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Expanded statistical analysis of squats on the Great Britain (GB) mainline network

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A B S T R A C T

Squat defects are one of the most common rail surface defects. Significant research effort has gone into understand squat defects over the last 10 years which has brought about important developments in the understanding of their initiation mechanism; however, further work is still required to fully understand squat and the best methods to control them.

This study considers records of squat defects over a period 9 years, considering 2600 km of track across 8 different routes on the GB mainline network. The analysis separately reviews squats on: plainline, crossings, joints and welds. Results include an overview of the main factors influencing the development of each type of squats, practical methods to immediately reduce and manage squat defects and recommends focus areas for further research to understand squat defects.

Results suggest that squats on plainline, crossings, joints and welds, all correlate with different influencing factors; headcheck defects appear to significantly influence the probability of squats and how other factors influence squat development.

There is a strong connection between total head wear rate (combined material removal due to traffic and grinding) and squats; 90 % of all squats appear on rail with a headwear rate of <0.2 mm/year. Overall larger section rail (60 kg/m vs 56 kg/m) and harder material (260 Brinell vs 220 Brinell) is significantly less susceptible to squat damage. Track curvature has an influence of squat development, especially in rail with no headcheck cracking, where the tightest curves are significantly more likely to sustain squat damage. The probability of squat at vertical discontinuities, i.e. joints and crossings are significantly more likely as train speed increases. Whilst squats on joints are 1000 time more likely than squats on welds.

1. Introduction

1.1. Background

A squat is defined in IRS 70712 Rail Defects [1] as a rail defect that ‘is visible on the running surface of the rail head as 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’. Although there is a significant body of research investigating squats, the combination of factors influencing squat development and the best methods to manage squats is still not completely understood. Squats account for a large proportion of railhead defects in rail networks in a broad range of countries, including the GB mainline network [2–6].

An example of a rail squat is shown in Fig. 1. Cracks underneath the darkened surface depression(s) present a risk if they grow down through the rail. Rail inspection (ultrasonic and eddy current) usually identify defects early enough to avoid rail breaks. However, squats cause a significant amount of maintenance to manage the risk of rail failure.

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Fig. 1. Example squat defect [authors own photograph].

1.2. Previous work

The work presented in this paper builds on the previous research of Muhamedsalih et al. [7,8] which carried out an initial statistical analysis of the influence of various track parameters on the probability of squats developing. The previous work considered records from the GB mainline Infrastructure Manager, Network Rail's, Rail Defect Management System (RDMS) of 4264 plainline squat defects from 990 km of track, across 3 routes, recorded over a 7-year period. The influence of: curvature, rail age, tunnels and bridges, traction and braking, rail wear rate (due to traffic or grinding) and rail grade, were considered. Unfortunately for some parameters incomplete records were available. Outputs of that work suggested that:

- Squats tend to be more common in curves between 600 and 1000 m radius
- Rails installed since 2000 tend to have less squats
- Squats are rarely found in tunnels
- Traction and braking zones tend to have more squats
- Squats are more likely on wooden sleeper (vs concrete sleepers)
- Rail with a higher wear rate (due to traffic and grinding) doesn't tend to get squats
- R220 grade rail steel has a higher rate of squats than R260 grade rail steel[1]

Some limitations of that work include: the influence of track geometry quality was not considered; data on rail age, rail section and rail steel were sometime missing; the influence of grinding was only considered on a very small section of track; the work considered only plainline squats; squat growth rates were not evaluated; influencing factors were compared against squats/mile/year and did not directly consider the influence of traffic volumes.

1.3. Objectives

The purpose of this work is to refine and extend the previous statistical study [7,8]; previous findings may have been misleading as rates of squats measured in squats/mile/year with no consideration of volumes of traffic may not give an accurate representation of the influence of the various factors considered. The new analysis in this paper is based on significantly more complete data and considers a larger selection of routes to take into account a wider variety of parameters. This new work also considers the factors that contribute to squats on crossings, squats on rail ends and squats on welds which have not previously been investigated and published.

The objectives of this work are to:

1. Identify the factors influencing the development of squats on plainline, joints, welds and crossings, and quantify their effect.
2. Identify the factors affecting crack growth rate in squat defects and quantify their effect.
3. Investigate how headcheck cracking influences the development of squats.
4. Propose practical methods to manage squats.
5. Identify focus areas for further research to better understand squats.

[1] R220 and R260 are different types of rail steel with corresponding hardness' of 220 Brinell and 260 Brinell.

2. Squats research and existing understanding

Squats have been recognised as a rail defect since the 1960s in Britain and Japan [4,9]. There has been significant work developing the fundamental understanding of squats over the last 20 years. However, squats are still not completely understood, findings from studies carried out on a particular rail network are not always directly transferable to other networks depending on the different track structures, rail steels and combination of vehicle types and characteristics. There appears to be a range of initiation mechanisms for squats, along with a variety of factors influencing their initiation and growth.

Squats research has been carried out with a wide range of methodologies and different focuses, including: metallurgy studies based on samples of squats removed from track [3,10–13], lab based metallurgy experiments [14,15], wheel-rail interaction simulations [15–18], FEA analysis [6,19,20,21,22], and statistical analysis [19,20,22,23,23,24]. Previous statistical analysis has typically focused on specific routes with a limited variation in train types.

A focus of recent research has been to split squats into two groups, defined as 'classic squats' and 'squat type defects' (studs) [4,13,25,26]. Whilst the two categories of squat have the same visual appearance on the surface of the rail, the crack initiation mechanisms and crack growth behaviours are suggested to be different. A classic squat is defined as a squat formed due to sheer induced Rolling Contact Fatigue (RCF) cracking in rail with a plastically deformed zone at the surface of the rail caused by the rolling contact of passing wheels; where cracks initially grow along grain boundaries of the deformed microstructure. Headchecks are another type of RCF driven defect where multiple fine cracks appear in the rail head also initially growing along grain boundaries in the microstructure; these cracks occur over 10's of metres of track rather than as single isolated defects such as squats.

A stud is a squat type defect which develops in rails with no (or minimal) plastically deformed zone. In the absence of significant plastic deformation, a highly aligned microstructure along which cracks can initially grow is not present; studs have been linked to initiation in a thin hard and brittle surface layer, knows as the White Etching Layer (WEL), which may be caused by thermal events associated with wheel spin or high levels of wheel rail creep [4,6,13,14,19,26,27,28–30].

3. Methodology

3.1. Data sources

Records of squat defects used in this analysis are from the Network Rail, Rail Defect Management System (RDMS) [31], including defects reported between 2010 and 2018; each squat record has a unique ID and includes range of associated parameters, including: Date recorded; Location; Defect type; Line speed; Rail section; Rail steel grade; Jointed or Continuously Welded Rail (CWR). Squat defects recorded in RDMS are 'actionable defects' and are at least 10 mm deep; it is therefore not possibly to completely separate squat initiation from squat growth as the date of initiation is not known. As with all RCF defects the cracks need to grow at a certain rate to reach the stage they become an actionable defect within the life of the rail.

Track characteristics for the whole network have been extracted from Network Rail's Integrated Network Model (INM) [32] (as RDMS only records track characteristics where defects have occurred). INM divides the network into 'segments'; segments are sections of track with the same characteristics, they can vary in length from 1 m to 100 m. Each segment has a record of: Location; Track category; Line speed; Rail profile; Rail steel; Jointed or Continuously Welded Rail (CWR); Sleeper type; Curvature; traffic carried per year.

