Squats on the Great Britain rail network: Possible root causes and research recommendations

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Abstract

Rail squats are a type of isolated railhead fatigue defect that costs Network Rail millions of pounds every year. Despite significant research into the topic there is still a lack of detailed understanding on how squats are initiated and propagated or the best methods to maintain track in order to manage squat defects.

This paper presents a correlation analysis examining which track characteristics might be associated with the initiation and development of squats defects on the Great Britain (GB) railway network. Data was analysed for 4,265 squats from three routes (two Intercity routes and one Suburban route) using records of squat for a seven year period between 2011 and 2017.

The correlation analysis show that different route characteristics (such as track geometry, type/number of vehicles and traction and braking cycles and maintenance activities) would have an important influence on the probability of squats defects.

The results suggest that rail grinding is an important method to control the development of squats. There is some evidence, based on limited data from the suburban route, that squats rates could be reduced by 85-90% if the combined wear from traffic and grinding exceeds 0.2 mm/year.

Keywords: squats, rail damage, rolling contact fatigue, correlation analysis

1. Introduction

Squats are 'a widening and a localised depression of the rail/wheel contact band, accompanied by a dark spot containing cracks with a circular arc or V shape' [1]; Figure 1 shows a typical squat. As the crack(s) propagates, these may turn down, eventually resulting in a rail break. Remedial action (e.g. grinding, milling, local weld repair or rail replacement) is essential before the crack lengths grow to significant depths.

Figure 1: Typical squat defect [3]

For many railway networks, squats and squat-like defects are one of the most common rail defects[2]–[5]. In the UK, the main rail infrastructure manager, Network Rail (NR), recorded on average more than 7000 new squats per year (2011-2017) throughout their infrastructure. During this period, corrective maintenance cost £4 million/year [4]. In other European countries, reported rail replacement costs due to squat damage now constitutes a significant percentage of total track maintenance costs [5].

There has already been a significant amount of research into squats and a number of plausible initiation and/or growth mechanisms have been suggested. Table 1 tentatively suggest three broad groupings of proposed initiation mechanisms.

Grassie et al. [3] has proposed that squat defects should be separated into: a classic squat defects and a stud defects, which are not associated with RCF cracks. Their hypothesis is that studs have a different cause to classic squats and different crack propagation. Currently Network Rail standards do not distinguish between studs and classic squat defects, and therefore the data in Rail Defect Management Systems (explained in section 3.1) [14] is inconclusive to determine which type of Squat is predominantly found in the inspected sections.

Previous studies tend to focus on either a particular theory or a specific aspect of the system. For example, a specific track feature (e.g. welds [6]) may be modelled in detail. Some studies place more emphasis on either the wheel-rail contact dynamics, rail metallurgy or fracture mechanics. Supporting evidence provided for each theory often consist of limited field surveys. However, it appears likely that all three squat initiation mechanisms occur. Sometimes, more than one mechanism will work in tandem. This is true of squats originating in shortwave length vertical irregularities. These squats can be viewed as RCF phenomena, origination in dynamic loading rather than curving forces. From a metallurgical view, the two groups will be indistinguishable. Therefore, the prevalence of squats is difficult to link to a specific initiation mechanism.

It is currently not completely understood whether any specific features of modern vehicles, tracks or operational methods promotes the initiation or growth squats. Certain features may tend to promote a particular mechanism over others, as hypothetical groupings in Table 1 suggest. However, it is clear that many features could link to more than one initiation mechanism or promote growth regardless of initiation mechanism. Operationally, it may not be necessary to understand the exact mechanisms involved. For example, even a qualitative understanding of the relative prevalence of squats dependent on vehicle or track features could potentially yield significant savings by allowing these to be 'designed out'.

Initiation	Description	Potential factors promoting initiation & growth	Potential mitigating factors
Thermal events (known as studs [7])	Thermal events including wheel spin or micro-slip generate localised heating, followed by rapid cooling. A brittle surface layer forms; through or at boundaries of which cracks form. Plastic deformation of surface above crack generates the darkened depression. Commonly referred to as 'studs'. See for example [3], [7].	traction zones [8] , vehicle type (traction control)	wear, grinding or milling, absence of water (eg. tunnels),
Rolling contact fatigue (RCF)	RCF crack form due to conventional mechanisms. Cracks may spall to cause a local squat like depression. Alternatively, plastic deform above results in the depression. See for example [9], [10].	vehicle type (suspension characteristics), rail age, amount of traffic, track curvature [2]	wear, grinding or milling, absence of water, premium rail steels
Shortwave length vertical irregularities	Rail surface defects and stiffness gradients cause shortwave length, high frequency, excitation of the wheelset. The wheel-rail impact forces cause plastic deformation of the rail steel to form the depression. Cracking occurs once ductility is exhausted. See for example [11], [12].	short-wave length defects or irregularities (eg. welds or structural transitions) , dynamic track properties [6] (e.g. sleeper type [13]), vehicle type (unsprung mass?)	Wear (less important?), grinding or milling

Table 1: Potential causes of squats or squat-like defects

Two previous studies have sought to use the data collected during routine railway operation and maintenance to inform this discussion. Farjoo et al [13] used statistical analysis to examine the relative prevalence of squats based on different track features. The dataset for this statistical analysis is based on an extensive visual survey of 163 track miles [2]. Li et al [5] conducted a correlation study on a smaller sample size of 75 track miles in the Netherlands. Between these two studies some evidence has been found linking relative squat prevalence to features including shortwave length vertical irregularities, rail wear rate, track curvature, rail age and sleeper type. Whilst such studies do not intend to definitively link actual squat occurrence to a specific initiation mechanism they can provide some significant insights.

2. Aims and Objectives

The aim of this work is to take a sample of recorded squat defects and investigate what possible factors can be correlated with locations that have experienced squats.

A sample of 4265 plain line squats, from a 7 year period, considering 773 track miles has been analysed.

The primary input is a Network Rail database, recording rail defects for a seven year period between 2011 and 2017. 4265 squats on plain line were recorded on these track sections through entire seven year period, resulting in a substantial dataset. Supplementary data sources have been merged to enable the squats prevalence to be associated with track features or vehicles. In some cases, features of interest (eg. traction zones) were not directly available, but have been assessed based on informed judgement. The different data sources used and the track sections considered are described in Section 3.

3. Methodology

The correlation analysis in the current paper followed two approaches:

- Firstly, A correlation study based on the final merge data is used to link specific vehicle or track characteristics with higher squat prevalence (for the total sample of 4265 plain line squats). The analysis results described in Section 4.2.
- Secondly, the analysis was extended to investigates the squats rates in areas (denoted as 'hotspots') which either suffered from a disproportionate number of squats or, more often, where repeated reoccurrence of squats were found over an extended period of time. The analysis outcomes described in Section 4.3.

Additionally, a case study is used to explore routine grinding as squat management measure.

3.1. Rail Defect Management System records

A Network Rail database, known as Rail Defect Management Systems (RDMS) [14], recording rail defects, including squats, across the UK mainline network forms the primary input for the current study. For each defect, RDMS records a defect code, identifying the defect type (e.g. squat , wheel burn , surface defect etc.). Additionally, the defect's location, location type (plain line or on switches and crossings), rail assembly type (jointed or welded), track category, line speed, steel grade, rail age and rail profile are recorded.

