified contact conditions. However, there is a knowledge gap in the understanding of the influence of microstructural constituents of various steel types on their ability to counter effectively other damage mechanisms such as rolling contact fatigue (RCF), plastic deformation and corrugation.

To address these gaps the aim of the first phase of this research was to understand the response of various microstructural constituents of steels to the loads imposed on them during wheel-rail contact, identify the characteristics of the steel which are important to resist the key degradation mechanisms and develop a methodology for optimising steel grade choices at a granular level based on the outputs from a cost-benefit analysis. This paper summarises some of the outputs from this research and focuses on the classification of the susceptibility to rail degradation in various parts of a mixed-traffic network, the metallurgical attributes of the currently available rail steels and the economic assessment of the life cycle costs and wider economic impacts associated with selection of an alternative rail steel which provides improved resistance to the key degradation mechanisms of RCF and wear.

2. Background

Recent developments in rail steels have shown, through laboratory and in-track testing undertaken by rail manufacturers and infrastructure maintainers, that improvements in the resistance to both wear and RCF can be achieved through judicious choice of alloying elements to alter the microstructural characteristic of the steel (e.g. HP335 rail, developed in the UK by British Steel (formerly Tata Steel)) and successfully deployed at a number of sites by Network Rail [3], and carbide-free bainitic steels, developed in France and deployed in Eurotunnel (carried >1000 MGT without developing RCF and the consequent need for grinding) and by SNCF on High Speed Crossings to address severe Head Checking (HC) rail defects. However, the understanding of the reasons for the success of such steels requires further fundamental research.

A total of nine pearlitic steel grades covering levels of hardness between 200 HBW and 440 HBW are defined in current EN standards [4]. Rail manufacturers have more recently also developed a variety of new steels which have been shown, through laboratory and in-track testing to provide improved resistance to key degradation mechanisms of wear and RCF. The composition and properties of these steels are compared in this paper, however these properties do not fully define the potential performance of new rail steel grades. Therefore, further research is required to understand the influence of steel microstructures on the resistance of the material to damage.

The primary drivers for developments in rail metallurgy are to increase their resistance to the key degradation mechanisms of wear, RCF and plastic deformation.

- Rail wear – remains a significant cost driver for European railways. Only approx. 20 – 30% of the rail section weight is available for consumption through wear. Therefore there is a need to maximise the life of this 20% of rail weight through a reduction in the rate of wear. Current increases in traffic density make the reduction in wear rate even more desirable in order to increase track availability.
- Rail RCF – A key cost driver in most railways arising from increased costs of grinding and inspection and premature replacement before the rail has reached the wear limit.

- Plastic deformation – A further cause of premature rail replacement, particularly on the low rail of highly canted track or routes with high volumes of freight traffic, both of which generate high forces on the low rail.

3. Methodology for Determining Susceptibility to Rail Degradation

The railway is a complex web of interconnected systems whose hub is the contact between the wheel and rail. Running steel wheels on steel rails leads to arduous contact conditions that place very challenging demands on the maintenance of track. Damage to the rail (and wheel) is dependent on the characteristics of the vehicle and track. In the context of the track; this includes the rail, fastening system, sleepers and finally the substructure and formation. Thus, durability and longevity of rail has very significant implications for the other components and the life cycle costs of the track system. The complexity of the entire system is, therefore, very apparent and hence the determination of the conditions that any rail has to endure requires consideration for long stretches of track, such as entire routes or networks, together with the full range of vehicle types that operate on the network.

The methodology developed to determine the susceptibility to rail degradation for the selected routes of the GB railway network is summarised in Figure 1 and described briefly in the subsequent sub-sections. This methodology builds on previous work conducted by the authors and other researchers in the field [5, 6 and 7].

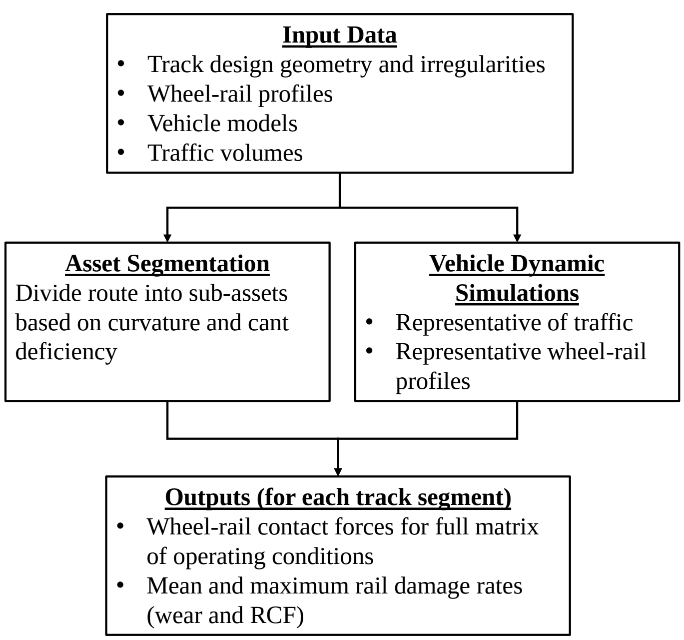


Figure 1 Methodology for determining susceptibility to rail degradation

3.1. Input data

The input data, as defined in Figure 1, required to determine the susceptibility to rail degradation and for use in vehicle dynamic simulations are in the majority of cases routinely captured as part of the asset management process.

Data acquired by the track recording vehicle (TRV) is utilised to describe the horizontal and vertical alignment features of the track geometry. This includes the long wavelength track features associated with curvature and crosslevel and shorter wavelength data typically associated with lateral and vertical track irregularities. The data acquired from the TRV is post-processed to generate a track irregularity file for input into the Vampire vehicle dynamic simulations.

A vehicle speed profile is generated for each vehicle type based on the linespeed and representative acceleration and braking rates. Using the developed vehicle speed profile, the traction at each axle can also be determined for each vehicle type by calculating the resistance due to acceleration, braking and aerodynamic effects. These are combined using empirical formulas to produce an estimate of the torque at each axle which is applied within the vehicle dynamic simulations.

In order to get an accurate representation of the wheel-rail contact conditions seen on track, a statistical distribution of actual measured wheel and rail profiles from all vehicle types and routes being modelled should be used. In the simulation cases presented in this paper representative worn wheel profiles were selected to represent the distribution of wheel wear for the vehicle types operating on the simulated routes. Worn rail profiles were selected to represent the typical shape of the rail head seen in tangent, shallow and tight radius curves. These profiles were varied through the route simulation depending on the actual curve radius.

Mathematical models of the range of rolling stock which operate the analysed routes were developed in the Vampire vehicle dynamics package. These models include wheelsets, bogies and car body masses interconnected with suspension elements which include non-linear characteristics and estimates of dynamic stiffening of rubber elements where appropriate. The models were developed based on the available parameters, with interpolation and engineering judgement applied as necessary to deduce values for the unknown parameters. The vehicle models were validated against laboratory or in-service test data where possible.

3.2. Asset segmentation

In general, development of rail steels has been largely left to the manufacturers while deployment of the available rail steels has been the responsibility of the Infrastructure Manager (IM) with frequent delegation to the experience of the track engineer with local knowledge. In view of the very significant progress in the understanding of wheel-rail contact conditions that govern the two most common rail degradation mechanisms of wear and RCF, a methodology of segmenting a route or network into sub-asset segments is proposed that permits their classification based on their susceptibility to the known degradation mechanisms. A more detailed description of the segmentation approach is presented in deliverable D1.2.5 from the Innotrack project [6], which treated all structures and S&C etc. as separate segments with their own rates of degradation.

To illustrate the segmentation approach 4 routes with different vehicle-track characteristics have been selected. Whilst all of these routes consist of ballasted track, the curve distribution, traffic levels and vehicle types are different. This allowed the influence of these characteristics on the predicted damage susceptibility to be investigated. These routes are highlighted in Figure 2 and included the Great Western (GWML) and Midland (MML) mainlines along with the Trans-pennine (TPE) and Wessex routes. The results from the segmentation of the 4 selected routes from the GB rail network are summarised below.

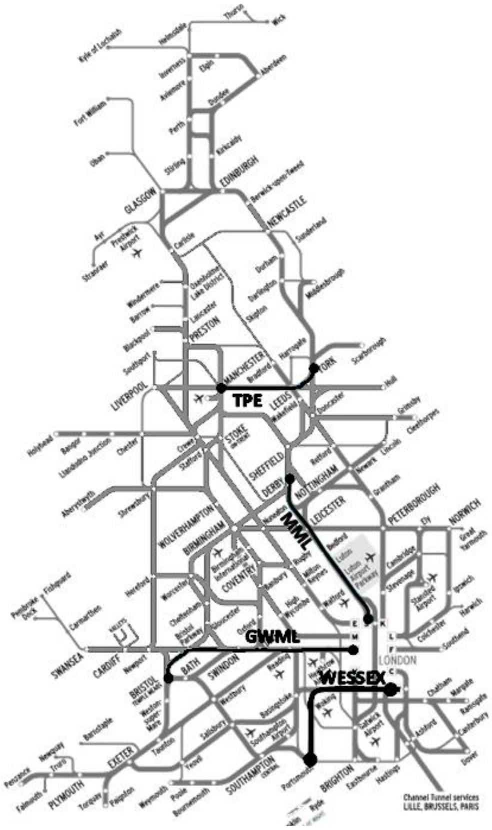


Figure 2 Selected analysis routes – Trans Pennie (TPE), Midland Mainline (MML), Great Western Mainline (GWML) and Wessex

Figure 3 shows a comparison of the curve distribution for the 4 selected routes. Excluding the tangent sections (e.g. R > 5000 m), it can be seen that as expected the mainline routes (MML and GWML) consist of the largest proportion of shallow radius curves (e.g. 5000 m < R > 2000 m), whilst the TPW and Wessex routes contain the largest proportion of moderate to small radius curves (e.g. R < 1500 m)