The following information was also obtained from other databases:

- Traffic volumes were obtained from the Network Rail AccTraff database [33].
- Rail head wear was obtained from the Network Rail KLD rail profile monitoring system [34].
- Track geometry quality was provided from the Network Rail track monitoring system [35].
- Recors of headchecks, measured with eddy current inspection, were obtained from the Network Rail RCF database [36].
- Characteristics of crossings was obtained from the Network Rail crossings database [37].
- Detail of vehicle acceleration and braking values was obtained from Railsys vehicle simulations.[2]

3.2. Selection of track locations for the statistical analysis

The GB mainline network is divided into 837 sections, each with a unique identifier, known as an 'Engineers Line Reference' (ELRs), with boundaries at stations or significant junctions. ELRs can contain single or double (or more) parallel lines and vary in length from around 5 to 200 route km. Fig. 2 shows the distribution of squats/km/year by ELR. There is significant variance of squats/km/year by ELR, range from 6.8 squats/km/year, down to less than 0.01 squats/km/year. The average across the network is 0.3 squats/km/year. A sample of ELRs was selected for this study, with a range of squats/km/year; selected ELRs are highlighted as solid bars in Fig. 2. Table 1 shows a summary of the selected ELRs, grouped by route. Intercity Route 1 fast lines, Intercity Route 2 fast lines and Suburban Route 1 are the same sections of track used in the previous work by Muhamedsalih et al. [7]. Numbers of different types of squats are shown using IRS 70712 [1] defect codes (code 127 = squat on joint, code 227 = squat on plainline, code 427 = squat on weld, code 727 = squat on crossing).

[2] However, this has only been supplied for a section Intercity Route 1.

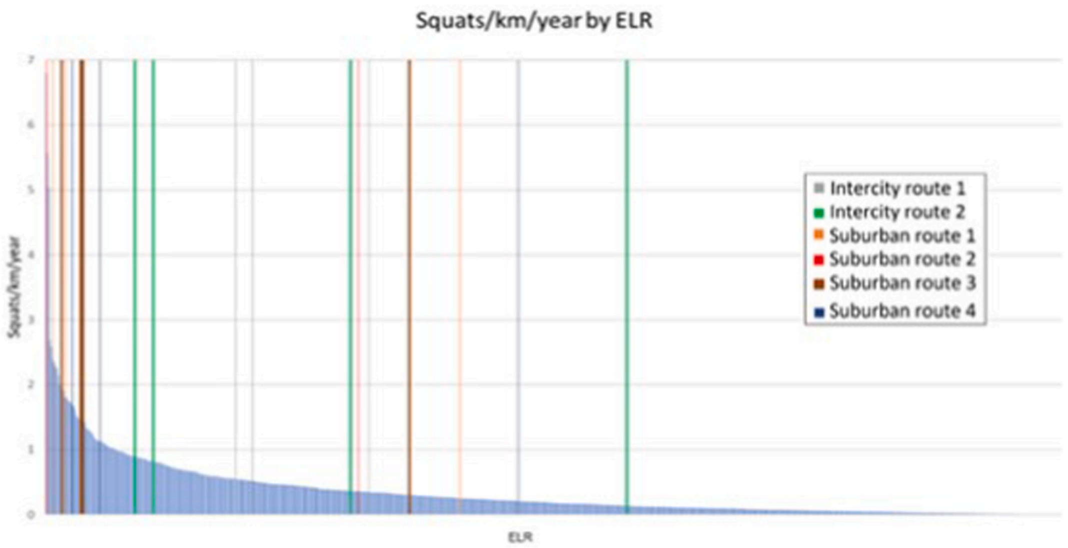

Fig. 2. Selected ELRs for statistical analysis.

3.3. Analysis approach

This work analyses the factors influencing the development of squats in plainline, crossings, joints and welds. Factors being compared to squat probability are: rail steel type (Grade 220 to 260), rail age, track geometry quality, curvature, line speed, rail section (CEN56 or CEN60 [38]), traffic type, sleeper and pad type, rail head wear rate and crossing angle (for squats on crossings). A separate (more limited) study has been carried out to consider the influence of traction and braking.

For each combination of factors, RDMS is searched to find the number of squats; these numbers are then normalised by the total kms of track that contain the same combination of factors, and the window of time of the defect records (9 years) to give records of squats/km/year (or squats/crossing/year, squats/joint/year, squats/weld/year). These results are then further normalised to squats/km/MGT, using the weighted average of traffic volumes on the selection of tracks meeting the combination of factors.

An evaluation of the factors affecting the rate of crack depth growth in squat defects has been carried out based on records of 'suspect squats', i.e. squats with a damage depth greater than 5 mm compared to their linked 'actionable squats' i.e. squats with a damage depth greater than 10 mm. Using records of the cumulative traffic it takes for a squat to grow from a 'suspect' to an 'actionable' level it is possible to estimate a crack growth rate in mm/MGT (based on depth of crack into the rail). It has not been possible to investigate crack growth rates from the point of crack initiation up to 5 mm deep.

As discussed in Section 2, studs and squat defects appear to develop based on different initiation and early growth mechanisms; their development can therefore be expected to correlate with different characteristics. When using non-destructive (e.g. eddy current or ultrasonics) inspection techniques there is no method to clearly differentiate between a classic squat and stud defects in track; therefore, there is no separate defect code for studs in RDMS. As defined in Section 2 a classic squat develops from a shear induced RCF crack which initially grows along the grain boundaries of the deformed microstructure in a plastically deformed layer underneath the surface of the rail; whilst a stud is a type of squat which develops in rails which have not been subject to severe plastic deformation. The only way to differentiate between a classic squat and stud in a piece of rail is to remove sections of that rail to examine the microstructure underneath the defect. In the statistical analysis, squats on plainline have been split into two groups; squats in locations of track that also have a history of headcheck cracking and those which do not. Note that Network Rail headcheck records do not identify every single discrete crack which could develop into a squat defect; but lengths of headcheck cracking which occur over metres or tens of metres of rail.

As studs are squats which occur on rail which has no significant deformation of the steel microstructure underneath the defect, it appears less likely they will occur in rails that also contain headchecks (as headchecks grow in steel with a deformed microstructure). Equally it appears unlikely that a crack which forms a squat in a piece of rail subject to headcheck cracks has formed completely independently of those headcheck cracks. Very localised sections of longitudinal/vertical plastic deformation and associated microstructure deformation may cause isolated cracks to grow. However, these would not be picked up in the RCF database which records lengths of track subject to headchecks.

4. Results

Records of squats in RDMS are 'actionable defects', containing cracks which have already reached a depth of 10 mm into the rail; the squat may have initiated a number of years before it grows to a size where it will be recorded in RDMS. In the sections of route considered in this analysis there are rails as old as 50 years (i.e. installed in the 1970s). In this section where squat rates are given as squats/km/MGT, or squats/joint/MGT etc it should be noted this is based on the rate of squats recorded in RDMS between 2010 and 2018. It is not possible to comment on squats which were already identified and removed from track before 2010.

Table 1
Overview of selected routes for statistical evaluation (127 = squat on joint, code 227 = plainline squat, 426 = squat on weld and 727 = squat on crossing).

