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Geospatial and temporal data mining to combine railway low adhesion and rail defect data

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Rolling contact fatigue (RCF) damage to rails and low adhesion at the rail–wheel interface remain significant problems in maintaining railway performance, fully utilising network capacity and reducing running costs. A novel approach has been developed to understand these problems through analysis of data on RCF and low-adhesion incidents from the UK rail network. This augments understanding of specific mechanisms such as the roles of rail plasticity in crack initiation and environmental moisture levels in low adhesion, which have not given sufficient information to prevent these problems to date. A moving-window filtering technique and temporal and geospatial approaches were used to identify correlations between sites of low rail–wheel adhesion subject to transient sliding contact, crack initiation and underbridge locations where vertical and lateral track stiffness typically change rapidly. The analysis showed that a high density of otherwise unexpected RCF defects occurred close to underbridges and that there was a strong correlation between momentary slides during braking and RCF sites. The temporal analysis indicated that, although concentrated in the autumn period, 55–60% of transient low-adhesion incidents occur outside that period, with the highest risk in the very early morning.

1. Introduction

Numerous investigations into rail rolling contact fatigue (RCF) have been conducted to understand how stresses at the contact patch contribute to the initiation and propagation of cracks, relevant examples being the studies by Fletcher and Beynon (2000), Kapoor *et al*. (2002), Grassie and Elkins (2005), Fischer *et al*. (2006) and Grassie (2015). With the development of harder rail steels, the forces present at the rail–wheel interface during normal operation generate much less extensive plastic flow than in conventional steel grades, thus restricting crack initiation or delaying the development of RCF unless some other factor is present to increase rail–wheel forces. It is known that residual stresses (Fletcher *et al*., 2006) or the lateral forces generated during cornering (Burstow, 2013) help drive RCF, yet a definitive picture of the factors influencing crack initiation and growth has not yet been established. Armstrong and Allery (1987) suggested that the location of RCF cracks is, in part, influenced by the occurrence of low adhesion, and this paper presents data analysis to establish if there is any correlation between low adhesion and RCF sites. It is hoped that better establishment of the factors that may contribute to crack formation and growth will focus future modelling of RCF damage.

Since the primary interest of this work was the factors that are not already well known to drive RCF damage, the Track-Ex package (Dembosky *et al*., 2011), which is based on the contact patch energy ($T\gamma$) approach, was used to remove from the analysis locations of RCF that are predicted, for example, at curves. Comparison of the Track-Ex prediction with data from Network Rail's rail defect management system (RDMS) highlighted RCF sites that were not predicted, supporting the existence of an alternative initiation process. Track-Ex makes several assumptions with regard to dynamics at the rail–wheel interface, focusing on lateral forces as a driver of damage. A key area in which vertical rather than lateral forces are increased is around underbridges (Evans and Burstow, 2006), where there are often rapid changes of track support stiffness and a high potential for vertical and lateral track misalignment. These can lead to wheel unloading and therefore an increased risk of a wheel reaching the adhesion limit. The influences of very localised stiffness change and misalignment on RCF cannot be predicted within Track-Ex, but removal of RCF sites that it does predict allowed this study to focus on these less-well-explored areas.

1.1 Geospatial approach

A moving-window filtering technique and a geospatial approach were used on data from a section of the UK rail network. These techniques were used to correlate locations where RCF occurs with the locations of factors that are known to increase rail–wheel forces or damage. These include

(*a*) wheel slides, during which there can be a high level of heat generated at the contact patch and material damage such as transformation of pearlite to brittle martensite;

this may subsequently lead to rail defects as described by Armstrong and Allery (1987), RSSB (2003), Fletcher (2014), and Scott *et al.* (2014)

(*b*) underbridges, where the higher support stiffness over the underbridge relative to the surrounding embankments means that the rail deforms less under lateral and vertical loads, leading to track misalignment, as described by Evans and Burstow (2006).

1.2 Temporal approach

In addition to geospatial correlation of RCF, the temporal distribution of wheel slide events was investigated using a methodology building on previous studies by the Rail Safety and Standards Board (RSSB, 2014), Arnall *et al.* (2015) and White *et al.* (2017). Although usually associated with autumn problems such as rail head leaf film described by Zhu *et al.* (2014), Poole (2007), Pearce and Watkins (1987) and Ishizaka *et al.* (2017), low adhesion also occurs outside the autumn period and therefore cannot be solely attributed to leaf fall. On an hourly timescale, reports of low adhesion are non-uniform throughout the day, but understanding of this is complicated since traffic density also varies throughout the day. The aim of the temporal analysis undertaken in this study was therefore to gain better understanding of low adhesion on two timescales (over a year and over a day), taking account of traffic levels.