For the seven year period (2011- 2017) considered in this study, rail defects totalling approximately 190,000 were recorded; of which 100,000 defects were on plain line and 90,000 defects on switching and crossing. Figure 2 shows the relative occurrence of the most common defect types, excluding defects on switches and crossings. As shown, squats are the most commonly occurring defect on plain line. During the seven year period considered, 48,600 squats were recorded on plain line. The current study focuses on these **squats on plain line**, excluding any defects recorded on switches and crossings.

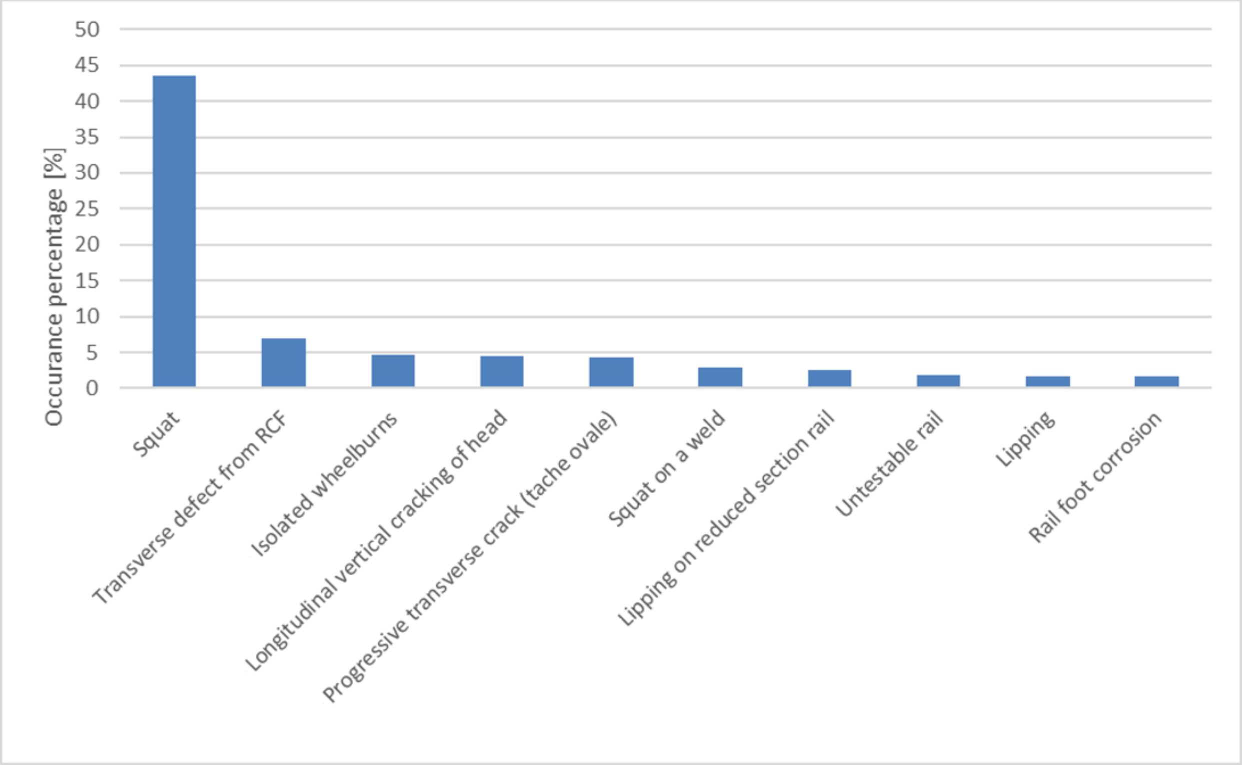

Figure 2: The 10 most common reported defects at plain line in the GB network from 2011 to 2017 (S&C defects were excluded)

Different data sources, such as RDMS, Rail Infrastructure Network Model (RINM) [15] and track geometry (curvature and cant) data were merged into a single data set. Later the information in the database is linked together using squat location.

This paper attempts to correlate squat occurrence with different factors by normalising the total number of squats by track length.

Whilst the idea of mapping the squat defects to the possible causal factors appears attractive, it presents several practical challenges due to the uncertainty of the available asset data. For example, the rail grade and age was missing in some records or if present contradictory. Therefore, the sample size will vary between causal factors hence the accuracy of the correlation analysis will also vary.

3.2. Route description

For the current investigation, three routes were selected for data analysis: Intercity Route 1, Intercity Route 2 and a Suburban Commuter Route.

386.5 route miles (773 miles track length) were analysed and the total number of squats included in the analysis was 4265. The summary of the routes and train characteristics is shown in Table 2.

Intercity Route 1’s rolling stock fleet consists of locomotive-hauled coaching stock. Whilst Intercity Route 2’s fleet consists of electric and diesel multiple unites. The suburban route operates an intensive passenger train services and used mainly electrical multiple unites.

The locomotive-hauled coaching stock on Intercity Route1 has higher tractive effort compared to passenger vehicle unites run on Intercity Route2 and Suburban Route. Additionally the locomotive-hauled coaching stock delivering all the traction through four axles.

The passenger vehicle unites in Intercity Route2 have higher tractive effort (nearly by 1.7 time) compared to vehicle unites in Suburban Route.

In general, Intercity Route 1 and Intercity Route 2 have similar track quality and alignment (i.e. few sharp curves, high running speed up to 125 mph, high annual traffic tonnage, etc.). Whilst suburban route has a lower line speed and annual tonnage.

The following sections will addresses the effects of rolling stocks type and route characteristics on the formation of squats

Route	Route Distance, miles	Number of Squats on plain line (fast / main line only) 2011-2017	Vehicle type	Track Category[1]	Max Line Speed mph	Typical axle loading
Intercity Route 1	188.5	1731	88% passenger trains (mainly loco hauled coaching stock) 12% freight trains	Cat 1A	125	Loco: 20t Coach: 11t Freight: 22.5t
Intercity Route 2	158.5	876	89% passenger trains (mainly multiple units) 11% freight trains	Cat 1A	125	Passenger: 14t Freight: 22.5t
Suburban commuter route	39.5	1658	99% Passenger multiple unit trains	Cat 3	75	Passenger: 10t

Table 2: Summary of selected routes

As explained in section 3.1, RDMS data defines defects by codes. The relevant RDMS squat codes are:

- 227 squat (refer to squat happened on plain rail and not on a weld or joint)
- 127 squat on rail end (refer to squat happened on joint)
- 427 squat on weld
- 627 squat on reduced section rail
- 484 squat on weld repair

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[1] Network rail sets out the procedure for categorising track in running lines by usage and speed, so that requirements relating to design, maintenance, renewal and inspection of the track may be specified and applied[16]. Based on this track categorisation, the track geometry requirements (such as track inspection and grinding) for the higher track category (denoted as Cat 1A) are tighter compared to the lowest track category (denoted as Cat 6).

Figure 3 shows the percentage occurrence of squat types across the selected routes. The vast majority of squats happened on plain rail (i.e. not on a weld or joint). For the Intercity Route 1 route, a reasonable percentage of squats (10.7%) happened on welds and around 3% of squats happened at rail ends (i.e. the rail joints).