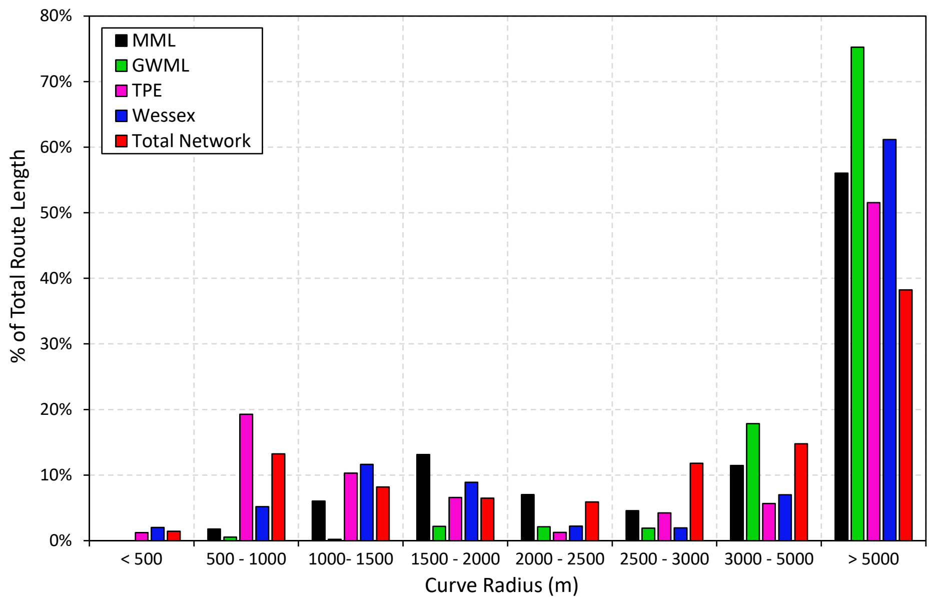


Figure 3 Comparison of curve distribution for selected routes

Each of the 4 routes were segmented into sub-assets based on curve radius and cant deficiency. If required, the segmentation process can be extended to treat rails within structures such a bridges, tunnels, and S&C as separate segments so that their different degradation behavior is better reflected. Similarly, other parameters, such as gradient, track type, and tonnage carried, can also be considered to provide a more refined criteria of segmentation. A routine was developed in Matlab to read in the TRV data and identify the location of the start and end of each curve, curve transition and tangent track section, as illustrated in Figure 4. The curve radius, applied cant and resulting cant deficiency are determined for each segment which is summarised in a route asset database.

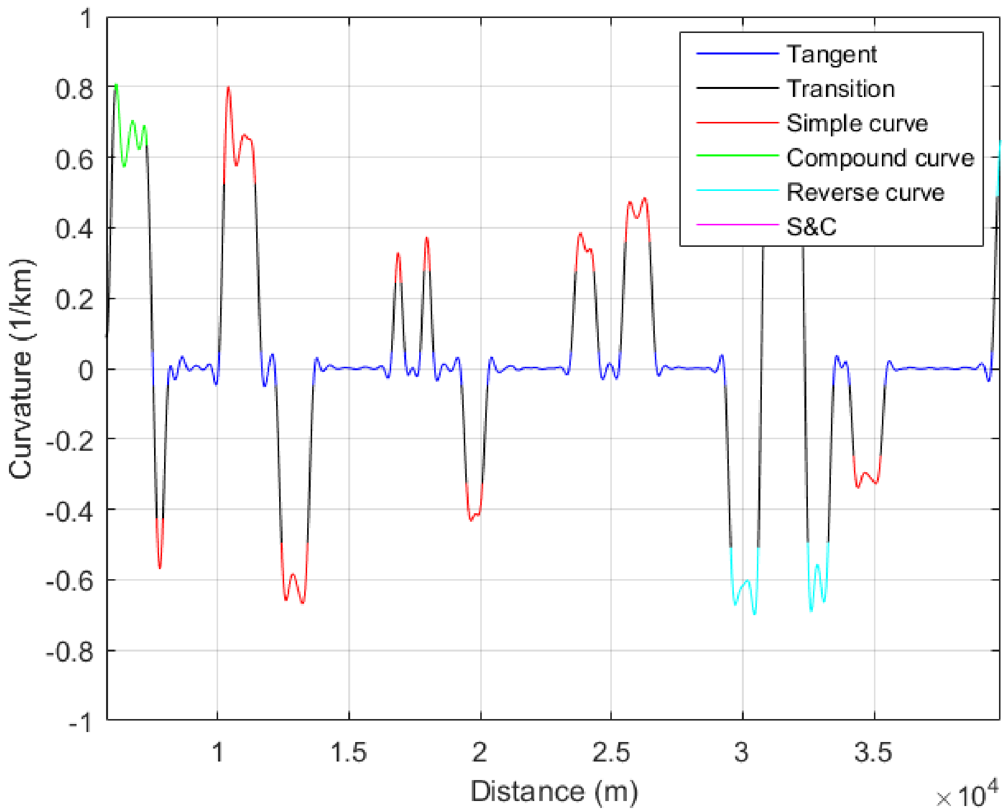


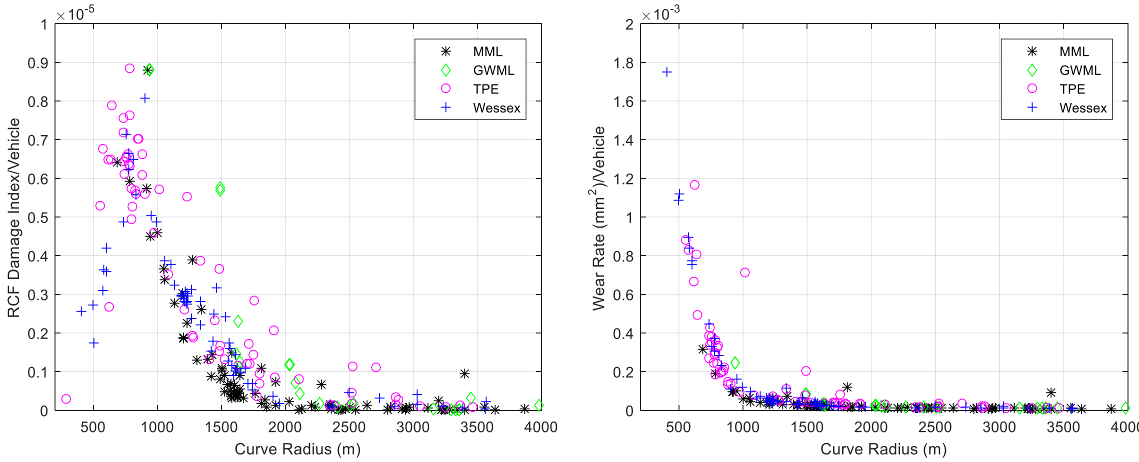
Figure 4 Example track segmentation by curve radius

3.3. Vehicle dynamic simulation and damage susceptibility

Vehicle dynamic route simulations were undertaken for the 4 selected routes using the measured TRV track geometry data. A range of vehicle models, representative of the vehicle types which operate on each of the routes, were simulated operating on their respective routes with new and worn wheel-rail profiles. The forces at the wheel-rail contact were output for inclusion in the rail damage modelling.

The susceptibility of a track segment to wear and RCF damage was predicted using the Whole Life Rail Model (WLRM) [7]. This includes an RCF damage function, which incorporates the interaction of RCF and wear, to predict the RCF propensity (defined as RCF Damage Index/vehicle, where a cumulated value of 1 is required for the formation of a visible crack) and a separate wear damage function (based on work by British Rail Research [8, 9]) to predict the loss of rail cross-section due to wear. Both of these damage functions relate the energy dissipated on the contact patch ($T\gamma$), output from the vehicle dynamic simulations, to damage. The calculated damage is accumulated considering the total number of axle passages over a given section of track for each vehicle type. It also considers the location of the wheel-rail contact patch on the rail, the direction of the creep forces and the influence of wear reducing the propensity of RCF cracking.

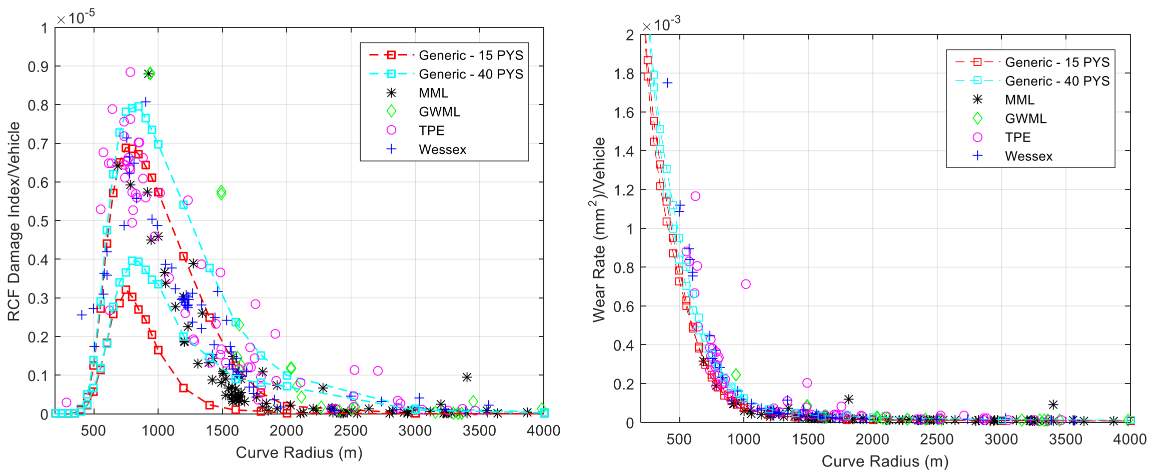
The mean susceptibility to RCF and wear damage for each track segment was calculated from the accumulated route damage based on the location of each of the track segments. This is plotted against curve radius in Figure 5 below. Similar trends in both the susceptibility to RCF and wear can be seen on all routes, with an increase in RCF damage as curve radius reduces until a curve radius of approximately 800 m, when RCF damage can be seen to decrease as wear increases. Variations in the predicted damage for each curve radius is associated with differences in cant deficiency.