Route	Track kms	No. Squats 2010–2018				Squats/ km/year	Traffic						Max Line Speed km/h
		127	227	427	727		Average Wheelset mpasses/year	Average MGTPA	Average EMGTPA[5]	Percent loco hauled passenger	Percent multiple unit passenger	Percent freight	
Intercity route 1 fast lines	859	75	2284	266	566	0.41	0.8	14	23	67 %	18 %	15 %	200
Intercity route 1 slow lines	398	13	458	105	146	0.20	0.4	6	9	3 %	48 %	49 %	145
Intercity route 2 fast lines	498	10	1386	22	194	0.36	1.3	19	33	2 %	85 %	13 %	200
Intercity route 2 slow lines	392	2	239	2	214	0.13	0.6	17	27	1 %	39 %	60 %	200
Suburban route 1	130	53	1829	63	24	1.69	0.9	11	13	0 %	99 %	1 %	120
Suburban route 2	15	3	84	5	3	0.70	0.5	6	7	0 %	92 %	8 %	65
Suburban route 3	150	15	1390	96	88	1.17	0.7	11	15	3 %	96 %	1 %	160
Suburban route 4	183	65	688	6	81	0.51	0.7	10	15	1 %	86 %	13 %	200
Totals	**2625**	**236**	**8358**	**565**	**1316**								

4.1. Squat initiation for plainline squats

Fig. 3 gives an overview of the results of the characteristics affecting the development of squats on plainline track. As shown in Fig. 3a, rail manufactured between 2010 and 2019 has very low numbers of squats/km/MGT. This suggests that it may take longer than 10 years for a squat to initiate and grow to a depth of at least 10 mm. Squats in rail with no history of headchecks have a strong correlation with age.[3] Since 1999 a heavier rail section, CEN60 (60 kg/m) has been introduced rather than CEN56 (56 kg/m) whilst harder grade rail steel, grade 260 has been installed since 2003. Whilst the influence of rail age appears to be significant, the influence of rail section and rail grade must play a significant role in this apparent trend. As shown in Fig. 3d, grade 260 steel appears to be significantly less susceptible to squat damage than grade 220. To remove the influence of rail age (as the oldest rails in the sample are all grade 220) results in Fig. 3d are shown only for sections of track with a cumulative tonnage up to 400 MGT. Grade 220 and grade 260 are named after the hardness of the different steels using the Brinell Hardness Number (BRN), i.e. grade 220 = BRN 220 hardness, grade 260 = BRN 260 hardness. Presumably, it is the increase in rail hardness that is reducing crack initiation and early growth rates. The increased hardness of grade 260 (compared to grade 220) appears to have a much bigger influence on reducing the rates of squats on track with no history of headchecks; there is also a reduction in the rate of squats on rails subject to headchecks but the benefits are significantly less.

As shown in Fig. 3f, CEN60 rail also appears to significantly reduce the rates of squats, compared to CEN56 (as with results for rail grade in Fig. 3b and d also only includes samples of rail with a cumulative tonnage up to 400 MGT). The larger rail section of CEN60 reduces rail bending stresses (CEN60E1 has a second moment of area of 3038 cm^4 vs 2321 cm^4 for CEN56 [31], i.e. 30 % bigger) which may reduce rates of crack growth. This reduction is significantly higher on sections of rail not associated with head checks. For CEN60 rail, the squats/km/MGT is much higher in rail also subject to headchecks.

Fig. 3c shows the trend of squats/km/MGT against the total depth of rail head wear, which is another factor that will be in some way proportional to rail age; in general a higher total wear correlates with higher rates of squats. As already discussed, a larger rail section appears to reduce the probability of squats and it therefore might be assumed that crack development in squats is influence by rail bending; 7 mm of head wear on a CEN56 rail would reduce the second moment of area by 10 %.[4]

Squats in rail where there is a history of headchecks do not have the same strong relationship with age. This is presumably because rails with significant head checks are being replaced more often; and therefore rails more than 30 years old are not commonly present at locations that are susceptible to severe headchecks. 85 % of track in the selected routes in this analysis has rail installed since 1990; for these rails, squats are 3 times more likely (measured in squats/km/MGT) in sections of rail with a history of headchecks. This suggests there may be some relationship between cracks in headchecks and the bigger cracks under squats which have reached an actionable size. For rails installed between 1980 and 1989 (11 % of the sample in this study), squats occur at relatively equal rates, irrespective of any history of head checks.

Fig. 3b shows the cumulative squats/km vs cumulative traffic. In this Figure numbers of both sets of squats are normalised by total track length to give an idea of the overall comparative accumulation of each type on a route level. As shown, whilst squats are more likely in sections of track that have experienced headchecks, overall the total number of squats in track with headchecks is lower than the total number of squats in track with no headchecks. As also shown in Fig. 3b, squats in rail with headchecks start to appear as actionable defects after approximately 150 MGT of traffic; whilst squats in rail with no headchecks, start to appear after around 40 MGT of traffic. For both groups of squats, once squats start to occur the rate gradually increases with cumulative MGT.

As shown in Fig. 3j squats on rail with headchecks are less likely to occur on straight/tangent track and the squat rate peaks on curves radii 600–3000 m; this is to be expected, as rail in curves is more susceptible to headchecks. The squats rate is approximately equal on high and low rails (i.e. outer or inner rail in a curve), though this does vary by curve radius. As shown in Fig. 3i, the squat rate in rail with no headchecks correlates strongly with reducing curve radii, the squat rate gradually increasing as curve radii reduces below 1000 m. Rail corrugation, which is linked to the formation of squats and studs is also linked to tight radius curves [39,40]. Squats on curves which no headchecks are more common on the high rail; if these squats are associated with instantaneous high creepages or micro-slip associated with the traction this would be expected to more likely occur on the high rail in tighter curves as the forces in the wheel/rail contact patch may already be closer to creep saturation due to the wheelset steering forces.

Track quality bands in Fig. 3e, considering vertical geometry only, are based on definitions in NR/L2/TRK/01 [41]. To simplify the analysis lateral track geometry was not considered, on the assumption that vertical track forces have the larger influence on crack growth; this will be reviewed in future work.

It appears that track geometry quality has no significant influence on squats in rail with no headchecks. However, for squats in rail with headchecks there is a significant correlation with worsening vertical track geometry quality. If the squats on rail with no headchecks are more likely to be initiated from the thermal effects due to instantaneous high wheel-rail creepage and or short wavelength corrugations, it may be logical not to expect vertical track geometry quality to influence their formation. However, for squats growing from shear induced RCF cracks the track geometry has a significant influence on the crack development.

Fig. 3h shows that rails on wooden sleepers are significantly more likely to be subject to squats. This may suggest the stiffer formation of rails on concrete sleepers reduces crack growth rate. Rail on wooden sleepers is likely to be older, grade 220 steel (rather than grade 260) and CEN56 rail section (rather than CEN60); all of which are factors that correlate with an increased probability of

[3] Though it should be noted that looking at the older groups of rail, the sample size of rails in that age bracket gets smaller which maybe affect the statistical reliability of the results.

[4] Calculated in AutoCAD2022.