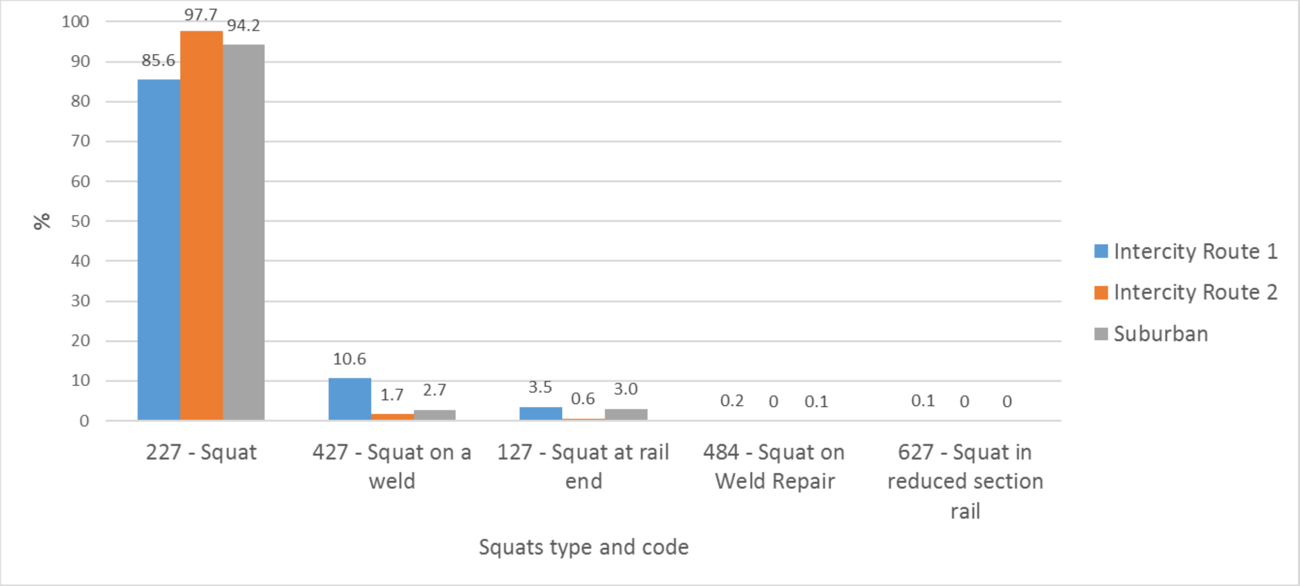

Figure 3: Percentage of squats by defect code for the selected routes

4. Results and discussion

4.1. Overview of squats by route

Table 3 shows an overview of the number of squats per mile on each of the routes. The suburban route has significantly more squats per mile than the two intercity routes (2.99 compared to 0.66 and 0.39 squats/mile/year). Comparing the two intercity route, Intercity Route 1 has significantly more (0.66) squats per mile than Intercity Route 2 (0.39); however, the intensity of squats (squats/ affected track mile) on Intercity Route 2 are more focused on smaller number track sections (i.e. the squats on Intercity Route 2 are focused on 4% of the track sections whilst they are spread across 9% of the track sections on Intercity Route 1).

In order to calculate the affected track mile, track in each route was divided into 50m sections. The 50m track sections that entirely without squats were excluded from the analysis. Later the remaining 50m sections were summed up to calculate the track length in mile.

Route	Squats per mile per year (for the whole route - Up and Down routes)	Percentage of track length with Squats	Squats intensity (squats/mile/year) for the affected areas only
Intercity Route 1	0.66	9%	7
Intercity Route 2	0.39	4%	9.4
Suburban commuter route	2.99	23%	13

Table 3: Rate of squat formation by route (2011 – 2017)

The differences in the number of squats per mile and how focused those squats are on certain areas would appear to suggest that route different characteristics (i.e. track geometry, track category, line speed, type/number of vehicles and traction and braking cycles, maintenance activates etc.) could have an important influence on the probability of squats defects.

4.2. Correlation analysis results

The following sections summarise results for each potential causal factors investigated. Whilst other potential causal factors were investigated, the current discussion focuses only on those found to correlate strongly with squat formation.

4.2.1. Squats in relation to curvature

The track in each route was categorised into seven curvature bands. Figure 4 summarises the squats per mile for each of the different curvature bands, split by route. As shown, squats occur across the full range of curvature. Whilst large numbers of squats occur on straight track (R >3000m) and shallow curves, track in these curvature bands make up the majority of all three routes. Therefore, the normalised squats/mile for straight track (i.e. R>3000 m), as shown in Figure 4, is small compared to tighter radius curves (i.e. R ≤3000 m).

For the suburban commuter route and Intercity Route 2, squats are most frequent in the 600–799m radius curves. Whilst on the Intercity 1 route, squats are most frequent on 800–999m curves. The higher line speeds on both intercity routes shift the track curvature away from the sharper radius curves. Therefore, radii smaller than 600 m are not found on Intercity 2 and 800 m radii on Intercity 1.