(a) (b)

Figure 5 Rail damage susceptibility for selected routes – (a) rolling contact fatigue and (b) wear

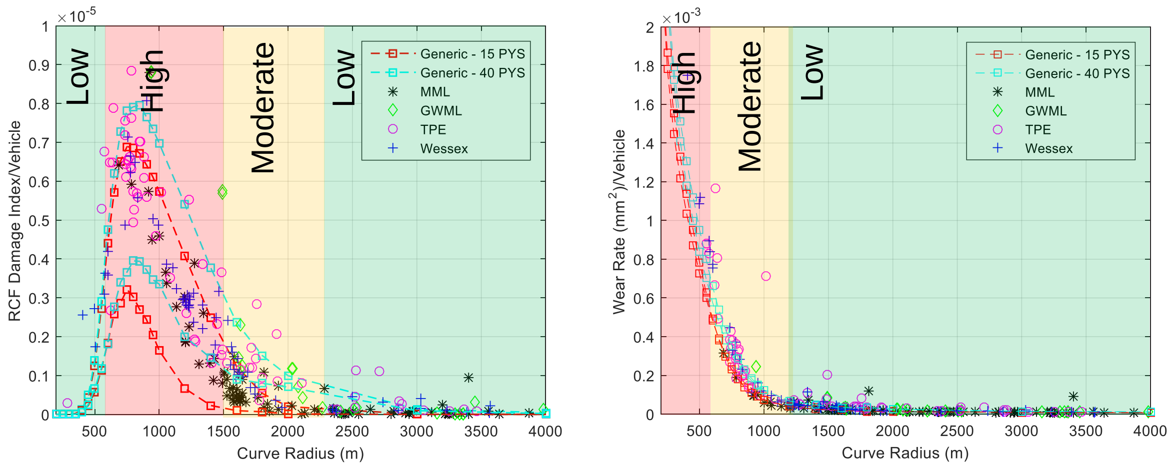
To illustrate the shape of the damage susceptibility map a generic passenger vehicle model (with a primary yaw stiffness (PYS) of 15 MNm/rad and 40 MNm/rad) was simulated on a range of curve radii with two values of cant deficiency. The resulting damage is overlaid on the route damage maps in Figure 6. As expected the poorer curving performance of the higher PYS vehicle and lower cant deficiency results in higher predicted damage. But the shape of the damage map is similar to that generated from the route simulations and illustrates that certain track sections are more susceptible to degradation and thereby the requirement for optimal rail steel grade selection based on track characteristics and damage susceptibility.



(a) (b)

Figure 6 Rail damage susceptibility for generic vehicle model – (a) rolling contact fatigue and (b) wear

Using the rail damage susceptibility maps presented above it is possible to identify regions of these maps which result in high rates of degradation for the selected routes. These have been divided into regions of high, moderate and low susceptibility to RCF and wear damage as highlighted in Figure 7. Due to the interaction of wear and RCF (e.g. wear reducing the formation of RCF damage), track sections with very tight curve radii (e.g. R < 600 m) indicate a low susceptibility to RCF, whereas curves with a radii between 600 m and 1500 m generate less wear and therefore a higher susceptibility to RCF damage. The dominant degradation mechanisms observed in-service for each curve radius band are summarised in Table 1.



(a) (b)

Figure 7 Track sections susceptible to high, moderate and low rail damage – (a) rolling contact fatigue and (b) wear

Table 1 Damage Susceptibility Criteria

Curve Radius Range (m)	**Damage Susceptibility**		**Dominant Degradation Mechanisms**
	RCF	**Wear**	
< 600	Low	High	High rail – side wear Low rail – plastic deformation and corrugation
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

Based on the damage susceptibility criteria defined in Table 1, the total number of track segments and track miles in each band for each route was determined. These are presented in Table 2, along with the assumed values for the entire GB rail network. With the exception of the low damage susceptibility band, mainly associated with tangent track which make up a large proportion of these routes, it can be seen that the high RCF – moderate wear band results in the largest number of track segments and miles.

To illustrate the trends presented in Table 2, the % of total track miles in each of the damage susceptibility bands for each route was determined and is presented in Figure 8.

The results presented in Figure 8 suggests that with standard R260 grade rail steel, 35% of the GB rail network is within the curve radius range which would indicate a moderate to high susceptible to RCF and wear damage.

Table 2 Total number of track segments and miles for each damage susceptibility range

Route	Curve Radius (m)	< 600	600 – 1500	1500 - 2500	> 2500
		Damage Susceptibility			
	RCF	**Low**	**High**	**Moderate**	**Low**
	Wear	**High**	**Moderate**	**Low**	**Low**
TPE	No. segments	3.0	38.0	15.0	74.0
	Track length (km)	0.5	11.7	3.2	25.0
Wessex	No. segments	5.0	32.0	18.0	87.0
	Track length (km)	1.1	8.9	6.3	39.9
MML	No. segments	0.0	20.0	43.0	111.0
	Track length (km)	0.0	7.5	19.4	69.3
GWML	No. segments	0.0	4.0	10.0	147.0
	Track length (km)	0.0	0.6	4.3	95.8
Routes Total	No. segments	8.0	94.0	86.0	419.0
	Track length (km)	1.6	28.7	33.2	230.0
Total Network	No. segments	152	1031	862	6410
	Track length (km)	740.0	3376.0	2230.4	11676.9

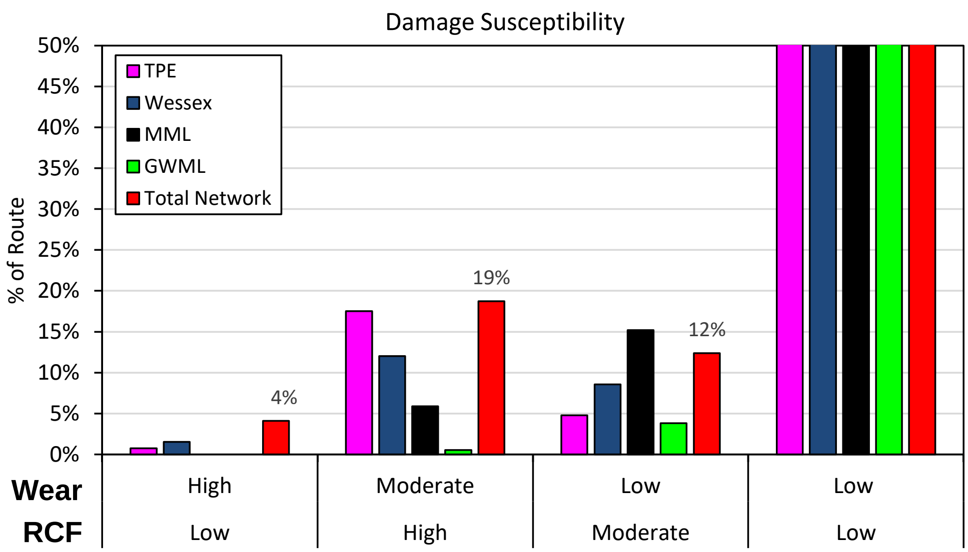


Figure 8 Percentage of total track miles in each damage susceptibility band

4. Key Attributes of Available Rail Steel Grades

EN 13674 -1:+A1 2017 [4] is probably the most widely accepted rail specification for mixed traffic railway networks. It lists a total of 9 rail steel grades for use in conventional and high speed railway tracks. A few additional rail steels that are yet to be included in EN specifications are being offered by the major manufacturers and details of all these grades are shown in Table 1 below.

The steels broadly fall into two categories based on their manufacturing route; non-heat treated (as-rolled) and heat treated rail steels. The non-heat treated steels derive their strength and hardness from the steel composition, whilst the heat treated grades derive their strength from a combination of composition and heat treatment. The steel grades depict a very wide range of hardness values, between 200 and 440 HBW achieved on the running surface. The desire to move to higher hardness steels has been driven by the need to reduce wear and thereby increase the life of the rails, particularly at locations exposed to high wear rates (e.g. tight curve radii).

Although the compositional ranges specified in the standards are very wide, it should be emphasised that manufacturers operate to narrower ranges to ensure the desired properties.

Table 3 Attributes of Available Rail Steels

Steel Grade Category	Steel Grade	Composition (Liquid), % by mass						UTS, min.	Elongation, min, %	Hardness Range (HBW)
		C	Si	Mn	P max	S, Max	Cr, max	Mpa		
"Soft"	R200	0.40-0.60	0.15-0.58	0.70-1.20	0.035	0.035	0.15	680	14	200 to 240
	R220	0.50-0.60	0.20-0.60	1.00-1.25	0.025	0.025	0.15	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	880	10	260 to 300
	R260Mn	0.55-0.75	0.15-0.60	1.30-1.70	0.025	0.025	0.15	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	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	1175	9	350 to 390
	R350LHT	0.72-0.80	0.15-0.58	0.70-1.20	0.02	0.025	0.3	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	1280	9	370 to 410
	R400HT	0.90-1.05	0.20-0.60	1.00-1.30	0.02	0.02	0.30	1280	9	400 to 440
British 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	1150	7	335 minimum
British 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	1100	13	320 min
	B360 Contains 0.10-0.20% Mo	0.25-0.35	1.00-1.50	1.40-1.70	-	-	0.30-0.70	1200	12	360 min
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

A brief commentary on each of the grades detailing their application is also provided in the following subsections.

4.1. Non-heat treated

Grade R200 is the softest grade defined within the EN specifications that has not been deployed in most railway networks for many years, although there may be residual rails left in older track in some networks. It remains in use in tight radii curves of tramway networks [10] in mainland Europe because of the belief that the lower carbon content of this composition better lends itself to the in-situ weld restoration of side wear. However, the French network (SNCF) have recently taken the decision to install this grade on the near straight tracks of their conventional lines (excluding TGV lines) as the increased rate of wear of this composition is thought to wear away the damaged layers and thereby prevent the formation of squat defects. The composition is also considered to be less susceptible to the formation of white etching layer (WEL) and thereby prevent the formation of squat defects. However, the usage of this grade in mainline and metro system tracks is very limited.

Grade R260 is by far the most dominant grade used in metros and mainline track throughout Europe and probably accounts for over 90% of rails in track in Europe. However, increases in traffic density and the desire to reduce frequent maintenance interventions, has led to the replacement of this grade with harder premium grade steels in curves sharper than 3000m. The major factor in favour of the continued use of this grade in straight and shallow radii curves is the vast past experience of maintenance activities, such as weld repairs. Furthermore, the expected life spans of this grade at such locations are sufficiently long, and hence do not justify the increased first costs of premium grade steels.