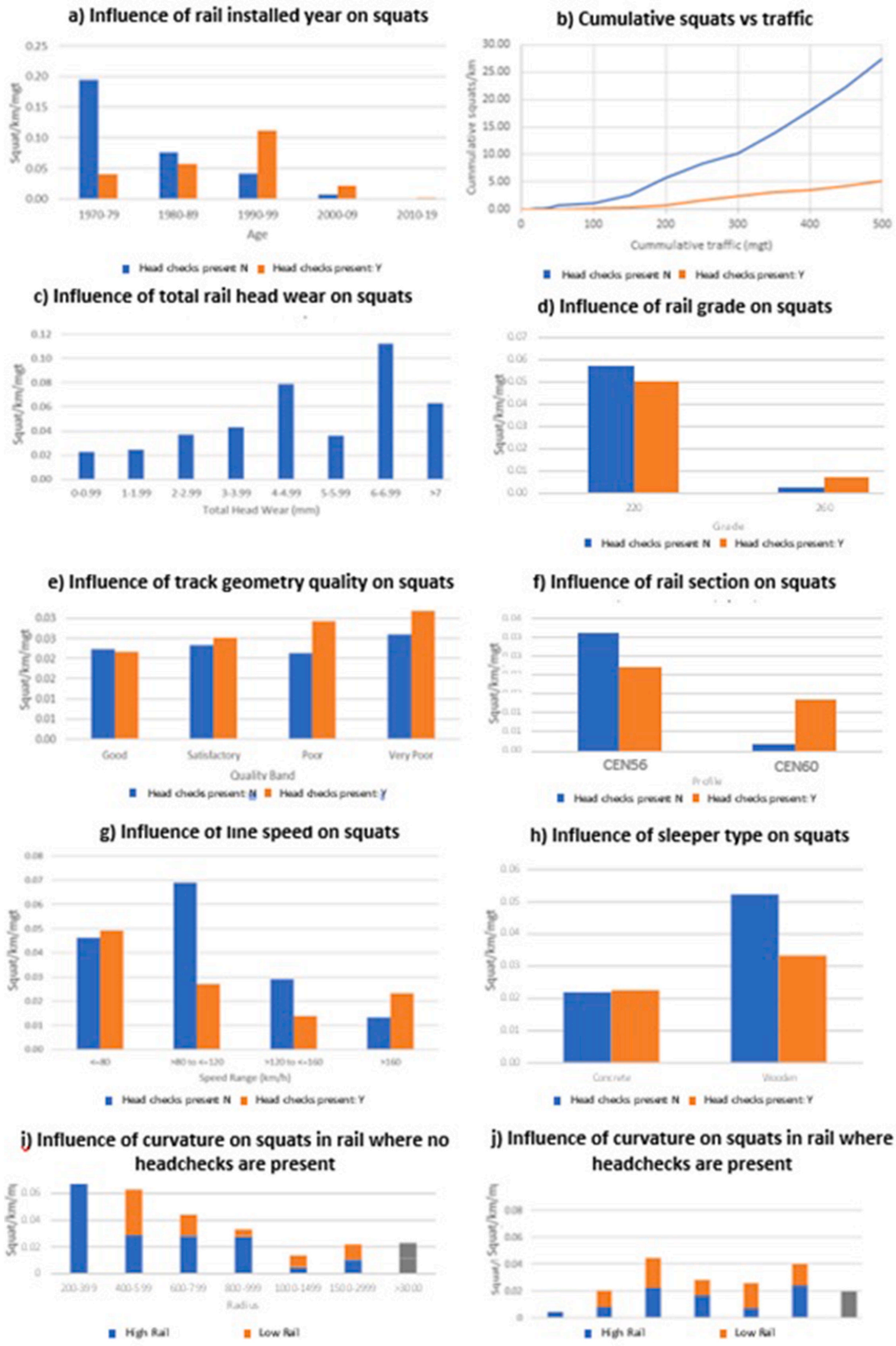

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Fig. 3. Overview of factors influencing squat development on plainline showing a) influence of rail installed year on squats, b) Cumulative squats vs traffic, c) Influence of total rail head wear on squats, d) Influence of rail grade on squats, e) Influence of track geometry quality on squats, f) Influence of rail section on squats, g) Influence of line speed on squats, h) Influence of sleeper type on squats, i) Influence of curvature on squats n rail where no headchecks are present, j) Influence of curvature on squats in rail where headchecks are present.

squats/km/MGT. Therefore, the influence of these factors is hard to distinguish. The increase in squats/km/MGT for track on wooden sleepers, compared to concrete sleepers, is especially marked for squats in rail with no headchecks.

For both group of squats, Fig. 3g shows that there appears to be a generally inverse correlation between line speed and squats/km/MGT: tracks with a higher linespeed tend to have fewer squats. This may be due to other factors that are related to line speed, i.e. tracks with the fastest line speed are more likely to be 260 grade steel, CEN60 rail section and laid on concrete sleepers. Also, as discussed in Section 4.6, rail grinding is more intensively focused on higher speed lines.

4.1.1. *Influence of traction and braking on plainline squat formation*

A number of recent research studies have shown a correlation between stud defects and locations of rail subject to high levels of traction [13,22,26]. For this study it has been difficult to obtain measured data for train speed profiles, including traction andbraking effort. In the absence of real measured data, train simulator data from the Network Rail Railsys software for a short section of Intercity Route 1 has been used, considering both the fast and slow lines.

Fig. 4 shows the acceleration and deceleration for typical trains on 250 km of the Intercity Route 1 fast line and 40 km of the Intercity Route 1 slow line (the commuter services operating on the slow lines have a shorter total journey length of only 40 km from the terminal station). The example train on the fast line is an intercity service operated by a locomotive hauling 10 Coaches; whilst the example train on the slow line is an 8 car Electric Multiple Unit (EMU). The figure shows squat rates presented in squats/100 m/year and the acceleration data has been sampled per 100 m of track with all plainline squats grouped together, irrespective of whether they are in a piece of track which also has headchecks.

In general, there are more squats per track km (or per 100 m) on the fast line (noting the difference in scale on the x axis) with an average of 0.16 squats/km/year vs 0.07 squats/km/year on the slow line. There are significant numbers of squats on the fast line in locations which are not subject to acceleration or braking[5]; whilst squat on the slow line appear to line up more with acceleration and braking zones.

Fig. 5 shows the proportion of squats/100 m/year on the fast and slow lines by sections of track subject to braking, constant speed and acceleration. For both the fast and slow lines, braking zones have more squats/100 m/year than track carrying traffic at constant speed. On the fast line, acceleration zones have fewer squats/100 m/year than the constant speed sections. However, on the slow lines there is a clear increase in squats/100 m/year in acceleration zones compared to track carrying traffic at constant speed' whilst this is also a more marked difference in squats/100 m/year in the braking zones compared to steady speed. It may be that the comparative slower acceleration rates on the fast lines are less likely to cause enough wheel-rail creep to initiate studs; whilst the higher acceleration rates on the slow lines do initiate studs. The longitudinal forces in traction and braking may also be causing accumulation of plastic strain at the rail surface leading to the formation of 'classic squats', i.e. cracks initiating and growing in a highly sheared steel microstructure, rather than thermally initiated cracks.

Further detailed work is required to fully evaluate the influence of traction and braking, including a larger statistical analysis and further fundamental investigation considering thermal inputs from different traction systems and detail metallurgical analysis (noting that other studies have already made progress in this area).

To give a high-level view of the influence of traction and braking across all routes in this study, Fig. 6 presents a comparison of the average distance between station (by route) compared to squats/km/MGT. Overall, the routes with smaller average distances between stations have higher numbers of squats/km/MGT. This provides some indication that acceleration and braking may have an influence on squats (as train services will be accelerating and braking more often if stations are closer together).

4.2. *Squat initiation for squats on welds*

There are two main types of rail weld, thermit (also known as aluminothermic) and flash-butt. Thermit welds are more commonly used on site or weld repairs; whilst flash butt welds are predominantly used in production of long continually welded rail strings in a factory.

Records of squats on welds in RDMS include details of the type of weld; however, there is no definitive record of the location of all welds or the proportion of each weld type in track. The INM segmented track data includes the track type (i.e. continuously welded rail (CWR) or jointed track), along with the age of rail. To estimate the number of welds/km it is assumed that:

- rail installed before 1980 has a rail length of 18 m;
- rail installed between 1980 and 2007 has a rail length of 36 m;
- and rail installed after 2007 has an average rail length of 100 m (mostly 108 m but some 72 m).

[5] Based on the simulated speed profile from Railsys.