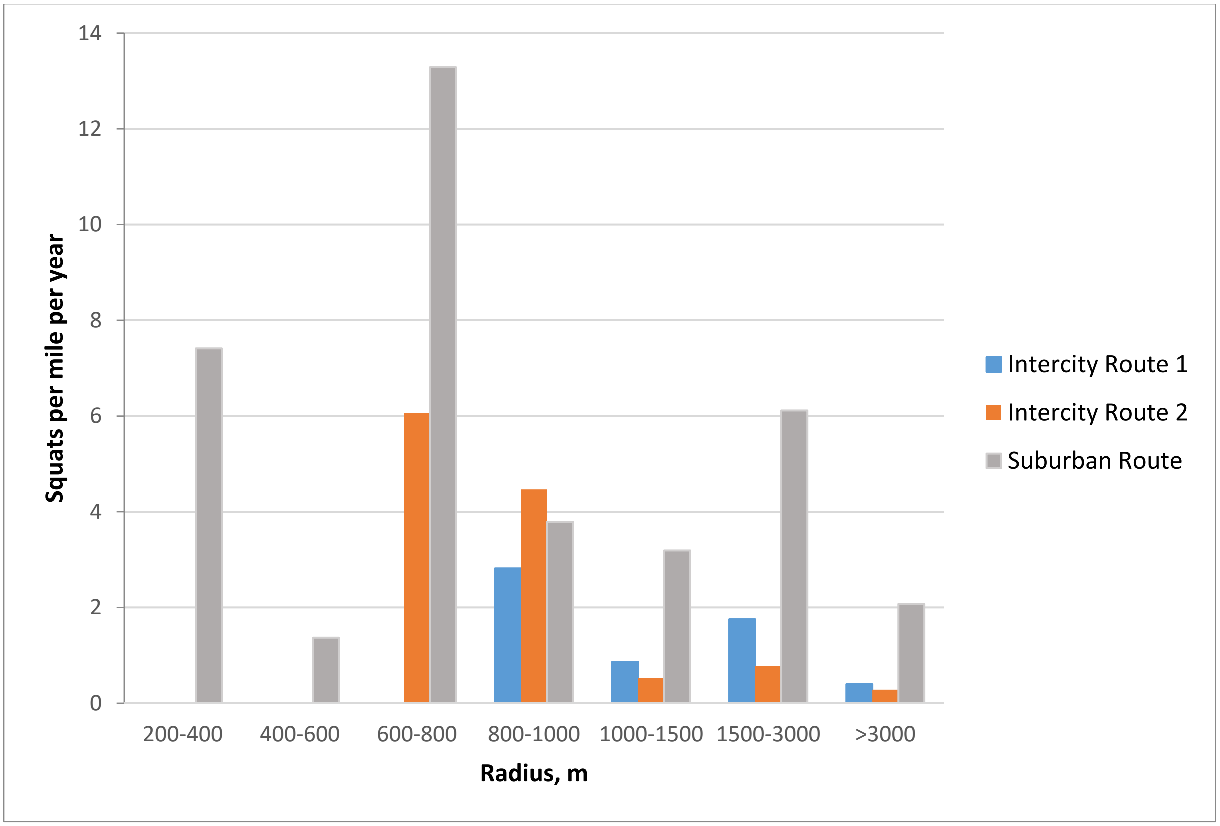

Figure 4: Squat rate vs. curve radius

It should be noted that some curve radius bands, for example curve radius band 200m - 400m, contain both relatively small numbers of squats and also represent a small percentage of the track length. As a result, they may be sensitive to relatively small changes in the numbers of squats. Despite this, it seems clear that squat rates are generally higher on 600 – 999m radius curves than they are elsewhere (i.e. nearly 10 times higher than the rate for straight track). This tendency was also reported in previous work [2,17], which showed that more squats occurred on curves between 350m to 425m radius and 800m to 1075m radius.

There is known to be a strong association between squats (at least in curved track) and other types of rolling contact fatigue (RCF). This could be because the tangential forces in 600m to 900m curves are high enough to generate RCF, yet the wear rates are not sufficiently high (at least at the shallower radii) to remove a defect once it initiates.

Curves in this range of radii will also be subject to regular maintenance grinding which may remove defects that initiate or prevent them growing to a detectable size. It is possible that the actual rate of initiation in these curves is higher than the data suggests.

4.2.2. Squats in relation to rail age

A significant proportion, approximately 90%, of rail on Intercity Route 2 was laid since 2000 as part of route modernisation works. In contrast, only 40 to 50% of rail on Intercity Route 1 and the Suburban Route was laid since 2000.

As summarised in Figure 5, the highest rates of squat take place on rails laid prior to 2000, with particularly high rates on 1990s rails on the Intercity Route 2 and the Suburban Route. It is also notable that the squat formation rate is significantly lower in rails installed within the last 18 years, approximately 10 – 16 times lower for 2000 – 2009 rail on the Suburban Route and even lower on Intercity Route 2. The squat rate in 2010 – 2018 rail is very low in comparison to earlier years.

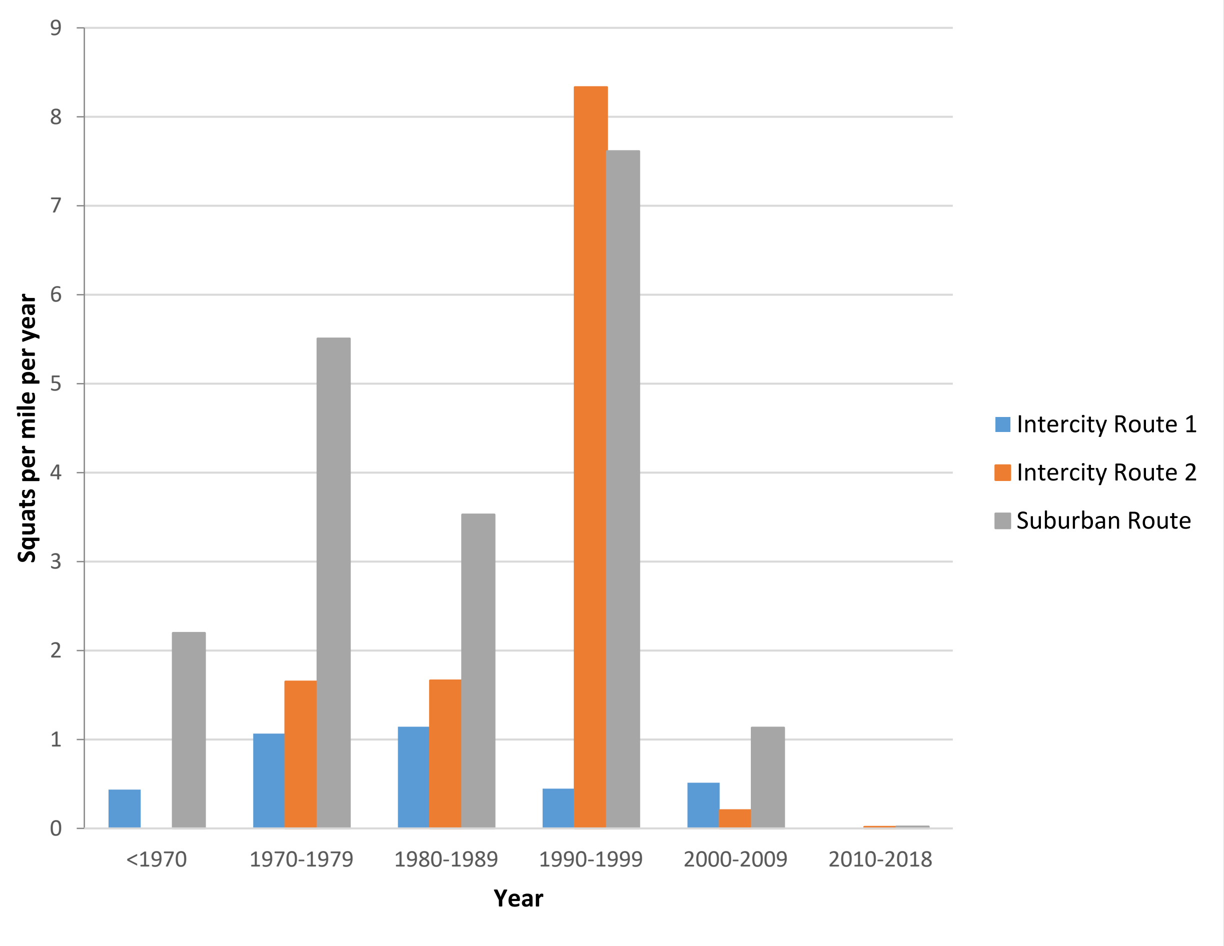

Figure 5: Squats formation rate vs rail age

The relatively low rate of squat detection in newer rails may have several explanations, however it is difficult to conclude which one of them is the dominated reason.

It may simply be that once initiated, squats grow very slowly and it therefore takes some years before they grow to a detectable depth. It is also possible that newer rails might be installed in sections that have a shorter rail life (i.e. due wear, RCF damages etc.) and hence squats does not have time to grow to a measurable depth.