Grade R260Mn is a variant of R260 with a significantly higher content of Manganese. Although the improved hardenability from the increased concentration of Manganese refines the pearlitic interlamellar spacing, the strength and hardness requirement mandated by EN specifications remains the same as that for Grade R260. The argument often put forward in favour of the use of this grade is that the finer interlamellar spacing, resulting from the higher Manganese content, provides a desirable increase in toughness. However, this theoretical improvement is not reflected in the observed performance of this grade. Furthermore, the increase in hardenability brings about greater challenges in welding, and particularly in repair welding. It should also be emphasized that the usage of this grade is limited to selected railway networks such as the Dutch network.

The desire to increase hardness and thereby increase its resistance to wear led to the development of this Grade R320Cr which is alloyed with much higher levels of Silicon and Chromium to develop a hardness of up to 360 BHN in the as-rolled condition. The highly hardenable composition has a greater susceptibility to the development of harder and less ductile microstructures and specific low temperature rolling techniques had to be established to improve the resulting microstructure and increase tensile elongations. However, the highly-alloyed composition is more difficult to weld, and particularly weld repair. Although the grade is included within the current EN standard, its usage has largely been overtaken by the availability of heat treated grades and, therefore, its inclusion within the specifications is difficult to justify.

4.2. Heat treated

Grade R350HT is the original heat treated rail steel which has the same composition as the standard R260 grade, but used accelerated cooling to increase hardness and tensile strength. Although EN specification permits alloying with up to 0.15% Chromium, the required properties can be equally achieved in accelerated cooled plain carbon-manganese variants. Accelerated cooling is achieved using water, air mist, or polymer in an in-line arrangement after rolling. An alternative is the use of controlled forced air cooling as an off-line post rolling heat treatment. The key difference between the in-line and off-line variants lies in the level of tensile residual stress in the foot. Generally, the rails do not undergo roller straightening after off-line heat treatment and hence have very low levels of longitudinal tensile residual stress in the base of the rail foot and are, therefore, much less susceptible to foot fatigue failures. This grade of steel has been available since the late 1980s and hence is likely to be largest proportion of the premium grade steel installed in European track. MHT rail that was supplied from the Workington plant of British Steel Track Products, is a variant of this grade that was used in many major networks including Network Rail.

Grade R350LHT is a variant of the R350HT grade in which the level of Chromium content has been increased from a maximum of 0.15 to 0.30%. The expected metallurgical contribution of this change in composition is a finer interlamellar spacing of the pearlite, although a similar microstructure could be achieved in R350HT grade with a slightly increased rate of cooling. However, it should be emphasized that the benefits of a marginally finer microstructure under the demanding rail-wheel contact conditions is yet to be proven. The grade can be manufactured using the “in-line” or “off-line” process with the effect on the level of residual stress in the foot identified in the case of Grade R350HT. This grade is used in a few of the smaller networks in mainland Europe such as the Paris Subway and has been selected for the Cross Rail network. The reluctance of wider adoption of this grade by the larger networks in Europe suggests that the claimed benefits of additional alloying elements into the composition have not been convincingly demonstrated.

The relentless desire to develop harder rail steels resulted in the combined use of additional alloying elements and accelerated cooling to achieve finer interlamellar spacing in the pearlitic microstructures. This approach is reflected in the design of the composition Grade 370CrHT, which permits the enrichment of the eutectoid steel composition with up to 0.6% Chromium combined with up to 1.1% Manganese, and 1% Silicon. The composition was tailored for greater hardenability through the use of top end of eutectoid carbon composition with increased Silicon and Chromium contents. The composition is compliant to the low alloy high strength grade in the AREMA standards for heavy haul railways. Such a rich chemistry requires very careful control of the cooling rate during heat treatment and it is reasonable to conclude that the upper levels of alloying elements (except carbon) are at the limit of what can be tolerated while ensuring a pearlitic microstructure after heat treatment. Consequently, it is important to point out that “in-line” heat treatment of this grade poses even more challenges because of the higher hardenability resulting from the larger prior austenite grain size. In the case of “off-line” heat treatment the shorter duration and lower temperature re-austenitisation results in finer grain size which reduces effective hardenability. However, it should also be emphasized that the benefits of very high resistance to wear and RCF, particularly wear, may make it the grade of choice for heavily trafficked tight curves. There has been quite widespread deployment of this grade although it is more targeted at heavy haul operations or in very tight radii curves that experience high levels of wear through hard flange contact.

Grade R400HT is a heat treated hypereutectoid (HE) steel and a range of HE compositions have been used by the heavy haul networks. Inclusion of R400HT in the EN specification is more recent and its application is likely to be restricted to the most demanding segments of mixed traffic networks, as was recommended in the guidelines for rail grade selection produced by the EU FP7 Innotrack project [11]. Since the composition does not incorporate any metallurgical measures to avoid the formation of grain boundary cementite, it is reliant on the control of cooling rate within narrow limits to prevent the formation of this deleterious phase. However, the non-uniform nature of the rail section leads to a wide variation in cooling rate and hence increases the probability of the formation of this phase in the slower cooled parts of the rail, away from the active surface of the head. It is extremely unlikely that the cost benefit analysis of this grade would favour its deployment in Metro networks.

4.3. New Steel Grades

Grade HP335 is a naturally cooled hypereutectoid steel from British Steel that has been approved for use by Network Rail, but not yet included in EN13674-1 2011. The inventors [12] of this rail steel have designed the composition with the follow specific targets:

- Increasing the volume fraction of cementite through an increase in carbon content. This objective provided the synergistic benefit of increased hardenability to refine the cementite lath thickness and the interlamellar spacing. Increasing the volume fraction of cementite ensures that this hard phase is the dominant phase at the rail-wheel interface and thereby imparts the desired reduction in wear and increased resistance to ratcheting and RCF.
- Increasing the strength of the pearlitic ferrite through solid solution strengthening from silicon additions and precipitation strengthening through vanadium addition. Additions of both silicon and vanadium have the synergistic effect of preventing/minimising the formation of potentially deleterious grain boundary cementite networks.
- Precise control of nitrogen and vanadium contents to capitalise on the hardenability effect of vanadium additions and to ensure the correct magnitude of lower temperature finer vanadium carbide precipitates within the pearlitic ferrite.

In contrast to the R400HT grade included in EN specification, the composition of HP335 was tailored to prevent the formation of grain boundary cementite and thereby achieve the desired property combination of high resistance to both wear and RCF. Although Network Rail was the first IM that approved the usage of this grade based on extensive laboratory and field testing. Regular monitoring of many sites has demonstrated significant increase in resistance to all the three key degradation mechanisms of wear, RCF, and plastic deformation. Network Rail has already installed >700 km of track with this grade and is its preferred premium grade rail steel. This grade has also been approved by several other networks- Irish Rail, LUL, Translink, and many UK tramways [10bExtensive research [13, 14, 15, 16 and 17] has been undertaken in the subject area of bainitic rail steels but meaningful commercial exploitation of any bainitic composition remains a step beyond. In metallurgical context, the term bainite covers a wide range of microstructures from the coarse upper bainite that begins to form at temperatures ~540^{0}C to the lower bainite that forms at temperatures down to ~180^{0}C [18]. In addition, highly alloyed low carbon steels have been developed whose microstructures are characterised by the absence of carbides. The grades that have been promoted by two of the major European rail manufacturers are:

- Grade B320 is a low carbon carbide-free bainitic steel [19] from British Steel. It is a highly alloyed composition with additions of Si, Mn, Cr, V, and Mo to yield a carbide free microstructure comprising bainite and austenite upon natural cooling following hot rolling. Although wear resistance of the grade is similar to R260, it offers excellent resistance to RCF and has given a long grinding-free life in a 4000 m radius curve in the Eurotunnel, carrying > 100 MGT per year. The grade is known to be weldable using flash butt and aluminothermic processes and the low carbon content also facilitates weld repair techniques. However, any benefits of the deployment of this grade in metro systems that are characterised by tight radii and high traffic density remains to be demonstrated.
- Grade B360 is a slightly higher carbon version (0.25/0.35%) of the B320 grade, also developing a carbide free microstructure comprising bainite and austenite upon natural cooling following hot rolling. The slightly higher hardness provides increased resistance to wear compared to Grade B320, while maintaining the high resistance to RCF. This grade has been approved by SNCF for use in high speed S&C. The higher resistance to RCF has been demonstrated in several trial sites in France, Germany, and Switzerland. However, critical and subcritical Heat Affected Zone (HAZ) regions of both flash butt and aluminothermic welds made in this grade can be susceptible to cracking. This shortcoming has severely restricted the realisation of the benefits of RCF resistance offered by this grade.
- DOBAIN 380 and 430 grades from Voestalpine are high carbon (0.80%) steels alloyed with Cr, Ni, Mo, and V and heat treated to develop a conventional lower bainitic structure. It is believed that Grade R400HT is being promoted in preference to the heat treated bainitic steel grade.

4.4. Comparative properties of available rail steels

The metallurgical attributes, included in the EN as qualification and acceptance tests, form the basis of comparisons of the available rail grades. A summary of the comparative properties of the various steel grades is shown in Table 4. The relevance of the majority of these attributes to the key rail degradation mechanisms of wear, RCF, and plastic deformation is not convincingly demonstrated.

It is apparent that the specified values of fracture toughness are broadly similar for all grades confirming the characteristic of high carbon pearlitic compositions and microstructures. Although the influence of fracture toughness on the critical defect size at fracture is recognised, a very significant improvement in this property would be required for rail steels to realise any appreciable benefits for track integrity.

The specified requirements for Fatigue Crack Growth Rate (FCGR) and fatigue strength are the same for all grades and hence their relevance to the comparative assessment of in-service performance is debatable and does not contribute towards the criteria for the optimum selection of rail grades. However, a degree of assurance could be derived from the requirement that the more recent and harder grades of steel are not permitted to have inferior properties compared to the accepted safe performance of the standard R260 Grade. Thus, the need for more discriminatory tests with proven relevance to in-track performance is apparent.

However, the reduction in wear rate with increasing hardness has been proven through controlled laboratory tests and in track trials. Consequently, the development of harder rail steel grades was justified, particularly for heavy haul operations that have much harsher rail-wheel contact conditions.