2. Methodology

Within the analysis, two scenarios were considered in which the factors outlined in Section 1.1 are present (Figure 1). Correlation between RCF and wheel slide locations would be a result of either scenario 1a or scenario 1b. The data are unable to reveal directly whether wheel slides precede the later formation of RCF-type defects or whether wheelset dynamics when crossing the RCF site triggers a slide. The correlation between RCF and underbridge locations would demonstrate that

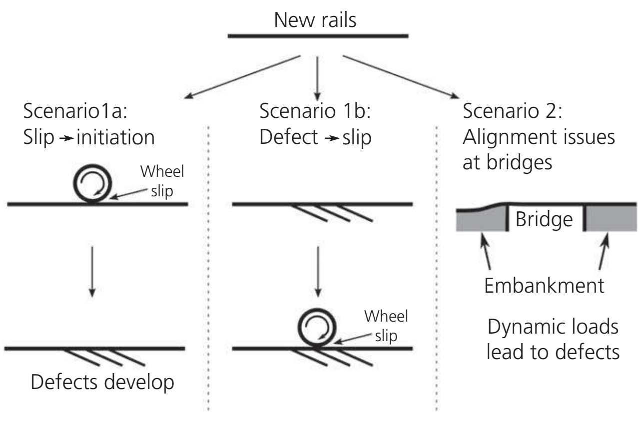

Figure 1. Relative slip at the rail–wheel interface and crack initiation scenarios for a newly installed rail initially free of damage. The stiffness and alignment fault at the bridge is exaggerated for clarity

alignment issues inherent in track where the support stiffness changes abruptly influence the formation of RCF (scenario 2).

Two types of wheel slides were considered as they were thought to have different causes and a different effect on the rail: (*a*) momentary sliding associated with traction peaks during low adhesion and its recovery and (*b*) longer periods of sliding associated with low adhesion over a large section of track. A location-based analysis was undertaken to identify whether these factors correlated with recorded RCF. It should be noted that these slides, identified by wheel slide protection (WSP) activations, are not caused by train faults but are a consequence of variations in rail–wheel adhesion and the reaction of train systems to this factor.

2.1 Data

Data collection focused on the UK West Coast Main Line (WCML), an overview of which is presented by Spoors (2012). The WCML is a busy mixed-traffic line connecting London with Birmingham, the north of England and Scotland. It carries a mix of high-speed intercity trains, regional passenger services and freight traffic, totalling some 2500 train movements each day. It has a mix of double and quadruple track layouts, is electrified at 25 kV AC, but also carries diesel-powered services. Due to hilly terrain and the history of construction by a series of different railway companies in the 1800s, 70% of the line is curved. In the early 2000s, the WCML was significantly upgraded to allow 200 km/h running over much of the line (Network Rail, 2011).

Rail surface damage data for RCF, together with locations, were collected over a 2-year period (2013–2015) through Network Rail's RDMS for the WCML 'down fast' line (i.e. the line travelling away from London, dominated by high-speed passenger traffic). Locations within this data set were specified using engineers' line references and track mileage, which were converted into global positioning system references using Omnicom Rail View (Omnicom Engineering, 2017).

Data on bridge locations focused on underbridges (i.e. where the railway goes over another feature). At these locations, the support structure of the track changes over a short distance, often leading to an abrupt change in track support stiffness and a high likelihood of dynamically generated forces as a train (and its suspension) crosses and reacts to the stiffness change. Minor alignment problems are also common near underbridges since both lateral and vertical stiffness change with the transition onto and off the structure. The combination of these factors is thought to increase rail damage in these areas. The underbridges considered within the analysis ranged from small culverts to large underbridges such as viaducts and bridges crossing motorways.

In addition to infrastructure data, WSP data were collected over a 5-year period (2009–2013) from class 390 passenger rolling stock that operates along the WCML. Only wheel slide events that occurred on the down fast line (the same track as the RCF) were considered. The WSP system on this rolling stock records a wheel slide event when the wheel speed on a free-rolling leading axle present on each train differs from that of one of the three remaining braked axles on the leading car. The majority of the data used within this study therefore represent an individual axle undergoing sliding and not the whole train experiencing a slide. The number of wheel slides found within the data was representative of any high-speed rolling stock operating within the UK (i.e. part of normal operation and not caused by a rolling stock fault).