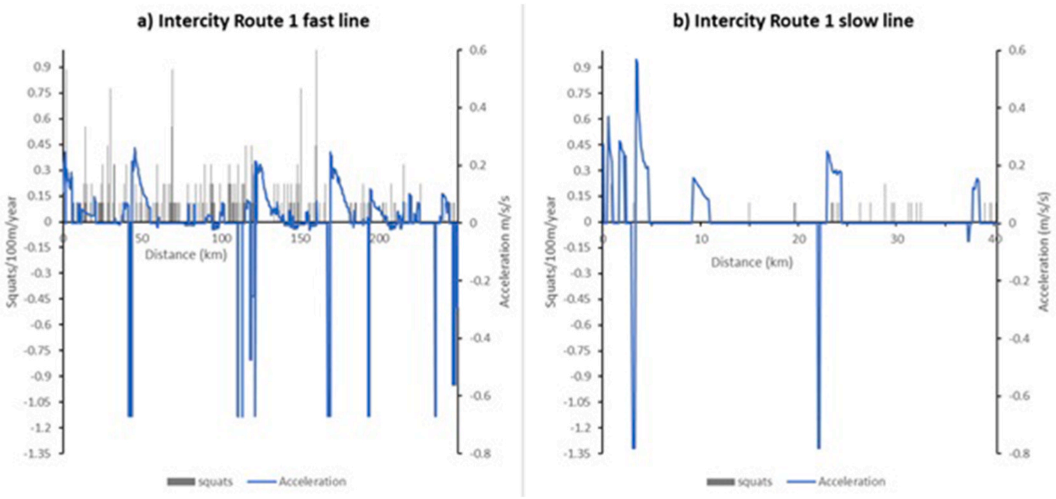

Fig. 4. Squats/100 m/year and acceleration profile for a) Intercity Route 1 fast line and b) Intercity Route 1 slow line.

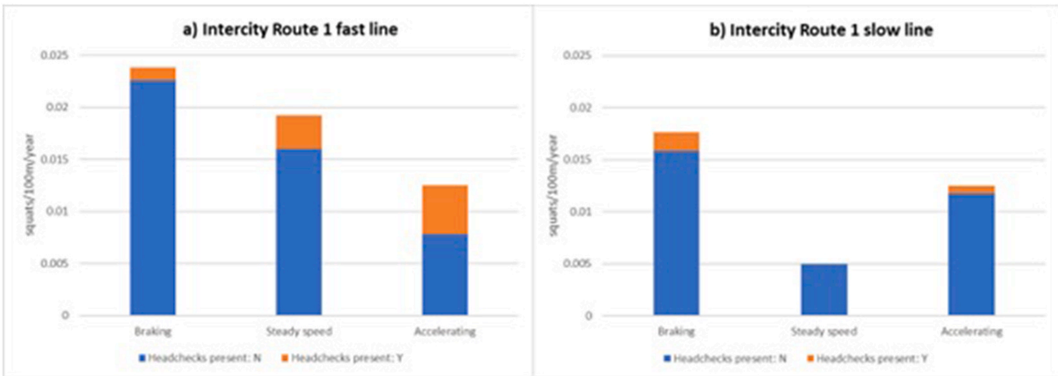

Fig. 5. Squats in acceleration and braking zones vs steady speed for a) Intercity Route 1 fast line and b) Intercity Route 1 slow line.

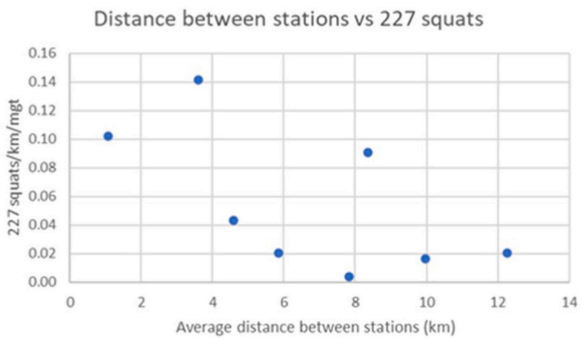

Fig. 6. Squats/km/MGT compared to average distance between stations.

It is estimated that there are 5 times as many thermit welds as flash butt welds in track.[6] Fig. 7 shows the influence of the main factors affecting squats on welds.

As shown in Fig. 7a, it appears that squats are significantly more likely on flash butt welds; this does not correlate with the expected behaviour; previous research suggests that the smaller heat affected zone and of a flash butt weld should result in less damage caused to

6 Based on advice from Network Rail engineers.

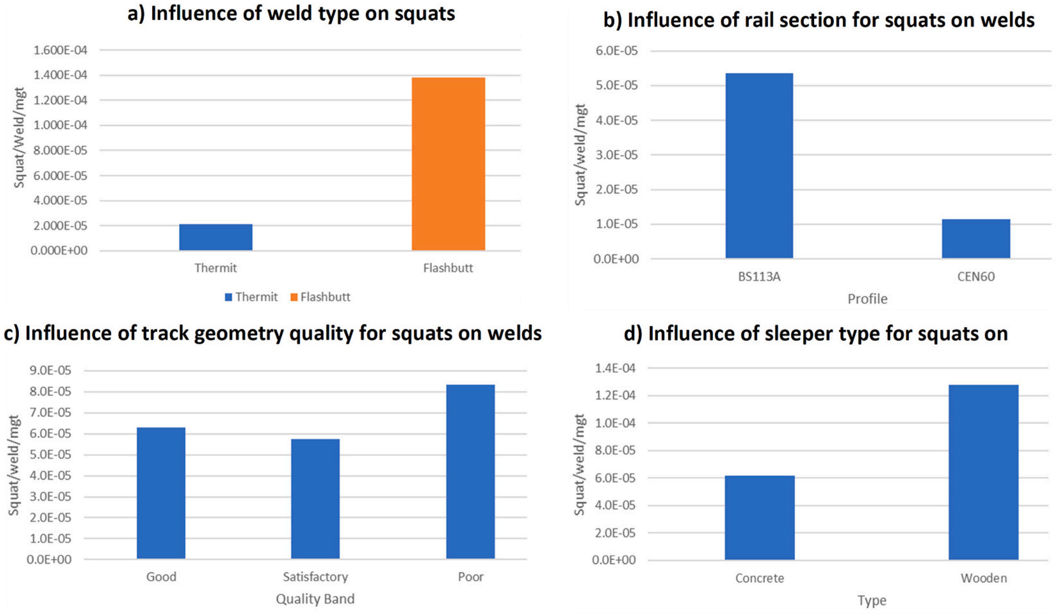

Fig. 7. Overview of factors influencing squat initiation on welds, considering a) Influence of weld type on squats, b) Influence of rail section for squats on welds, c) Influence of track geometry quality for squats on welds, d) Influence of sleeper type for squats on welds.

welds cause by traffic [34]. A more detailed study is required to fully investigate this. Assumptions made on the number of welds/km for rails of different ages and the ratio of thermit to flash butt welds in track will significantly affect these comparisons.

As shown in Fig. 7b, squats on welds are significantly less likely on welds in CEN60 rails, vs CEN56 rail, this is similar to the pattern for squats on plainline. This could be due to the influence of rail bending on squat formation and growth at rail welds, which would be reduced with a larger section of rail as discussed in Section 4.1. In addition, the larger CEN60 rail section may give a stronger weld due to the larger weldable surface.

As shown in Fig. 7c there appears to be a correlation with poor track geometry quality and increased squats on welds; whilst Fig. 7d shows rail on wooden sleepers has significantly higher probability of squats than rail on concrete sleepers. Both factors suggest that soft track support conditions have an influence, which may be connected to the levels of rail bending.