Table 4 Comparative Metallurgical Attributes of Available Rail Steels

Steel Grade	Fracture Toughness [MPa m1/2]		Max. Fatigue crack growth rate, [m/Gc]		Fatigue strength	Residual stress [MPa]	Hardness [HBW]	Tensile Strength [MPa]	Elongation [%]
	Min. single value	**Min. mean value**	**Delta K= 10, [MPam1/2]**	**Delta K= 13, [Mpam1/2]**					
R200	30	35	Not specified		$5X10^6$ 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		<250	335-380	1150	7
B320	Data not available but believed to be compliant with current specifications					<250	320-360	1100	14
B360	36	39	<13	<28	Compliant	<250	360-390	1200	13
DOBAIN380	Data not available but believed to be compliant with current specifications					<250	380-420	1250	10
DOBAIN430						<250	>430	1400	9

4.5. Assessment of in-service performance

Although comparative evaluation of composition and properties shows distinct differences between the various grades, it does not reveal the expected performance in track, particularly with respect to the locations that each of the grades are best suited for. It is therefore prudent to examine the magnitude of resistance offered by the available rail steels to the known degradation mechanisms of wear, RCF, and plastic deformation.

The advances in the simulation of vehicle-track interaction and the understanding of the stresses within the wheel-rail contact patch has enabled a methodology to quantify the susceptibility to RCF of various stretches of track. The methodology described in Section 3 involves the derivation of a damage index for each track segment based on the assumed duty conditions. Such an assessment only describes half of the problem while the other needs to be provided by determining the resistance to degradation of the various steels under the full matrix of vehicle-track characteristics.

Although track trials of various rail grades have been undertaken in most of the major European railway networks, the complexity of the wheel-rail interface makes translation of results into general guidelines of rail grade selection extremely difficult. Furthermore, a comparative trial of various rail grades under identical conditions in commercial track is not practical and is affected by maintenance interventions such as grinding and tamping. Consequently, the alternative is to establish the resistance to degradation of different steel grades under controlled laboratory tests. However, it needs to be emphasized that the complexity of wheel-rail contact conditions cannot be fully reproduced in laboratory tests but this difficulty can be overcome by grading the magnitudes of degradation predicted through simulation and similarly the resistance of the different steels determined in the laboratory.

A variety of different laboratory testing arrangements have been used at Universities [20], leading rail manufacturers [21] and within the research facilities of some railway IM [22, 23]. A very large number of tests of both wear and RCF were undertaken on a twin disc facility at the research centre of British Steel (formerly Tata Steel) and an overview of some of the results are presented below.

4.5.1. Resistance to wear

The wear test data collated and analysed in this paper were generated over a period of over 40 years and covers a very wide range of steel compositions (including those defined in EN13674 and some experimental steel grades) tested under a contact pressure of either 560 MPa or 750 MPa. It should be emphasised that the population of steel grades tested at the two contact pressures are not the same and more of the softer grades were tested at the lower contact pressure. The results are summarised in Figure 9. Although there is visible spread in the results, the strong dependence on hardness is very apparent and appears to be independent of whether the hardness has been achieved through alloying, heat treatment, or a combination of the two. Comparison of the data at the two contact pressures used indicates that the influence of the higher contact pressure is pronounced at hardness levels below 300 Hv but is virtually eroded for hardness levels above 350 Hv.

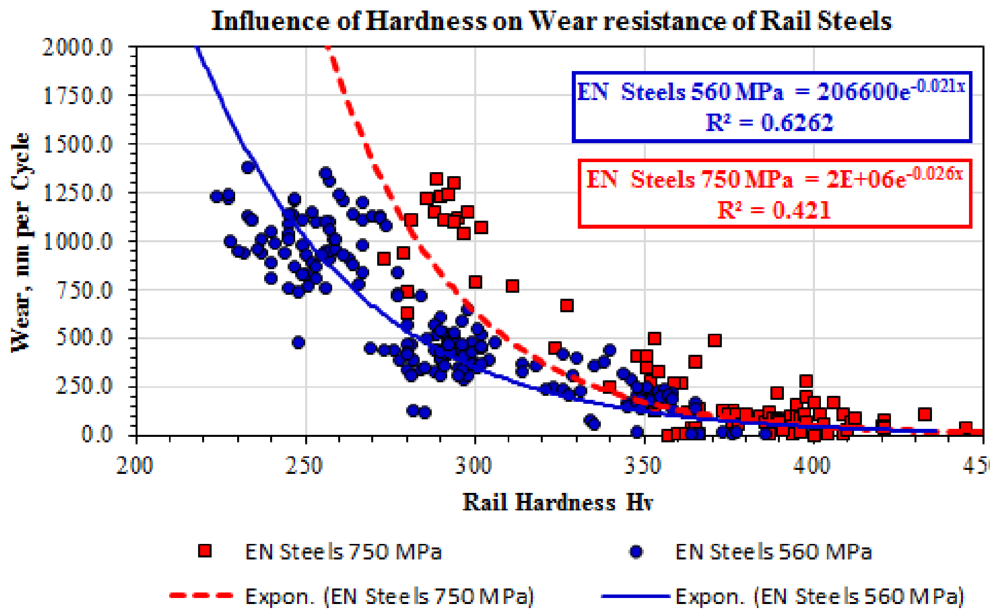


Figure 9 Influence of Hardness on Wear Resistance of EN Rail Steels

Further confidence in the dependence of wear resistance on steel hardness comes from consideration of a wide range of experimental or non-rail pearlitic steels not covered by the EN, as shown in Figure 10. It should be noted that at the difference between the trend line for EN steels and all pearlitic steels is largely because of the larger population of softer steel grades. However, the observed dependence of wear resistance on hardness for such a wide range of pearlitic steels suggests that increasing hardness through either alloying, accelerated cooling, or a combination of the two will enhance the resistance to wear. Thus, the microstructural parameters that are likely to be the key contributors to wear resistance are interlamellar spacing and the cementite lath thickness.

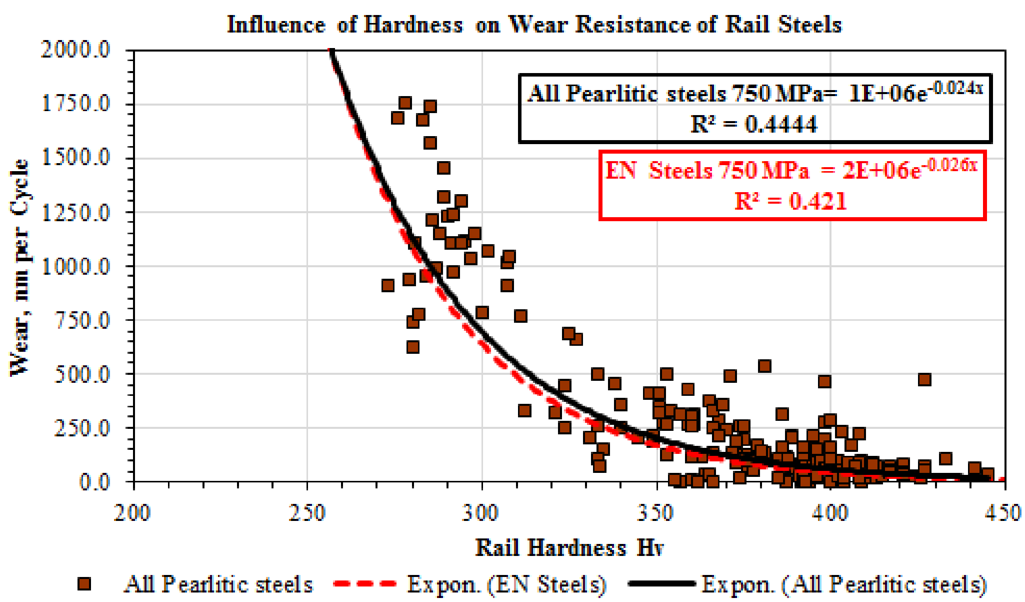


Figure 10 Wear Resistance of All Commercially Available Pearlitic Rail Steels

It is also appropriate to examine the wear resistance of two other groups of steels not included within the EN, namely HP335 and the low carbon carbide-free bainitic steels (B320 and B360) from British Steel, as both of these grades are commercially available. The wear resistance of these steels and some of their variants are shown in Figure 11.

It is apparent that despite its lower levels of hardness, the wear resistance of Grade HP335 is similar to that produced by many of the harder grades specified in the EN. The Ultra High Carbon (UHC) steels included in the charts below are variants of Grade HP335 with different levels of microalloying additions. Heat treated versions of these variants are also included but they are not a commercially available grade. The second group of steels that have undergone considerable track trials and are approved for use for movable points within the SNCF network is the bainitic steel grades (B320 and B360). These steels were tested at the lower contact pressure and the results suggest that their resistance to wear is commensurate with other pearlitic grades of similar hardness which is in broad agreement with data from commercial track trials.

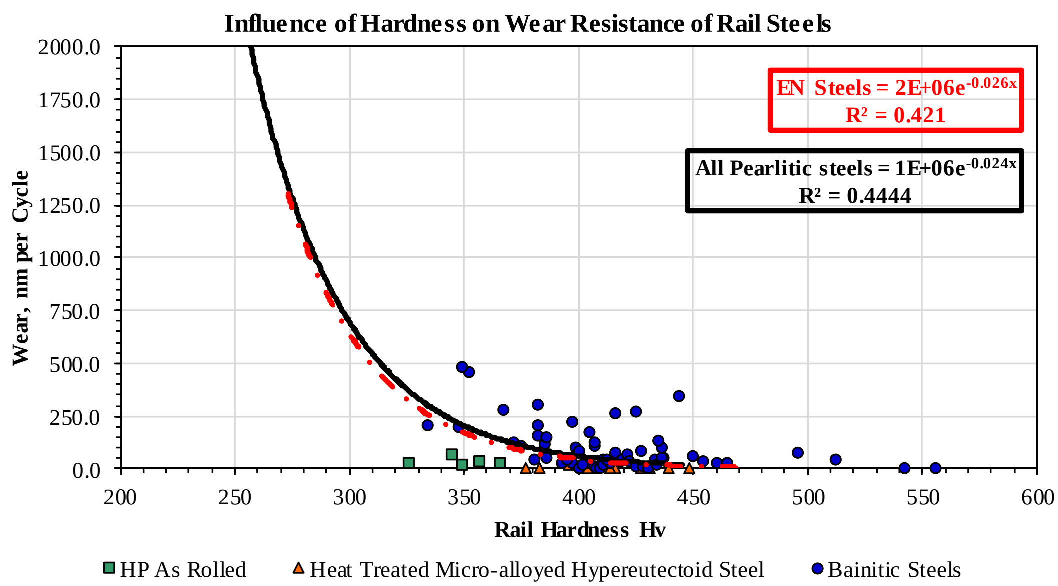


Figure 11 Wear Resistance of Novel Commercially Available Rail Steels

4.5.2. Resistance of rolling contact fatigue

The twin disc tests were undertaken at a contact pressure of 900 MPa and the number of cycles to crack initiation was recorded. Although RCF is most commonly found on curves where the level of creepage is generally low (< 1 %), to provide a comparison with historic twin-disc results a nominal creepage of 5% was used in these tests. Future testing will be undertaken with levels of creepage that are more representative of in-service values. The tests were interrupted at regular intervals and the sample examined visually for any evidence of RCF cracks. Any suspect cracks were noted and the test continued to verify whether they became more apparent. The cycles completed at the previous inspection was taken as the cycles to initiation.