During the period of data collection there were no major upgrades to the WCML and only routine maintenance was undertaken. The mix of rolling stock, their proportion in total traffic and the line speeds did not change significantly during the study period, meaning that locations with a high density of RCF-type defects would not be expected to change.

2.1.1 Filtering wheel slide data

Wheel slide is, by its nature, transient, but long slides potentially resulting in signals passed at danger and long sections of rail damage are of greatest concern from a safety perspective. Conversely, much shorter slide events have the potential to correlate with regions of RCF crack initiation, which range from a size comparable to the rail–wheel contact patch (~15–20 mm) to a few metres in cases where multiple RCF defects develop together. Long slides and momentary slides, both during braking, were therefore considered separately, with the aim that any correlation with underlying causes would be clearer than when also considering slides of intermediate length/duration. Two categories of long slides were defined as

- category LD: slide distance greater than 800 m (0·5 miles)
- category LT: slide time greater than 15 s.

The time criterion is based on the 800 m slide distance for a train travelling at a speed of 200 km/h (125 mph), the maximum line speed on the WCML. These severity criteria highlight events where the adhesion level available is insufficient over a prolonged distance or time.

Two categories of momentary slide were defined as

- category MD: slide distance less than 4·8 m (0·003 miles)
- category MT: slide time less than 0·1 s.

The momentary slide time criterion was based on the shortest time that it would be reasonable for the WSP system to detect and record 'an event' (i.e. a wheelset slide). The distance criterion is based on the 0·1 s slide time for a train speed of 200 km/h.

2.1.2 Filtering RCF data

A Track-Ex route fleet analysis was carried out for the down fast line at engineers' line references LEC1–LEC2 (London Euston to Stafford South), LEC4 (Stafford North to Crewe) and CGJ1–CGJ7 (Crewe to Carlisle). LEC3 (Stafford station area) and LEC5 (Crewe station area) are within-station areas only and were therefore not considered. RCF and adhesion data were removed from further analysis for sections of line where analysis of measured track geometry using Track-Ex predicted any RCF development. This is demonstrated in Figure 2: the example section of line shows how the RCF site at 0·7–0·9 km is predicted by the Track-Ex analysis and would therefore be removed from further consideration. This filtering process removed from the analysis RCF linked to macro-scale track geometry (i.e. curving). The remaining sites of observed RCF (grey bands in Figure 2) are not explained by Track-Ex and it is therefore of far greater interest to investigate potential causes further.

2.2 Geospatial distribution and visualisation

To gain an overview of the data and any locational correlations between low adhesion and RCF, the geospatial distribution of RCF sites that occurred within ±40 m of underbridges or wheel slides was examined using a geospatial visualisation. The choice of proximity distance was guided by research looking at track damage associated with the approaches to underbridges (Li *et al*., 2010). Other track misalignments, for example at welds or rail joints, are known to excite the suspension of passing trains, with the potential for wheel unloading and peaks in rail–wheel load some distance further along the line from the cause of excitation (Hou *et al*., 2003). The exact distances to the point of peak force or maximum damage will vary, for example depending on speed and

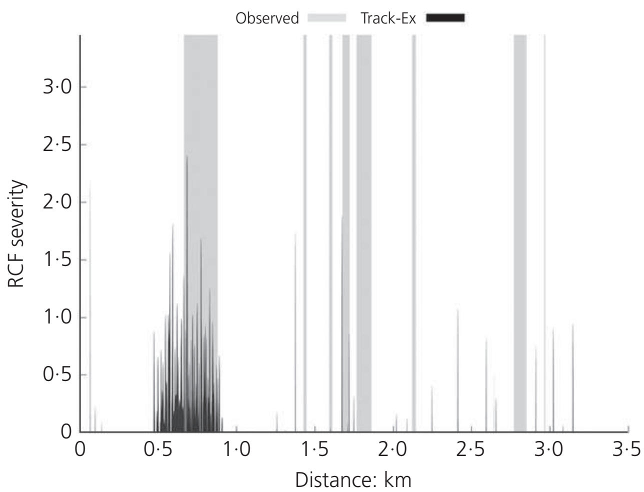

Figure 2. Predicted RCF from Track-Ex output against actual RCF sites from RDMS data, demonstrating which sites will be removed from the analysis

whether damage generated by surface contact pressure is of interest, or rail interior or foot damage. In mapping the location of low-adhesion incidents, the severity criteria outlined in Section 2.1.1 were used to define an 'event', which then becomes a single data point. Although this inherently means a loss of data in terms of the duration or severity of low-adhesion events, the data reduction is necessary to reveal the bigger picture and sufficient data remain to do this.