Additionally, there have also been significant changes in GB maintenance practices over the life of these rails, in particular the frequency and quality of rail grinding which has increased steadily since 2000. It is plausible to suggest that the lower squat detection rates in post-2000 rail are the result of this grinding removing newly initiated defects before they can grow to a detectable size. Similarly, the high rates in rails beyond 2000 could be explained by the lack of grinding during this period allowing defects to grow to a size which subsequent grinding cannot remove (i.e. cracks have been slowly growing, below reportable levels but faster than grinding, can remove them, and the more frequent grinding since the early 2000s hasn't 'caught up' with the crack depth). The topic of grinding impact will be discussed later in this paper

4.2.3. Squats in relation to braking and traction events

Braking and traction events could lead to a rail surface / sub-surface microstructure that is more susceptible to fatigue crack initiation and therefore squats defects. Wheel spin or micro spin under heavy traction forces has also previously been associated with local changes in rail micro-structure (known as a White Etching Layer), potentially leading to squat type defects [18]. For this study there was no available data that could be used directly to identify sections of track that are regularly subject to high traction or braking forces. To identify potential traction and braking zones, the analysis assumes that:

- Braking and traction zones will be near stations and major junctions.
- Average acceleration and braking rates of 3% of gravity (i.e. 0.3m/s2) have been used to estimate the length of track over which traction and braking will occur.
- Braking and traction distance could be calculated using equation 1:

$$S = \frac{0.5\,U^2}{a} \tag{1}$$

where S is the braking/traction distance (m), U is the speed of the train and a acceleration provided by the braking/traction system (i.e. 0.3 m/s^2)

Table 4 summarises the squats rate of squat within and outside these assumed traction and braking zones.

Route	Number of Squats in Traction & Braking zones	Number of Squats in Plain Line	Squat Rate – Traction (Squats /mile/year)	Squat Rate - Braking (Squats/ mile/year)	Squat Rate – Traction& Braking (Squats/ mile/year)	Squat Rate – Outside Traction / Braking Areas (Squats/ mile/year)
Intercity Route 1	1118	607	0.5	0.6	1.1	0.4
Intercity Route 2	472	407	0.3	0.2	0.5	0.3
Suburban Route	784	849	1.5	1.6	3.1	2.8

Table 4: Squat formation rate within and outside assumed traction and braking zones

As shown in the above table, the squat rate for all routes is higher in traction and braking zones compared to outside these areas. For the Intercity Route 1, the squat rate is nearly three times higher in traction and braking zones than outside them. For the Intercity Route 2 it is 1.7 times higher whilst the rates for suburban route are similar. On suburban route, the squats rate in traction and braking zone is higher by nearly three times than that in Intercity Route 1 and six times than that in Intercity Route 2.

Although some of the literature proposes different squat initiation mechanisms, and hence rates, for traction zones and braking zones, the analysis shows no significant difference in squats rate (squats/mile/year), as shown in Table 4.

There are several possible reasons why squats occur more frequently in traction and braking zones. The presence of high levels of traction and braking forces may contribute to exhausting the ductility of the material leading to a higher propensity of surface damage around geometric features such as welds. Additionally, the high flash temperature at the wheel/rail interface due to braking and acceleration events could generate WEL to promote studs-type squat.

The results shows that the greatest difference between traction/braking zones and other areas occurs on Intercity Route 1 routes. This might be because Intercity Route 1 has a large proportion of loco hauled trains. It is possible that delivering all the traction through four axles, and hence higher tractive effort, makes them more prone to initiating squats. Additionally, the dynamic braking forces in loco hauled train are significantly high (i.e. could reach up to four times higher than the braking forces in passenger vehicle unites), and hence more likely to introducing squats.

It is notable that on Suburban Route where the overall squat formation rate is much higher than on the other routes, the differential between traction/braking areas and other areas is comparatively small. There are a number of possible reasons for this which might include lower overall speeds, a lack of freight traffic (i.e. less rail wear) and a fleet of modern distributed traction multiple units with later generation Wheel Slide Protection (WSP) and traction control.

Additionally, the analysis shows that several hotspots (i.e. areas with higher numbers of squats or repeated squat formation) occurred near junctions and stations.

4.2.4. Squats in relation to rail wear

Network Rail provided a spreadsheet of total rail headwear along the Suburban Route, based on train borne surveys carried out in 2016. As data was also available on rail age, it was therefore possible to estimate head wear rate per year (i.e. measured vertically at the middle of the railhead). It was not possible to investigate the influence of rail wear rates on the Intercity Route 1 and Intercity Route 2 as equivalent data was unavailable.

Figure 6 summarises the number of squats per mile against the average rate of head wear/year. Note that the measured headwear represents the material removed by wear due to traffic and maintenance grinding.

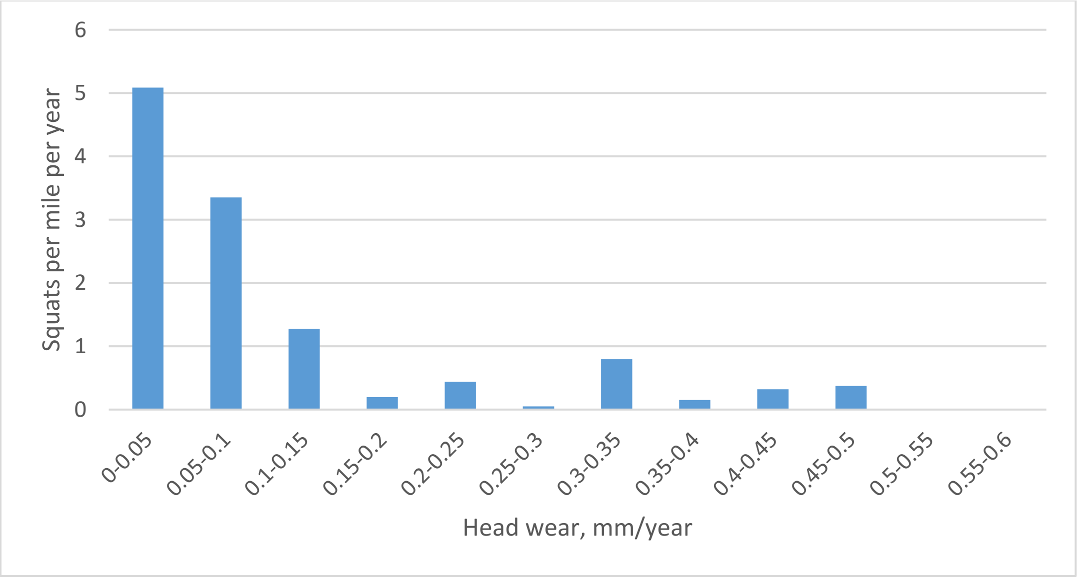

Figure 6: Rate of squat broken down by rail head wear rate – suburban route

As shown in Figure 6, the majority of squats occurred on rails with head wear of less than 0.05mm per year. As the wear rate increases, the squat rate reduces. No squats were found on rail with headwear higher than 0.6 mm/year, whilst the rates of squats on rail with a wear rate greater than 0.2mm per year were relatively small.

It is likely that the higher rate of material removal from the rail head, due to headwear and / or grinding, are big enough to remove the initiating cracks before they could propagate into the rail material. It seems probable that the type of wear (i.e. due to traffic or grinding) is immaterial, i.e. it is the material removal rate which is critical.

Figure 6 suggests that there is a distinct wear threshold beyond which squat formation drops to a very low rate at head wear rates greater than 0.15 – 0.25 mm/year.

This amount of material removal can usually be achieved by a rail grinder in one or two passes and this finding suggest that where the 'natural' wear rate isn't high enough, grinding is an important mitigation in the preventing squats growing once initiated. This re-enforces some of the early research into RCF and wear, such as Magel et al's [19] who suggested that grinding should be used in addition to the wear caused by traffic to achieve a 'magic wear rate' that is just high enough to remove cracks before they grow.

4.2.5. Squats in relation to rail grade

The majority of rail currently in use on the UK rail network is standard carbon R220. A smaller percentage (nearly 35%) of wear resistance grade R260 is also present [20,24]. However, head hardened rail (R350) was only introduced relatively recently and therefore it is difficult to assess its performance in terms of squat resistance. Table 5 shows the material concepts for R220 , R260 and R350HT rails.