RCF resistance of the various steel grades are shown in Figures 13 to 15. Although the test programme spanning many years was undertaken on the same machine, subtle differences in procedure may have occurred and are reflected in the spread of results. Nevertheless, certain trends can be drawn from the data:

- The resistance to RCF presented in Figure 12 shows a linear dependence on the hardness of all rail steels specified within the EN, with the highest resistance offered by the hardest grades. It is interesting to note that the fatigue tests specified in the EN also show a similar dependence on hardness.
- As shown in Section 3.5.1, the hardest grades also possess the greatest resistance to wear and hence the competition between wear and rolling contact fatigue does not appear to detract from the benefits of the harder steel grades.
- A group of microalloyed hypereutectoid steels not included in the EN also show a linear dependence with hardness, but offer greater resistance than the EN grades at equivalent hardness, as shown in Figure 13. Grade HP335 manufactured by British Steel and approved for use on the Network Rail infrastructure is the commercially available grade from this group.
- Figure 14 shows the results from tests of low carbon carbide-free bainitic steels. These cover a very wide range of hardness values and also show a greater resistance to RCF than the EN grades with equivalent hardness values. The wider spread in results is a reflection of the wide range of compositions tested.
- Similar tests were also undertaken on steels with tempered martensitic microstructures, but did not show any advantages over the conventional rail steel grades. Limited tests, undertaken on as-serviced (work hardened) Austenitic Manganese Steel, revealed the very high resistance to RCF of this grade.

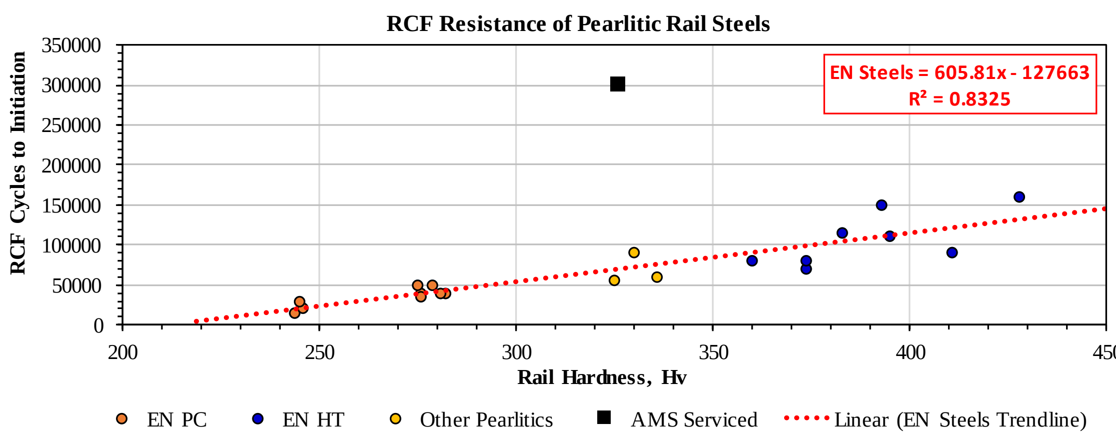


Figure 12 RCF Resistance of Pearlitic Rail Steels defined in the EN

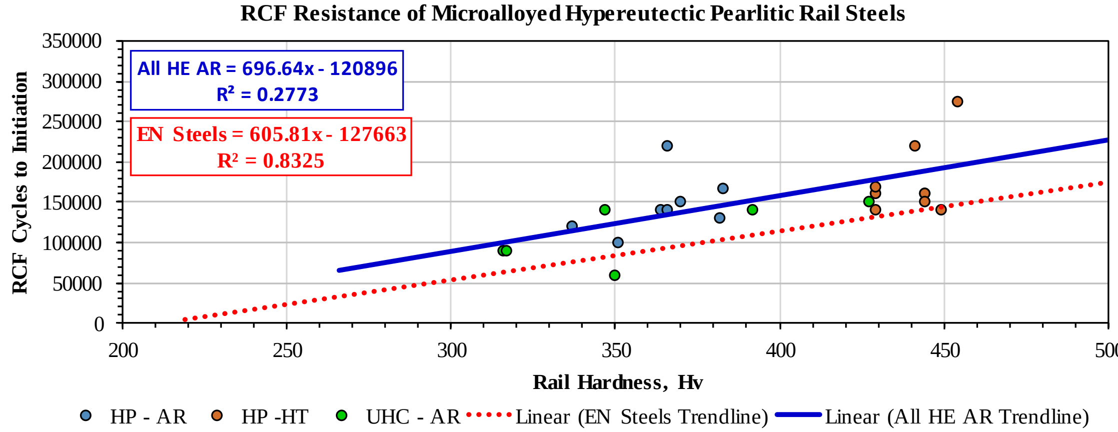


Figure 13 RCF Resistance of Microalloyed HE Steels

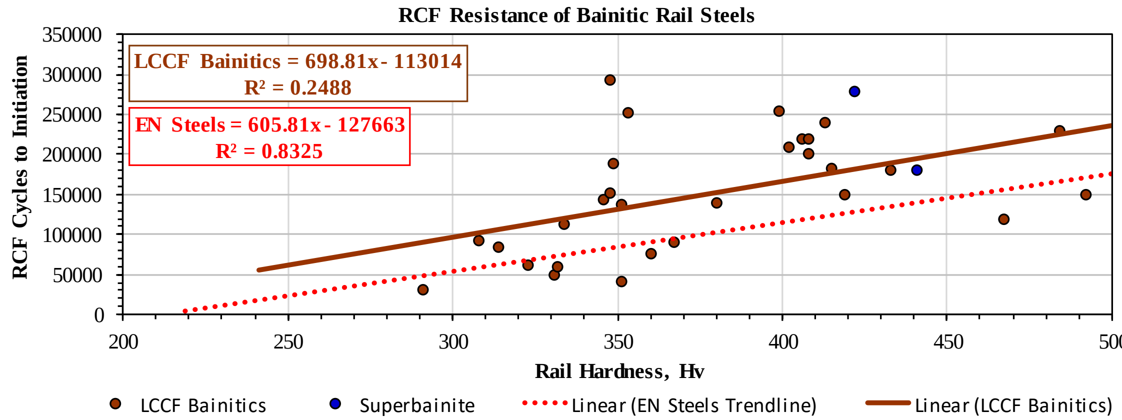


Figure 14 RCF Resistance of Bainitic Rail Steels

5. Life Cycles Cost Modelling and Economic Assessment

Rail tracks suffer from a number of degradation mechanism (such as RCF, wear and plastic deformation) and are regularly inspected, maintained and renewed to preserve safety and performance. As illustrated in the previous section, the implementation of high performance rail steels (such as HP335) can help reduce the damage rates and hence significantly influence the frequency of inspection, maintenance and renewal activities.

The optimum deployment of HP335 rail steel, instead of the standard R260 grade steel, in curves susceptible to damage as discussed earlier in the paper has been investigated. Whilst the purchase cost of this type of steel is slightly more expensive, it provides more resistance to key damage mechanisms resulting in less frequent inspection, grinding (e.g. reduction in maintenance activities) and renewals (e.g. increase in rail life) activities. This will directly influence the costs to the IM and therefore it is expected that HP335 rail will bring cost savings, especially on routes with a large proportion of track that is highly susceptible to RCF and wear damage. Additionally, HP335 rail may also have positive effects in one or more of the following areas: track availability, reliability and safety. These are, however, less straightforward to quantify and more uncertain than the cost savings. Additionally, the impact of changes in rail steel composition on the performance of the wheel steel (e.g. influence of increasing rail material hardness on wheel wear), have not been quantified. However, previous research in this area has concluded that increasing hardness of one material has little or no effect on the wear rate of the other material [24].

This section of the paper outlines the business case for the implementation of HP335 rail steel on the four selected routes. A Cost-Benefit Analysis (CBA) approach has been followed. All the possible effects from the use of HP335 rail have been considered, and the scenarios have been set out using realistic and conservative assumptions to avoid overstating the value for money of the scenarios being evaluated.

5.1. Methodology

The core of the CBA is the life-cycle cost (LCC) assessment which is used to estimate all the costs for a route, for a given period, under a range of different scenarios – without and with the intervention. Hence, LCC analysis provides us with the changes in costs due to the implementation of HP335 rail steel. The changes are measured always in relation to the baseline or Do-Minimum scenario, which reflects the current maintenance regime for standard R260 rail.

The LCC modelling has been carried out using the GB rail industry tool VTISM [25, 26]. VTISM is a strategic cost modelling tool employed by Network Rail which can be used to predict the impact of vehicle-track changes on whole system costs. At the high level, VTISM can be used to determine the volume of inspection, maintenance and renewals activities and calculate the associated costs.

VTISM considers the track characteristics, traffic volumes and simulated wheel-rail forces on a route to calculate the vertical (e.g. ballast settlement) and horizontal damage (e.g. wear and RCF). Depending on the rate of degradation and traffic volumes (MGT) certain inspection, maintenance and renewal activities are triggered and the associated costs are determined for all activities required during the assessment period.

The flow diagram presented in Figure 15 summarises the VTISM LCC modelling approach implemented during this research. This illustrates how the introduction of HP335 rail results in updated wear and RCF damage rates along with modifications to the existing maintenance and renewals regimes.