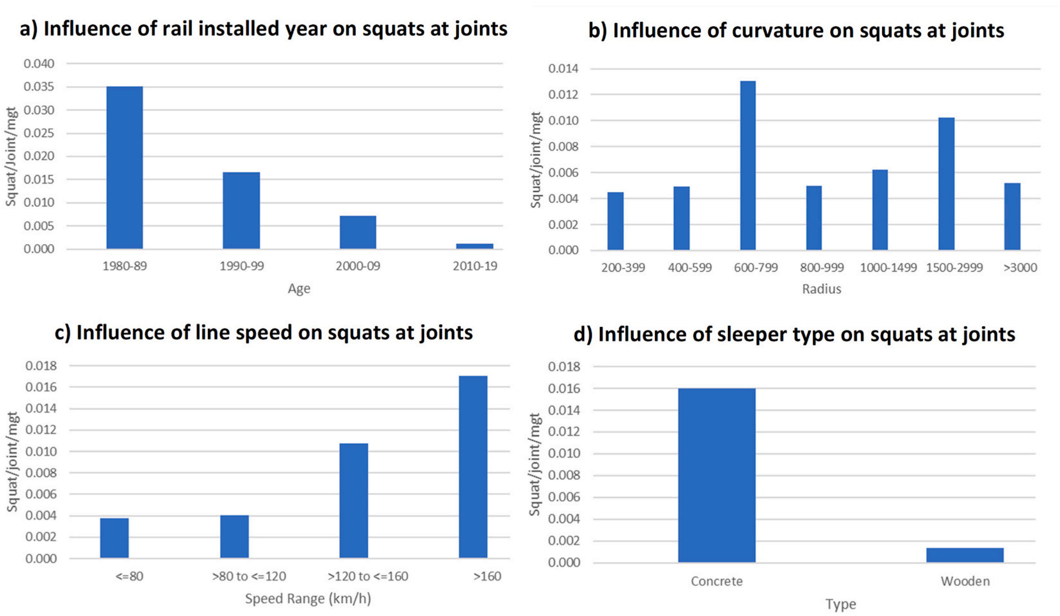

Fig. 8. Overview of factors influencing squat initiation on joints, considering a) Influence of rail installed year, b) Influence of curvature, c) Influence of line speed and d) Influence of sleeper type.

4.3. Squat initiation for squats on joints

As with results for squats on welds, there is no record of the location of every rail joint; the number of joints/km has been calculated based on the same assumed rail lengths given in Section 4.2. Fig. 8 shows the influence of the main factors affecting squats on joints.

Rail age appears to have a strong influence (Fig. 8a), which was also the case for squats on plainline and welds. Again, this suggests that squats can take a long time to grow to the size of an actionable defect (10 mm depth). Squats are significantly more likely on joints than welds; squats on joints are 1000 times more likely than squats on welds.

As shown in Fig. 8b curve radii between 600 and 2999 m generally has higher squats/joint/mgt than tighter curves or straight track (though 800–999 m radius curve have a lower rate than straight track).

As shown in Fig. 8c, there is a significant correlation between line speed and squats on joints; this strongly suggests a link between vertical dynamic loading and development of squats on joints.

Interestingly, where jointed track is laid on concrete sleepers (rather than wooden), as shown in Fig. 8d, there appears to be significantly increase in squats/joint. This differs from the effect of sleeper type on squats in plainline and welds. As a joint is the most flexible point on the track the more rigid track construction with concrete sleepers may results in more movement around joints; on a more flexible track structure with wooden sleepers there is less movement at joints as the track flexes more around the joint.

4.4. Squat initiation for squats on crossings

Fig. 9 shows factors affecting squats on crossings, the most important factors are line speed of the through route and crossing angle. Sharper crossing angle, and faster line speed correlate with increased numbers of squats (shown in Fig. 9b and c). This suggests that vertical dynamic forces play a significant role in the development of squats on crossings. Sharper crossing angles permit higher speeds on the diverging route, but also effectively give a longer gap for the wheel to jump from the wing rail to the crossing nose (hence the suggested correlation with vertical dynamic load). Rail age does not appear to have the same influence for squats on crossings as it does for squats on plainline, as shown in Fig. 9a.

As shown in Fig. 9d, squats are significantly less likely on explosion hardened cast crossings compared to non-hardened cast crossings. Squats on fabricated crossings occur at similar rate to those on hardened crossings (i.e. significantly less frequently than on non-hardened cast crossings).

4.5. Traffic type

Fig. 10 shows the influence of the mix between freight and passenger services on squats/km/vehicle pass, considering squat on plainline for the different routes in this study. Results are presented at a route levelling using average traffic mix on the route.

There appears to be a correlation between increased share of passenger vehicles with increased squats/km/vehicle; it is unclear why this is the case. There are several possible explanations:

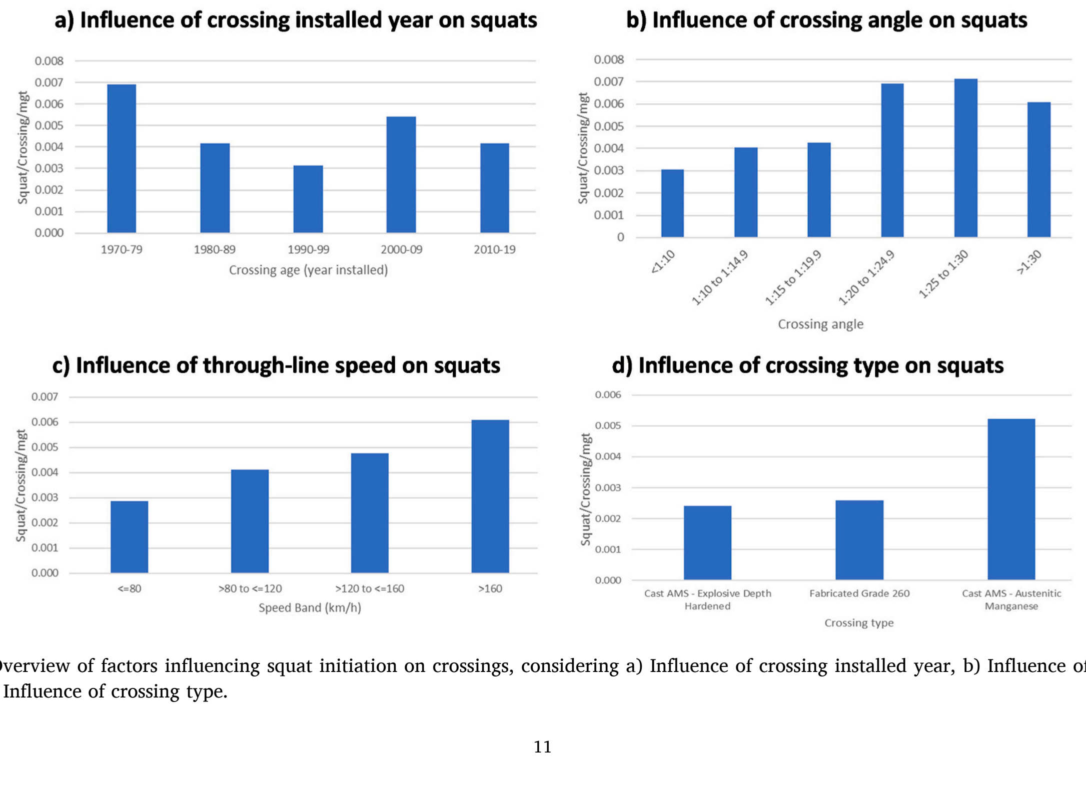

Fig. 9. Overview of factors influencing squat initiation on crossings, considering a) Influence of crossing installed year, b) Influence of crossing angle, d) Influence of crossing type.

- higher acceleration rates of passenger trains compared to freight trains may initiate more thermally induced material changes in acceleration zones leading to crack initiation, even though freight trains are loco hauled with tractive effort focused on a small number of axles (whilst passenger trains are more likely to have distributed traction);
- Or may be related to how maintenance is currently prioritised based on EMGT (which is explained further in Section 4.6);
- Freight trains may even reduce crack initiation due to higher rail wear rates in curves or higher levels of rail surface work hardening due to higher axle loads.

This needs to be fully evaluated by further work, which would benefit from considering a broader range of route types and consider methods that isolates the influence of traffic type over other factors, with further sub-divisions of traffic type.