Steel type	Material concept	Tensile strength (MPa)	Hardness range (HBW)	Elongation , min, %	Objective
R220	Naturally hard, 0.4 ≤ C ≤ 0.6% S ≤ 0.005%	≥ 770	220 to 260	12	To reduce RCF damage relative to higher-strength pearlitic steels by means of greater wear that is nevertheless confined due to a lower S content and sulphide spheroidisation
R260	Naturally hard, 0.6 ≤ C ≤ 0.8%	≥ 880	260 to 300	10	Standard grade wear resistance
R350HT	finely pearlitised, 0.6 ≤ C ≤ 0.8%	1,175	350 to 390	9	To define the line parameters under which head-hardened rails are beneficial

Table 5: Material concepts tested for rails - Pearlitic steels [28]

As previously stated, the total number of squats included in this analysis is 4265, but rail grade was recorded for only 1828 of these defects. Further, the rail grade distribution across the whole of each route is needed for normalisation; however, this was not available. Therefore, an alternative approach was needed to investigate correlation with this potential causal factor.

For this task, the Kruskal-Wallis H test[21] was used to determine if differences in squat formation between R220 and R260 are statistically significant. The Kruskal-Wallis H test is a rank-based nonparametric method, used to investigate if samples originate from the same distribution [21]. It determines the medians of two or more groups and checks if these are different. It is widely used in medical research to correlate diseases with causal factors [22,23]. For this study, the significance threshold level (p_value) in the Kruskal-Wallis H test was set at <5%. This statistical test indicates the pattern has not occurred by random chance. Therefore, a p_value less than 0.05 indicatives that a difference is statistically significant, for example, between squat formations in the two rail grades.

Using the 1828 samples including rail grade, the track was divided into 50m sections. 50m track sections either entirely without squats or for which the rail grade was not recorded were excluded from the analysis. For the remaining 50m sections, a squat intensity (i.e. squats number / 50 metre) was then calculated.

The statistical results show significant differences in squats intensity between the rail grades, the Kruskal-Wallis p_value is 0.014. The mean squat intensity was 2.5 for R220 rail and 1.75 for R260 rail.

For further investigation, the 1828 squats were broken down by curve radius and rail grade, as shown in Table 6.

	The mean number of squats in 50 meter section by rail grade			
Curve	**R220**	**R260**	**Total number of squats**	**P_value**
R<699m	2.1	1.7	40	0.85
700m<R<999m	2.8	2	142	0.59
1000m<R<1499m	2.1	1.6	160	0.06
1500m<R<1999m	2.4	1.2	223	0.07
2000m<R<2999m	2.2	1.2	346	0.02
R>3000m	2.6	2.1	917	0.22

Table 6: Intensity of squats by curve radius and rail grade (2011 – 2017)

For curve radii between 1000 and 3000m, these results show a statistically significant difference in squat intensity between the two grades, p_values were between 0.02 and 0.07. Within this range of radii, the mean squat intensity was 2.2 for R220 rail and 1.3 for R260 rail. It appears that R220 rail is almost 50% more likely to have squat damage than R260 rail for radii between 1000m and 3000m. A plausible explanation for this phenomenon can be found in the relationship for each steel between resistance to cracking and wear rate.

Closer examination of wear data for the Suburban Route (see Section 4.2.4) reveals that the vast majority of squats occur where headwear is less than 0.1 mm per year, regardless of rail steel. Interestingly, the reduced wear rates typically associated with R260 (compared to R220) [24] does not increase the squat intensity for curve radii between 1000m and 3000m, instead squat intensity decreases. Therefore, the higher number of load cycles required for RCF crack initiation in R260 could be suppressing squat intensity at low wear rates [24]. Alternatively, it could be said that a higher wear rate is need to suppress crack initiation in R220 (as for the Suburban Route) thus potentially promoting higher squat intensities.

For radii < 1000m, a statistically significant relationship was not found between squat intensity and rail grade. This could be due to more frequent maintenance activities (i.e. grinding and re-railing) for tighter curves.

A more complete data set allowing the normalised squat formation rate to be found would allow these considerations to be more robustly explored. In their absence, the adopted methodology provides valuable insights.

4.2.6. Squats in relation to freight traffic

The two mainline routes included in this study have both freight and passenger traffic. The ratio of freight to passenger traffic varies along the route and it is therefore possible to investigate how the relative proportion of freight and passenger traffic might influence squat initiation. For this, the squat rate was compared to the percentage of freight traffic operating over a route section.

The freight traffic analysis for both routes showed that, approximately 50% of these route sections have low freight traffic (i.e. less than 10% of the total traffic). Approximately 28% of the route sections have between 10 and 20 % freight traffic. Freight traffic for the rest of the track length was higher than 30% of the total traffic.

Figure 7 summarises the squat rate against the percentage of freight traffic for Intercity Route 1 route sections. The analysis in Figure 7 shows that track sections with the lowest levels of freight traffic (i.e. less than 10% of the total) showed the highest squat rates. A similar tendency was found in Intercity Route 2 sections, as shown in Figure 8.

The squat formation rate was 1.1 squats/ mile/year on the Route 1 routes and 0.65 squats/mile/year on Route 2 routes but in both cases falls steadily as the freight traffic increases.

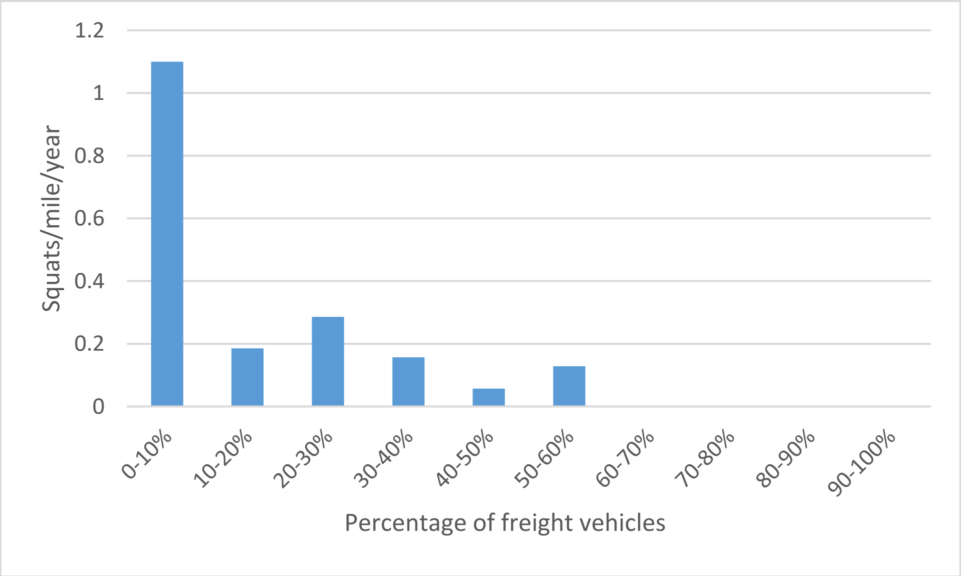

Figure 7: Squats rate vs percentage of freight vehicles – Intercity Route 1 route