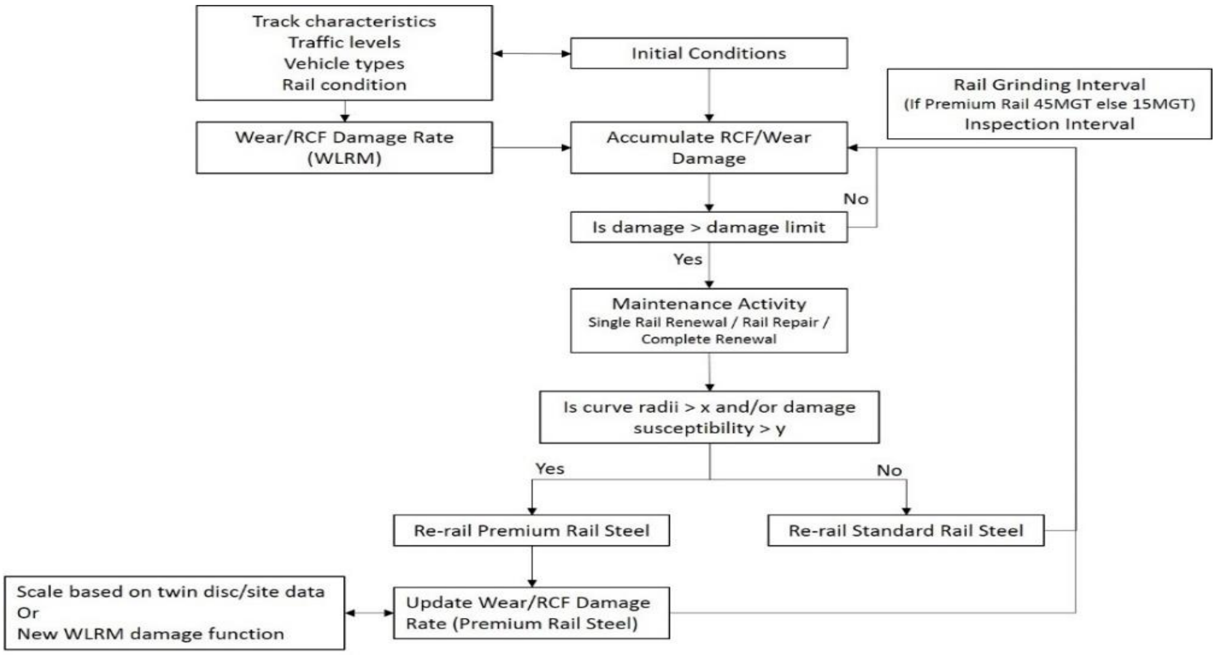


Figure 15 VTISM LCC modelling approach

5.2.LCC Scenarios

The aim is to quantify and compare the cost profiles when using standard and HP335 rail steel, over a given period of time, on the 4 selected routes. To investigate this, we defined three scenarios as follows:

1. Baseline scenario (Do-Minimum): characterised by the current vehicle-track characteristics and maintenance regime as defined in the VTISM tool (e.g. using standard grade rail steel).
2. Optimal selection of HP335 steel (Do-Something Scenario 1): characterised by the deployment of HP335 rail in curves that are most susceptible to RCF damage (e.g. above the proposed damage susceptibility threshold) based on the criteria proposed in Section 2.
    a. This scenario includes an increase in the purchase cost of HP335 rail when compared to standard grade steel, resulting in higher unit costs for rail renewal activities with HP335 rail steel.
    b. Following renewal with HP335 rail, the grinding interval was also increased to reflect the fact that RCF resistance of HP335 rail will result in a lower damage depth requiring less metal removal during grinding. This means that grinding can now be performed at the same rate for curves and tangent track (currently Network Rail regime is to grind curves at 15 MGT and tangent track at 45 MGT).
    c. The RCF and wear damage rates (RCF) used by VTISM to accumulate rail damage were reduced based on the outputs from the twin disc testing.
3. Full implementation of HP335 rail (Do-Something Scenario 2): The same assumptions as defined above, but we assume that HP335 rail is deployed at any location irrespective of curve radius or damage susceptibility.

Generally infrastructure LCC assessments are conducted over a time period 30 - 40 years to capture a full renewal cycle, however in this case the assessment time period was selected based on the typical life of rail steels in track sections with high susceptibility to degradation. Therefore for all scenarios, a time period of 15 years has been assumed as generally we are interested in assets which were shown through assessment of the results from the baseline scenario to have a much shorter life (< 5 years). The LCC provides a measure of the Net Present Costs of the full railway operation during the 15 years for each scenario. A discount rate of 3.5% is chosen following the WebTAG guidelines for appraisal in the UK [27].

The main outcome is the total cost savings from HP deployment, and this is interpreted as the lower bound of the potential total benefits, since all other non-quantified benefits are positive (e.g. increase in track availability)[1].

5.3. LCC Results

Figures 16 and 17 illustrate the total cost savings obtained when HP335 rail steel is deployed optimally on all routes. Total LCC savings (maintenance and renewal) are identified for all routes and range between 0.4% and 17% of the total costs, depending on the characteristics of the route.

The results show that HP335 rail can bring significant cost savings to the IM. These benefits vary depending on the route due to the differences in the damage susceptibility associated with variations in vehicle-track characteristics of these routes. The savings were mainly associated with the maintenance activities, primarily grinding, and have been estimated to be between 3% and 48% of total maintenance costs depending on the route. For a somewhat average route (e.g. the distribution of curve radii and cant deficiency that could be regarded as the average of the four selected routes), the total maintenance cost savings are around 13%. It is also likely to find renewal cost savings, but this would normally require optimal deployment of the chosen degradation resistant steel[2], i.e. installing HP335 rail only in those sections the track that are more susceptible to RCF damage. These renewal cost savings are between 0.1% and 1.2% for average routes, but up to almost 8% for the Wessex route, a route with known RCF problems. In absolute terms, cost savings are significant for the two average routes (around £2 million and £3 million per each 15-year period), and remarkable for the Wessex route (£18 million). The GW route has low savings simply because it has very few track sections moderately/highly susceptible to RCF problems.

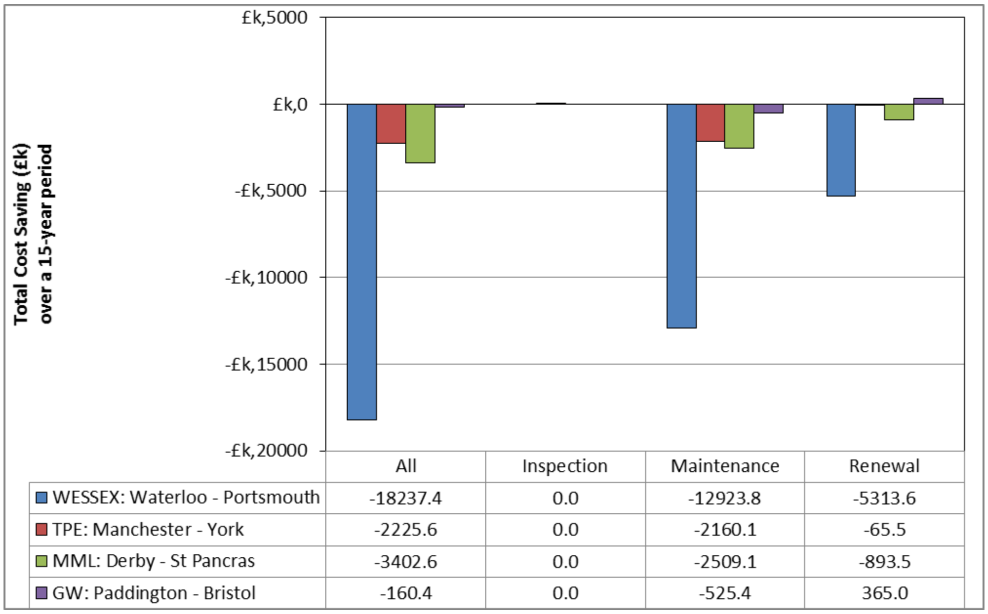
If HP335 rail is deployed indiscriminately throughout a route, its higher purchase costs can make renewals more expensive overall in some cases. However, importantly, even if HP335 rail is installed everywhere, the overall business case shows a positive NPV for 3

[1] Unfortunately it was not possible to obtain a monetary measure of these additional benefits. However, since grinding and renewal needs will reduce, the tracks will be available for other uses longer than in the baseline scenario.

[2] Wessex route was an exception, with an estimated 6% renewal cost savings even when HP was deployed everywhere.

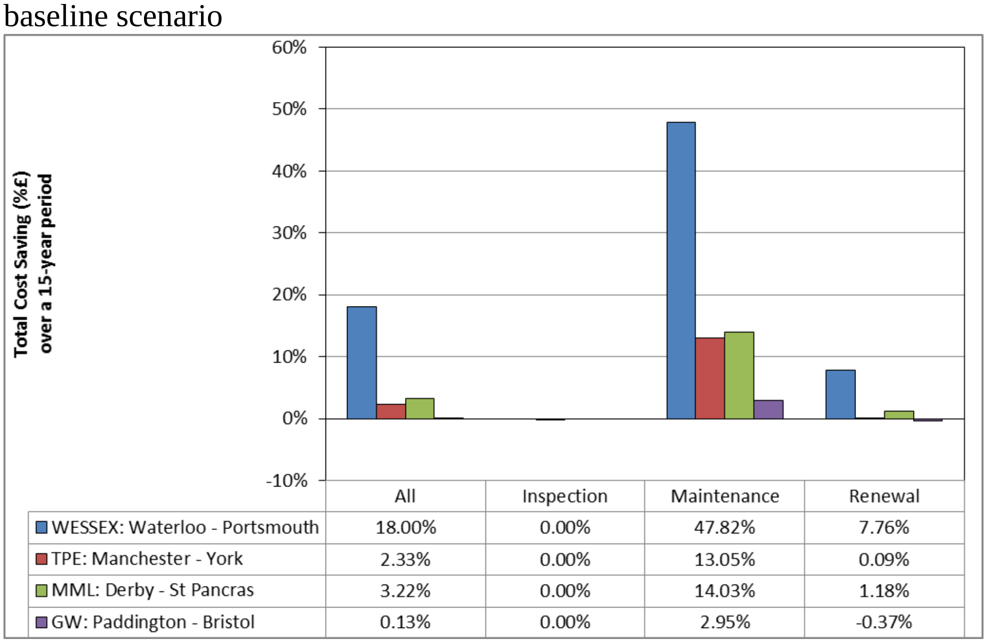
[3] Numerical details of the 'Do-Something 2' scenario are not provided here but are available from the authors on request.

out of 4 routes, reflecting that investing in this – more expensive but more damage resistant – steel represents good value for money[3]. This latter finding is important given that there could be increased labour costs associated with the logistics of adopting different steel types on the same route. Hence, for some routes it may be beneficial and convenient to fully switch to more damage resistant steels, unless the route is highly unaffected by RCF (e.g. GWML route). Further evidence from field trials is required to support the adoption of HP335 for the full range of vehicle-track characteristics.