4.6. *Influence of wear rate and grinding*

Network Rail schedule rail grinding every 45 Equivalent Million Gross Tonnes (EMGT) on straight track and curves with a radius greater than 2500 m and every 15 EMGT on curves with a radius less than or equal to 2500 m, as required by NR/L2/TRK/001/mod10 [42]. EMGT is a parameter based on the total traffic measured in Million Gross Tonnes, multiplied by factors for speed, power, axle load and vehicle type. Different sections track that have carried the same cumulative EMGT may have carried a significant difference in total wheel passes. The are therefore different numbers of grinding passes/wheel pass across different routes. Fig. 11 compares the influence of grinding/wheelset pass on squats/km/wheelset pass for the different routes in this study; considering plainline squats. The results are based on planned grinding frequency and defect records over a 9-year period; they have not considered any variations against the grinding plan that may have occurred over that period. It is assumed variations from planned grinding intervals would have a relatively small effect on overall results.

There is a clear correlation between increased grinding passes/wheel pass and significantly reduced squats/km/wheelpass. This suggests grinding at a suitable frequency can be an extremely effective measure to reduce the rates of rail squats. Note this study only includes rail with Grade 220 and Grade 260 steel; other researchers have suggested that for head hardened/premium rail, grinding can in-fact increase the risk of rail surface defects [43,44].

Fig. 12 shows the influence of rail head wear rate (this is total headwear rate due to traffic and grinding) on the probability of squats/year; there is a clear relationship between low headwear rate and probability of squats. 90 % of all squats on plainline occur on rail which has a head wear rate of less than 0.2 mm/year.

4.7. *Squat growth rate*

As stated in Section 3.1 'actionable squats' recorded in RDMS have a damage depth of ≥10 mm; all results presented in Sections 4.1 to 4.6 are based on these records of 'actionable squats'. 'Suspect squats' which have a damage depth of ≥5 mm and <10 mm are also recorded in RDMS. By linking a 'suspect squat' to an 'actionable squat' from RDMS records, it is possible to estimate a rate of growth rate in crack depth. It has been possible to link only 383 suspect plainline squats to the actionable squat they grew in to. This is a small proportion of the total 8358 actionable plainline squats. Fig. 13 shows factors influencing the calculated crack depth growth rate from a depth of 5 mm–10 mm.

Use of Grade 260 and CEN60 rail section reduces the rate of crack depth growth, compared to Grade 220 and CEN56 rail section, shown in Fig. 9a and b respectively. Curvature appears to have a relatively small influence, shown in Fig. 9c. Fig. 9d shows the influence of track geometry quality, which shows a surprising trend with the better track quality appearing to have the highest rate of crack depth growth. Further work is required to investigate this in more detail, note the results are based on a small sample of data.

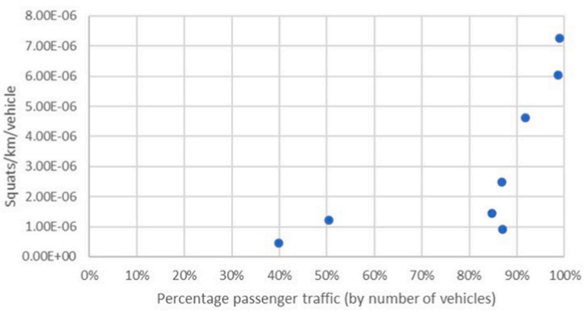

Fig. 10. Influence of percentage passenger traffic on squats/km/vehicle.

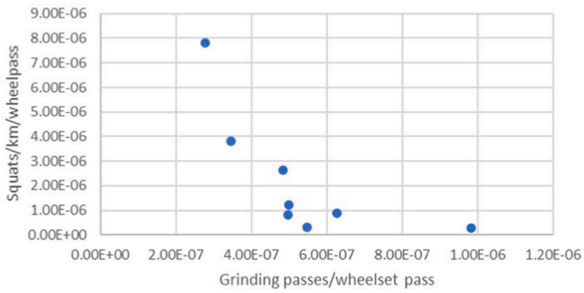

Fig. 11. Squats/km/wheel pass compared to grinding/wheel pass.

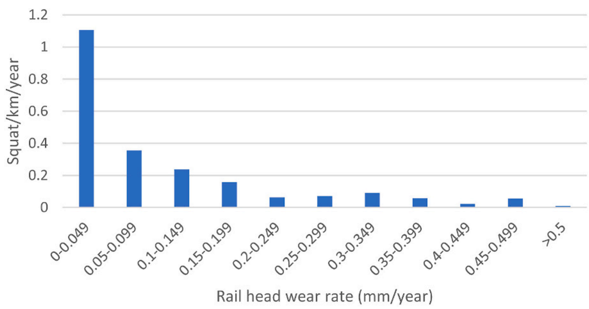

Fig. 12. Vertical rail head wear rate compared to squats/km/year.

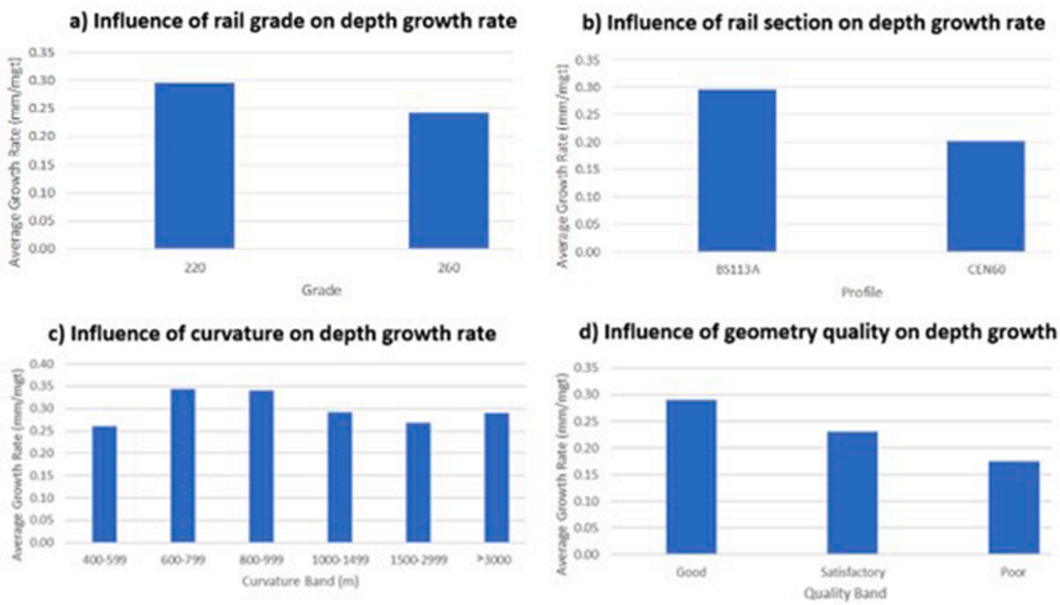

Fig. 13. Factor influencing crack depth growth rate, considering a) Influence of rail grade, b) Influence of rail section, c) Influence of curvature and d) Influence of track geometry quality.

5. Discussion

5.1. Most important factors for squat initiation and growth

There are a broad range of factors influencing the different types of squat. Plainline squats are significantly less likely on rails with CEN60 section compared to CEN56; 260 grade compared to 220 grade steel; rail on concrete sleepers compared to rail on wooden sleepers. Whilst, squats on joints and crossings have a clear link to the line speed. For squats in rail with no headchecks there is a strong correlation between tighter curve radius and increased numbers of squats. The tightest curves, with a radius less than 400 m are 4 times more likely to sustain squat damage than straight track, measured in squats/km/mgt; with the majority of these squats being on the high rail. This suggests there may be a link to high levels of positive longitudinal creepage. For squats on rail with headchecks, there are higher numbers of squats on curve with a radius between 600 m and 3000 m compared to straight track.

Based on analysis of records of squat defects that have already reached a depth of 10 mm it is very difficult to separately analyse factors affecting crack initiation and crack growth.