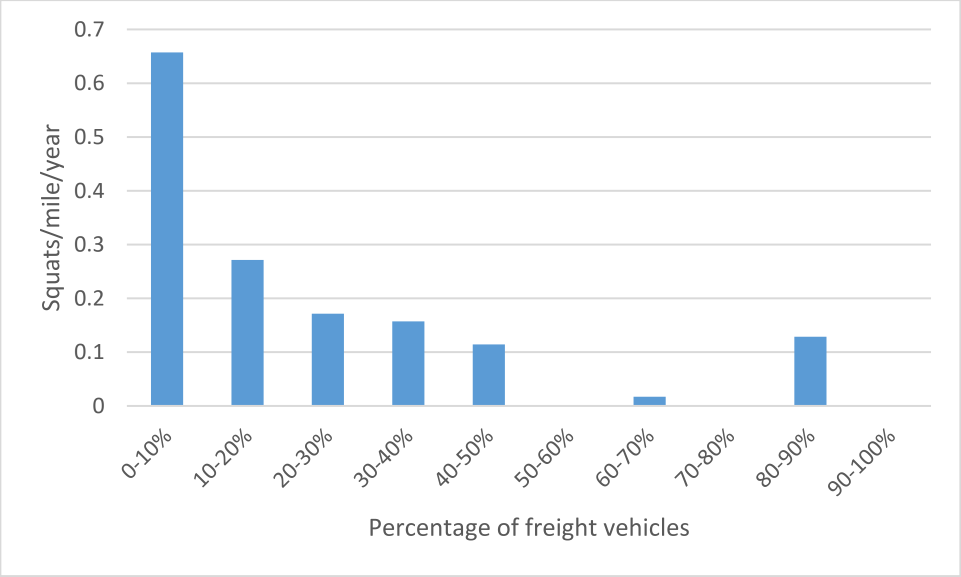

Figure 8: Squats rate vs percentage of freight vehicles – Intercity Route 2 route

Based on the analysis above, it appears that squats are more likely to occur on routes with low levels of freight traffic. Routes with higher numbers of freight vehicles will impact the natural wear through higher axle loads and potentially less maintained wheel profiles. Furthermore, such routes would also see denser grinding intervals / increases grinding activities.

4.2.7. Squats in relation with grinding activity

Cyclic-preventive rail grinding is known to be an effective maintenance practice to remove (or limit the growth of) early stage RCF cracks, including squat defects.

Network Rail has provided the grinding history for the Suburban Route between years 2005 and 2018. It was found that there were 8 hotspot areas (from total 28 hotspot areas in suburban route) with high rates of squat formation that corresponded to missed or limited grinding activities.

Network Rail company standard NR/L2/TRK/001/mod10 [25] requires fixed-interval grinding to be carried out based on accumulated Equivalent Mega Gross Tonnes EMGT. EMGT is calculated based on the real accumulated tonnage of vehicles traveling over a point on the route, measured in accumulated mega gross tonnes (MGT), with multiplication factors applied for, vehicle type, running speed, tractive power and additional multiplication factor for higher axle loads [26].

Based on NR standard, curves that ≤ 2500m radii should be ground every 15 EMGT, whilst curves that > 2500m radii and straight tracks should be grinded every 45 EMGT.

It is well known that the number of axle passes is an important factor in the growth of fatigue defects due to the fluid pressurisation effect [27]. Therefore, EMGT may not be the best metric to define a grinding frequency intended to manage RCF damage.

To illustrate this point, Table 7 shows the average number of vehicles passing over the selected routes, for a 4 week period from 18th August to 15th September 2012.

Route	Total number of vehicles per period	Number of wheel passes per period	Million gross tonnes per annum	Equivalent million gross tonnes per annum
Intercity Route 2	43,750	175,000	31.7	47
Intercity Route 1	25,000	100,000	15.4	33
Suburban Route	23,000	92,000	13.7	8.3

Table 7: Average traffic on each route period 240, (18/8/12 to 15/9/12)

It is clear from the table that Intercity Route 1 and the Suburban Route have a similar number of total axle passes but the EMGTPA on Intercity Route 1 is nearly four times that on the Suburban Route (because of the focus on speed, axle load and tractive power in the EMGT calculation).

Table 7 indicates that, based on current Network Rail standards, the Intercity Route 1 will be ground significantly more frequently than the Suburban Route. This provides a plausible explanation for the significantly higher rate of squats observed on the Suburban Route.

4.2.8. Influence of structures and track form

The analysis also investigated the influence of key infrastructure features including tunnels, bridges and sleeper types on squats rates. The following conclusions were made:

- Squats in tunnels: Squats are seldom found in tunnels. This may be because tunnels often (though not always) provide a controlled environment, with relatively uniform temperatures and without sudden changes in wheel–rail friction which may lead to wheel slip in traction or braking. Where the tunnel provides a dry environment cracks may grow more slowly due to the absence of fluid entrapment.
- Squats on bridges: In the sample studied there are a similar number of squats/mile on bridges as there are on plain line. There is some evidence that squats are more likely to occur on concrete bridges than on steel or masonry bridges.
- Squats on the transition onto and off bridges: In general, the variation in track stiffness at either end of bridges does not have a statistically observable effect on squat formation in this data sample.
- Sleeper type: Squats are more likely to occur on rail laid on timber sleepers than on concrete sleepers.

4.3. Squats hotspot/clustering analysis

In the data set considered it was reasonably common to find short sections of track (denoted as hotspots areas) which either suffered from a disproportionate number of squats or, more often, where repeated reoccurrence of squats were found over an extended period of time. For the current study, the selection of the hotspots has been undertaken according to the number of squats (i.e. number of squats/50 metre was 3 times higher than the average of number of squats /50 meter for the entire route) and/or the repeatability of their occurrence (at least occurs 2 times within 3 metre window in a 7 year period).
For the inspected routes, there were 27 hotspots on the Intercity Route 1 route, 13 on the Intercity Route 2 and 28 on the Suburban Route. Some hotspots were located less than 0.5 mile apart; in such cases hotspots were combined to form a single larger hotspot.

Based on this analysis, some general conclusions can be made regarding the hotspots:

- All the rails in the hotspots are R220 grade.
- Nearly all rails in hotspots were laid before 2000.
- The majority of hotspots are located in curves with a low values of cant and cant deficiency.
- The hotspots are located in the areas with the highest line speeds.
- Based on the available data, all hotspots occurred on rails that have a low headwear rates.
- The majority of rails in the hotspots were laid on concrete sleeper.
- Hotspots occur on route sections with both high and low tonnage.
- Nearly half of the hotspots areas located in braking and traction zones.
- The majority of hotspot areas are located on straight track or gentle curves (though they do occur across a range of curve radii).
- Squats hotspots occur within areas that have both high and low grinding activity.

The correlation analysis results in section 4.2 (performed on the total sample of 4265 plain line squats) showed that squats are more likely to occur on rail laid on timber sleepers than on concrete sleepers. Furthermore, squats rates are generally higher on radii < 1000m than they are elsewhere. It seems that these finding conflicts with the finding obtained from the correlation analysis inside the hotspot area.

The possible reason behind this conflict is that rail age and grade, headwear rates and braking/traction events in the hotspot areas might had higher influence on the probability of squat initiation compared to sleeper type and/or curvature.