	All	Inspection	Maintenance	Renewal
WESSEX: Waterloo - Portsmouth	-18237.4	0.0	-12923.8	-5313.6
TPE: Manchester - York	-2225.6	0.0	-2160.1	-65.5
MML: Derby - St Pancras	-3402.6	0.0	-2509.1	-893.5
GW: Paddington - Bristol	-160.4	0.0	-525.4	365.0

Figure 16 Total cost saving for optimal (Do-Something 1) scenario when compared to baseline scenario



	All	Inspection	Maintenance	Renewal
WESSEX: Waterloo - Portsmouth	18.00%	0.00%	47.82%	7.76%
TPE: Manchester - York	2.33%	0.00%	13.05%	0.09%
MML: Derby - St Pancras	3.22%	0.00%	14.03%	1.18%
GW: Paddington - Bristol	0.13%	0.00%	2.95%	-0.37%

Figure 17 Percentage saving for optimal (Do-Something 1) scenario when compared to baseline scenario

In addition to the cost savings presented above, a subsequent benefit of the selected premium steel (HP335) is the potential increase in track availability. This is a consequence of reduced maintenance and renewal needs. The following table summarises the main reduction in maintenance activities for each route. This gives an indication of the extent of these additional benefits, which are very difficult to value in monetary terms.

Table 5. Volumes of activity changes (in miles)

Work description	**% Change in volume of activity**			
	TPE	**WESSEX**	**MML**	**GWML**
Re-Rail	-85%	-41%	-93%	-5%
Single Rail Renewal	-91%	-81%	-86%	-63%
Rail Repair (lateral)	-71%	-66%	-73%	-76%
Rail Grinding	-41%	-46%	-30%	-1%

The reduced need for re-railing, rail renewals, rail repair and rail grinding would free up a substantial amount of slots that can be used for other purposes, e.g. other maintenance tasks, running more trains (passenger and freight) or to reduce inefficiencies associated with possession overruns. For instance, at the network level in Great Britain, 11,000 miles of the track are subject to grinding every year, with 6 grinding machines performing 230 shifts each every year. A reduction of 30% could potentially remove over 400 shifts.

Other additional benefits include the possibility to align grinding activities. Grinding shifts can become more efficient with premium steel because it allows grinding to take place at the same thresholds for all types of track.

6. Conclusions

Research has been undertaken to provide more detailed understanding of the response of the steel composition and various microstructural constituents to the loads imposed on them during wheel-rail contact and to identify the characteristics that contribute towards their increased resistance to the key degradation mechanisms.

During this research it was identified that different segments of a route on any network have different magnitudes of susceptibility to the key rail degradation mechanisms and a methodology for identifying the damage susceptibility of these segments was developed. To demonstrate this approach a number of routes of the UK mainline network have been segmented in to sub-assets based on the prevailing track characteristics. Using vehicle dynamic simulations and current best practice in relation to modelling rail damage, the susceptibility of these segments to RCF and wear damage has been quantified to support the selection of optimum rail steel grade to maximise rail life. This included grading the magnitude of susceptibility to wear and RCF damage of each segment as low, moderate, and high. Similarly, the resistance of the various steel grades to these key degradation mechanisms can be graded into similar categories.

A detailed review of the currently available rail steel grades and their key attributes has been undertaken. This has highlighted that, although comparative evaluation of composition and properties of these steels shows distinct differences, it does not reveal the expected performance in track particularly with respect to the locations that each of the grades are best suited for.

Experimental data for a range of steel grades from historic and recent twin-disc testing has been compared to quantify the resistance of these grades to key damage mechanisms. Where possible, the trends identified in the experimental data have been correlated with observation from in-service trials.

Using the outputs from the vehicle dynamic simulations (e.g. damage susceptibility criteria) and the assessment of experimental data (e.g. comparative damage resistance of various rail steel grades); a detailed cost-benefit analysis has been undertaken to assess the cost impact of optimum rail steel grade selection on whole routes. This approach included a life cycle cost assessment using the UK industry-standard VTISM tool which showed that the optimal use of HP335 rail steel can bring significant cost savings to the IM (up to 17% saving of total costs depending on track characteristics) and the additional benefit of increased track availability, which could have value in terms of supporting additional train services or enabling more efficient track possessions.

The research has helped to quantify the benefits of current Network Rail strategy for the optimal deployment of HP335 rail steel grade:

- In critical curves where RCF and wear causes the premature replacement of the rail.
- In moderate curves to preserve the ground rail profiles and increase the rails resistance to RCF.
- In tight curves with high rates of wear. However, it is worth noting that in some cases the use of harder rail steels on tight curves may show greater incidence of RCF initiation than previously observed. Further work is required fully understand the reasons for this and how it might influence the future deployment of premium rail steels.
- Based on the route sections analysed during the research, for some routes there could be cost savings and associated operational benefits of applying premium rail across the whole route section.

Further controlled testing and microstructural assessments have been completed during the research and further details can be found in [28] and [29].

7. Acknowledgements

The authors are thankful to British Steel for supplying the test data and rail samples and Network Rail for providing cost data for use in the research.
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 the Rail Safety and Standards Board (RSSB), the Department of Transport, University of Cambridge and Cranfield University.

8. References

1. J. Evans, Application of the “HALL” hydraulic radial arm bush to a 200 km/h inter-city coach, IAVSD 2011: 22nd IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks. Manchester Metropolitan University, UK, 2011.
2. A.Bevan, P.Allen and S.Iwnicki, Development of an anti-RCF wheel profile, T547 project report, RSSB, 2005.
3. L. Smith, British Steel rail products and their applications, London Technical Seminar – Rails: On our Mettle, May 2017.
4. EN 13674-1:2011+A1:2017, Railway applications - Track - Rail - Part 1: Vignole railway rails 46 kg/m and above, 2017.
5. J. Stow, A. Bevan, M. Burstow and K. Timmis, Developing effective, evidence based control measures for rolling contact fatigue, 9th World Congress on Railway Research, Lille, May 2011.
6. Corus, Innotrack Deliverable D1.2.5 – Track Segmentation, 2009.
7. M. Burstow, Whole life rail model application and development – continued development of an RCF damage parameter, T115 project report, RSSB, 2004.
8. T.G.Pearce, N.D.Sherratt, Prediction of wheel profile wear, Wear 144, 343–35, 1991.
9. I. McEwen, R.Harvey, Interpretation of wheel/rail wear number, Report Ref: TM VDY004, British Rail Research, 1986.
10. UrbanTrack FP6 31312; D0208_STIB_M24.doc
11. P. Pointner, A. Joerg and J. Jaiswal, Definitive guidelines on the use of different rail grades, Innotrack project report, D4.1.5GL, 2006.
12. R. Carroll, H. Smith and J. Jaiswal, Rail Steel with an excellent combination of wear properties and rolling contact fatigue resistance, European Patent EP 2 247 764 B1.
13. G. Girsch and R. Hyder, Advanced pearlitic and bainitic rails promise to improve rolling contact fatigue resistance, 7th World Congress Montreal, Canada.
14. G. Girsch and N. Frank, New rail grades – a technical performance overview, 8th International heavy haul conference, Rio de Janerio, 2005.
15. H. Bhadeshia, Materials Science Forum, 500/501, 63/74, 2005.
16. J. Kristan and K. Sawley, Wear and rolling contact fatigue in Bainitic microstructures, AREMA Symposium, 2003.
17. E A. Shur et al, Bainitic rails for heavy haul operations, IHHA, 2005.
18. H. Bhadeshia, Bainite in Steels; The institute of Materials, ISBN-10: 1861251122, London, 1992.
19. Method for producing carbide-free bainitic Steels – European Patent EP 0 804 623 B1.
20. D. Fletcher and J. Benyon, Development of a machine for closely controlled rolling contact fatigue and wear testing, Journal of Testing and Evaluation, 267-275, 2000.
21. D. Eadie et al, The effects of top of rail friction modifier on wear and rolling contact fatigue: full scale rail-wheel test rig evaluation, analysis and modelling, CM2006 – Proceeding 7th international conference on contact mechanics and wear of rail/wheel systems, pp 411 – 419, 2006.

22. D. Ullrich and M.Luke, Simulating rolling-contact fatigue and wear on a wheel/rail simulation test rig, WCRR 2001 – Proceedings 5th World Congress on Railway Research, Cologne, Germany, 2001.
23. D. Ullrich, K. Maedler and A. Zoll, Testing of wheel/rail technologies on test rigs and in operational trials, RTR - Railway Technical Review, 29 - 33, 2005.
24. M. Burstow, Wheel-Rail Hardness and Total System Wear, V/T SIC Report, 2012.
25. A. Jablonski and J. Williams, Development of vehicle/track interaction strategic model – stage 1. T353 project report, RSSB, 2009.
26. A. Bevan, Optimisation of wheelset maintenance using whole-system cost modelling, Proc IMechE Part F: J Rail and Rapid Transit 227(6) 594–608
27. Department for Transport (DfT) (2016). Transport Analysis Guidance: WebTAG. https://www.gov.uk/transport-analysis-guidance-webtag
28. W. Solano-Alvarez, E.J. Pickering, M.J. Peet, K.L. Moore, J. Jaiswal, A. Bevan, H.K.D.H. Bhadeshia, Soft novel form of white-etching matter and ductile failure of carbide-free bainitic steels under rolling contact stresses, Acta Mater. 121 (2016) 215–226.
29. Solano-Alvarez, Wilberth , Peet, M , Pickering, E , Jaiswal, Jay , Bevan, Adam and Bhadeshia, Harry (2017) Synchrotron and neural network analysis of the influence of composition and heat treatment on the rolling contact fatigue of hypereutectoid pearlitic steels. Materials Science and Engineering: A: Structural Materials: Properties, Microstructure and Processing. ISSN 0921-5093 (In Press)