Higher numbers of squats on smaller rail sections, either by design (i.e. CEN60 vs CEN56 rail), or due to cumulative wear, suggest there may be an influence of rail bending in crack propagation during the development of squats. CEN60 rail has a significantly higher second moment of area compared to CEN56; 3038 cm^4 vs 2321 cm^4. Whilst, 7 mm of head wear on a BS113A/CEN56 rail reduces the second moment of area by 10 % (to 2085 cm^4). Previous work by Li et al. [19] suggests that squats are more common directly above a sleeper, rather than mid span. This also infers that rail bending contributes to squat growth as rail above the sleeper will bend in the hogging direction, causing tension at the rail surface promoting crack growth (as opposed to mid sleeper rail which bends in the sagging direction causing compression at rail surface). As rail wears the exposed rail surface will also have lower residual stresses from the manufacturing process and potential slightly lower hardness properties which might increase the probability of crack initiation: further work is required to investigate this.

The influence of rail grade is presumable due to the harder rail, i.e. 260 BRN vs 220 BRN, being less susceptible to cracking.

Rail wear rate, i.e. combined in-service wear due to traffic and ‘artificial’ wear from grinding, has a strong inverse correlation with squat rate. As discussed in Section 4.6, 90 % of all squats occur on rail with a head wear rate lower than 0.2 mm/year. This confirms earlier findings by Muhamedsalih et al. [7,8] which were based on a much smaller sample of rail.

Poor vertical track geometry quality has a clear correlation with numbers of squats in rail with headchecks. This may suggest a crack initiated due to ratcheting failure in the highly deformed microstructure at the rail surface may also required some dynamic vertical loading to develop into a squat (of an actionable size).

Previous studies suggested traction and braking have an influence on the development of studs [4,13,25,26]. In this study it was not possible to conduct a wide-ranging investigation to confirm this is the case for GB mainline track. However, initial findings based on simulated train speed profiles for a small section of track suggest that traction and braking may influence the probability of squats. Results show squats in traction zones are significantly more likely for commuter services with higher acceleration rates than intercity services with lower acceleration rates.

Sleeper type has an influence across all squat types, which suggest support conditions have an influence on squat formation; this may be due to dynamic vertical loading influencing squat initiation and early growth or the influence of rail bending on squat growth.

5.2. Headchecks and squats

In recent years there has been significant research effort into investigating studs [15,26,29,45–47]. When investigating the factors affecting squat formation it would be useful to separate records of plainline squats into the categories of classic squat and stud. However, it is virtually impossible to differentiate between a squat and stud without sectioning the rail to examine the microstructure beneath the defect. In this study, squats on plainline have been split into squats in rail which also has headchecks and those that do not. For rails up to 40 years old, 79 % of plainline squats were on rails with no headchecks. The 21 % of squats on rail with no headchecks were focused on 12 % of the track. When considering traffic volumes, a squat is 3 times more likely to occur in rail with headchecks. This suggests that squat initiation has a relationship with shear induced RCF cracking. Squats on rail with no headchecks are presumably more likely to be initiated due to other factors.

As studs are squats which occur on rail which has no significant deformation of the steel microstructure, it appears unlikely they will occur in rails that also contain headchecks (as headchecks grow in steel with a deformed microstructure). Equally it appears unlikely that a crack which forms a squat in a piece of rail subject to headcheck cracks has formed completely independently of those headcheck cracks. It might therefore be assumed that squats in rails with a history of headchecks are more likely to be classic squats, i.e. initiated from shear induced RCF cracks which initially grow in the plastically deformed zone at the rail surface. It might also be assumed the squats in rail with no history of RCF are more likely to be studs. Without carrying out an investigation to remove sample of rails from track and studying the microstructure of the steel, it is difficult to conclusively prove if the assumption is valid. Results shown in Fig. 3b suggest that squats in rail with no headchecks start to appear sooner than squats on rail associated with headchecks. This does correlate with the comparison of squats vs studs described by Grassie et al. [13] where classic squats, which are linked to shear induced RCF cracking, reach a size where they are detectable by ultrasonics after 100 MGT whilst studs could appear with significantly less traffic. This gives some indication that the assumed groupings may broadly align.

There are differences in the factors which correlate with squats in rail with headchecks and squats in rail with no headchecks. Poor track geometry quality clearly correlates with an increase in squats linked to headchecks and does not influence the numbers of squats in rail with no headchecks.

Published research on studs suggests that the cracks in studs are more likely to grow parallel to the rail surface and will therefore penetrate less deep into the rail [13]. The squat defects in RDMS have a damage depth of 10 mm or greater; if studs in track are growing parallel to the rail surface and not reaching an actionable size they won’t have been taken into account in the analysis presented in this work.

Overall, there can be some confidence that the separation of squats by the location with and without headchecks can give an indication of the locations of classic squats vs studs; however, this needs to be confirmed by further work.

6. Conclusions

Further work is still required to completely understand the factors affecting squat initiation and growth and the best methods to reduce the rates of squat damage and best maintain track to manage squats. This work extends and expand the previous analysis carried out by Muhamedsalih et al. [7,8]; the main improvement is comparison of causal factors with squats/km/mgt (or squats/-joint/mgt) rather than squats/km/year irrespective traffic density. An estimate of squat growth rate, from a damage depth of 5 mm–10 mm has been used to evaluate factors affecting squat growth rate, which has not previously been evaluated in published work. A larger and more compete set of defect and network characteristic data has been considered, and for the first time the factors specifically affecting squats on joint, welds and crossings have been analysed separately; whilst the connection between headchecks and squats has been analysed, which was not done in the previous work. This study has taken steps to validate some of the more fundamental investigations carried out by other researchers, and built on the output of earlier, smaller statistical studies. This study has not been able to thoroughly investigate the influence of traction braking and further research should consider how to carry out fundamental work to compliment and further extend the statistical analysis with a focus on traction and braking. A fully validated method to differentiate classic squats and stud from defect records would also be useful.

Key practical steps to reduce the likelihood of squats developing are: use larger rail section (i.e. CEN 60 rather than CEN 56); use grade 260 rail rather than 220; use concrete sleepers rather than wood; use explosion hardened crossings; use longer rails to reduce the number of joints and welds; minimise numbers of rail joints (noting joints are 1000 times more likely to be subject to squats, compared to welds); avoid very sharp crossing angles if possible. These steps are already standard practice in GB mainline when replacing track. Results from this work also suggest that a suitable grinding regime to maintain adequate total wear rates can be a very effective methods of managing squats (the influence of grinding for squats in premium grade steel has not been evaluated in this study). Whilst maintaining good levels of track geometry quality can also have a significant beneficial influence on reducing the probability of squats developing.

Based on the significant influence of smaller rail sections, either by design or from cumulative wear, on increased levels of squats, it appears rail bending may have a significant influence on the development of squats. This does not appear to have been highlighted by previous work and requires further investigation.

There is a clear correlation between train speed and probability of squats at a vertical discontinuity in the rail (i.e. joint or crossing), which suggest that peak dynamic forces are a key influence for the development of squats at these locations. This has also not been strongly drawn out by previous studies, which more often focus on squats on plainline, this also requires further in-depth analysis.

This work suggests that there is a link between headchecks and squats; overall squats in plainline are 3 times more likely (measured in squats/km/MGT) in sections of rail with a history of headchecks; further work focusing on this would also be beneficial.

CRediT authorship contribution statement

G. Tucker: Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **K. Sztrauch:** Data curation, Investigation, Software, Writing – original draft. **A. Bevan:** Investigation, Writing – original draft, Writing – review & editing. **Y. Muhamedsalih:** Conceptualization, Resources. **S. Hawksbee:** Conceptualization, Resources. **P. Shackleton:** Conceptualization, Investigation. **P. Mistry:** Data curation, Formal analysis. **B. Whitney:** Investigation, Resources, Supervision. **M. Burstow:** Conceptualization, Investigation, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

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