5. Conclusions

A database recording squats detected over a seven year period on three UK rail routes of differing characteristics, mixtures of vehicle type and stopping patterns was been used to investigate potential causal factors. To enable this analysis, complementary data sources linking directly or indirectly with potential causal factors have been merged with the squats records. The main criteria used for the current analysis is the average squats rate (per mile/year) for track meeting specific criteria, linked with potential causal factor. Each of the three route had different average rates of squats/mile/year; which it is suggested can be linked to the differing characteristics of these routes.

5.1. Causal factors linked to squat initiation

Squats were more commonly found on curves with radii between 600 and 1000 m, a range in which RCF type defects are also often found; this may be related to steering forces as vehicles negotiate these curves. The grade of rail steel used in moderate curves can have influence on squat formation. For example, for curve radii between 1000 and 3000 m R260 grade rail appears to have better 'squat resistance' than R220 rail; this is assumed to be because of the harder R260 grade is less susceptible to crack (even though the wear rate may be slightly lower).

New rails (installed since 2000) have a lower squats rate than older rails. Potentially, small cracks (potentially growing to form mature squats) have initiated but have not yet grown to detectable depths and hence are not recorded in RDMS. The lower squats rate may also be due to the improved rail maintenance practices since 2000s.

Track sections assumed to experience higher traction and braking levels are appear significantly more likely to experience squats. Of the three routes, this was trend was most clear for the route with predominantly locomotive hauled passenger trains (the traffic on the other two routes being mostly multiple units with distributed traction).

5.2. Grinding to manage squats

The majority of squats occur in locations with low rail headwear, as the wear rate increases (either due to the effects of traffic or maintenance grinding) the number of squats reduce.

This suggest that cyclic-preventive rail grinding is an important method to control the development of squats. There is some evidence, based on limited data from the Suburban Route, that squats rates could be reduced by 85-90% if the combined wear from traffic and grinding exceeds 0.2 mm/year. Current Network Rail maintenance standards specify grinding based on intervals defined by 'Equivalent Mega Grose Tonnes (EMGT). Instead, grinding intervals based on the number of wheel passes appears more appropriate, as these relate more directly to rail surface damage.

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Reference:

[1] *UIC Code 712: Rail defects*, 4th ed. Paris: International Union of Railways, 202AD.

[2] M. Kerr, A. Wilson, and S. Marich, "The epidemiology of squats and related rail defects," in *CORE 2008 Conference on Railway engineering: rail- the-core of integrated transport*, 2008, pp. 83–96.

[3] S. L. Grassie, “Studs and squats: The evolving story,” *Wear*, vol. 366–367, pp. 194–199, Nov. 2016.

[4] Network Rail, “Challenge Statement: Rail Head Squats,” 2018. [Online]. Available: https://cdn.networkrail.co.uk/wp-content/uploads/2017/03/Challenge-Statement-Track-Plain-line-rail-head-squats.pdf.

[5] Z. Li, X. Zhao, C. Esveld, R. Dollevoet, and M. Molodova, “An investigation into the causes of squats—Correlation analysis and numerical modeling,” *Wear*, vol. 265, no. 9–10, pp. 1349–1355, Oct. 2008.

[6] Z. Li, X. Zhao, R. Dollevoet, and M. Molodova, “Differential wear and plastic deformation as causes of squat at track local stiffness change combined with other track short defects,” *Veh. Syst. Dyn.*, vol. 46, no. SUPPL.1, pp. 237–246, 2008.

[7] S. L. Grassie, D. I. Fletcher, E. A. Gallardo Hernandez, and P. Summers, “Studs: a squat-type defect in rails,” *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 226, no. 3, pp. 243–256, May 2012.

[8] Z. Li, X. Zhao, and R. Dollevoet, “An approach to determine a critical size for rolling contact fatigue initiating from rail surface defects,” *Int. J. Rail Transp.*, vol. 5, no. 1, pp. 16–37, Jan. 2017.

[9] M. Steenbergen and R. Dollevoet, “On the mechanism of squat formation on train rails – Part I: Origination,” *Int. J. Fatigue*, vol. 47, pp. 361–372, Feb. 2013.

[10] M. Steenbergen, “Squat formation and rolling contact fatigue in curved rail track,” *Eng. Fract. Mech.*, vol. 143, pp. 80–96, Jul. 2015.

[11] Z. Li, R. Dollevoet, M. Molodova, and X. Zhao, “Squat growth—Some observations and the validation of numerical predictions,” *Wear*, vol. 271, no. 1–2, pp. 148–157, May 2011.

[12] X. Deng, Z. Qian, Z. Li, and R. Dollevoet, “Investigation of the formation of corrugation-induced rail squats based on extensive field monitoring,” *Int. J. Fatigue*, vol. 112, no. December 2017, pp. 94–105, Jul. 2018.

[13] M. Farjoo, W. Daniel, P. Bellette, and P. A. Meehan, “Field statistical and finite element analysis of rail squats,” *Eng. Fract. Mech.*, vol. 109, pp. 117–129, Sep. 2013.

[14] Network Rail, *NR/SP/TRK/057: Rail Failure Handbook*, issue 4 ,2001.

[15] Network Rail, *NR/L2/TRK/3100: Topographic, Engineering,Land and Measured building surveying – Strategy and general* , issue 5 ,2019.

[16] Network Rail, *NR/L2/TRK/001/mod01: Glossary*. 2012, pp. 1–17.

[17] W. Daniel, “Final Report on the Rail Squat Project R3-105,” 2013.

[18] Zhao, X., & Li, Z. (2015). A three-dimensional finite element solution of frictional wheel–rail rolling contact in elasto-plasticity. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 229(1), 86–100. https://doi.org/10.1177/1350650114543717

[19] Kalousek, J. and M. Magel, *Achieving a balance: The 'magic wear rate'*,Railway Track and Structures, March 1997, p. 50 – 52.

[20] British Standards Institution, *Railway applications track rail :part 1: vignole railway rails 46 kg/m and above*. 2007, BSI.

[21] Lund Research Ltd, "Kruskal-Wallis H Test using SPSS Statistics",2018. [Online]. Available: https://statistics.laerd.com/spss-tutorials/kruskal-wallis-h-test-using-spss-statistics.php

[22] Kruskal, William H., and W. Allen Wallis. *"Use of Ranks in One-Criterion Variance Analysis."* Journal of the American Statistical Association, vol. 47, no. 260, 1952, pp. 583–621. JSTOR, www.jstor.org/stable/2280779.

[23] Lachin JM. *Power and sample size evaluation for the Cochran-Mantel-Haenszel mean score (Wilcoxon rank sum) test and the Cochran-Armitage test for trend*. Statistics in Medicine, 2011;30:3057–66.

[24] Bevan, A, Jaiswal, J, Smith, A et al. (1 more author) (2018) *Judicious selection of available rail steels to reduce life-cycle costs*. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. ISSN 0954-4097.

[25] Network Rail, *NR/L2/TRK/001/mod10: Rail profile management*. 2012, pp. 1–5.

[26] Network Rail, NR/L1/TRK/002: Categorisation of track, 2011.

[27] Fletcher, D. I., Hyde, P., & Kapoor, A. (2007). Investigating fluid penetration of rolling contact fatigue cracks in rails using a newly developed full-scale test facility. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 221(1), 35–44. https://doi.org/10.1243/09544097JRRT63

[28] K. Mädler et al. Rail Materials: Alternatives and Limits. Proceedings of the 8th World Congress on Railway Research (WCRR), May (2008), 18–22.