2.3 Moving-window correlation quantification

To quantify correlations revealed in the geospatial visualisations, a moving-window filtering technique (Figure 3) was used to ascertain if a correlation existed between the occurrence of underbridges, low-adhesion and RCF sites not already explained by the Track-Ex analysis. With track data segmented at 8 m intervals, the analysis window considered data from ten of these segments at any one time (80 m of track, for which chord and arc lengths are almost equal for any curve radius found on mainline track). As the analysis window 'slides along' the data, the model adapts as it iterates to include data from the newest point and discard data from the oldest point (Lee *et al.*, 2001; Wang *et al.*, 2005). Through this method of gradual introduction of new points and removal of old points, the distribution of quantities over distance is smoothed, permitting an improved analysis in determining proximity relationships.

The numbers of underbridges, RCF sites and low-adhesion events within each analysis window were counted. A baseline value of the likelihood that a factor would occur in any given analysis window and the average number that occurred per analysis window was obtained by consideration of the whole line. A comparison was then drawn between the baseline value and the value when both factors were present. For example, when considering the likelihood of locational correlation between RCF sites and underbridges, the proportion of analysis windows that contained both RCF sites and underbridges was compared with the baseline proportion of analysis windows that contained only RCF sites. From this, a relative likelihood ratio of the occurrence of RCF sites near underbridges was obtained and the degree of locational correlation was quantified.

2.4 Adhesion temporal analysis

In line with a methodology used in research on rail–wheel adhesion (RSSB, 2014), an analysis was undertaken on how the frequency of wheel slides varied over a year and over a day.

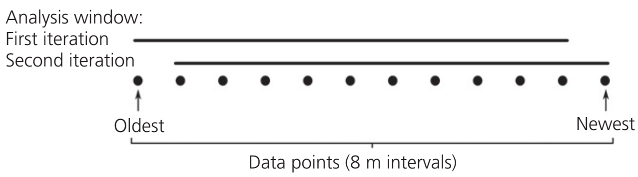

Figure 3. Schematic representation of the moving-window filtering technique

This highlighted the time periods for which wheel slide events are more prevalent and whether the trends observed remained consistent throughout the 5-year period studied. This allowed identification of whether there is a significant rise in wheel slide events during the autumn period when there are leaf layers present (Zhu *et al.*, 2014) or whether they are distributed more evenly throughout the year, indicating that other factors such as moisture on the rail head (RSSB, 2014) are a significant cause of wheel slides. A similar analysis was undertaken on hourly data for wheel slide events to determine if there are periods during the day when wheel slide events are more likely to occur. A comparison was drawn between the years to ascertain whether the pattern of wheel slide events remained consistent over the 5-year period studied.

3. Results and discussion

3.1 Geospatial distribution visualisation

Figures 4–6 show geospatial visualisations of RCF site locations on the WCML, filtered to remove RCF sites already predicted from track geometry using the method described in Section 2.1.2. For the London to Carlisle WCML, 67% of the RCF sites occurred within the area highlighted by a 10× zoom along the section of line between Crewe and Runcorn. This suggests that the characteristics of this section of line have led to an increased number of RCF sites occurring that have not been predicted by conventional consideration of track geometry. This section is just over 8% of the overall London to Carlisle distance and averages one underbridge every 1·6 km, compared with approximately one every 0·5 km for the line overall.

3.1.1 Underbridges and RCF

RCF sites where an underbridge was present within ±40 m are indicated by the larger shaded circles in Figure 4. It was found that 23% of the RCF sites had an underbridge within ±40 m, although quantified analysis (see Section 3.2.1) showed that only 10% of the 8 m line segments considered included an underbridge. This supports a strong correlation between bridges and RCF sites, although it does not pinpoint the physical cause. For example, if the railway crosses a busy road there may be contamination from traffic or the rail temperature may be lower on the bridge relative to the surrounding ground, leading to earlier dew formation that will reduce rail–wheel adhesion levels. Adhesion can vary with only minor changes in rail head condition and the change at a bridge is likely to be too rapid for train systems to respond, as described by Scott *et al.* (2014) for more general adhesion variations. The sites of RCF–underbridge coincidence were distributed throughout the study area, therefore the geospatial distribution did not highlight any other features as being influential (such as proximity to cities or the coast).

3.1.2 Long slides and RCF

In Figure 5, sites at which a long slide occurred within ±40 m of RCF damage are indicated by shaded circles. Over the

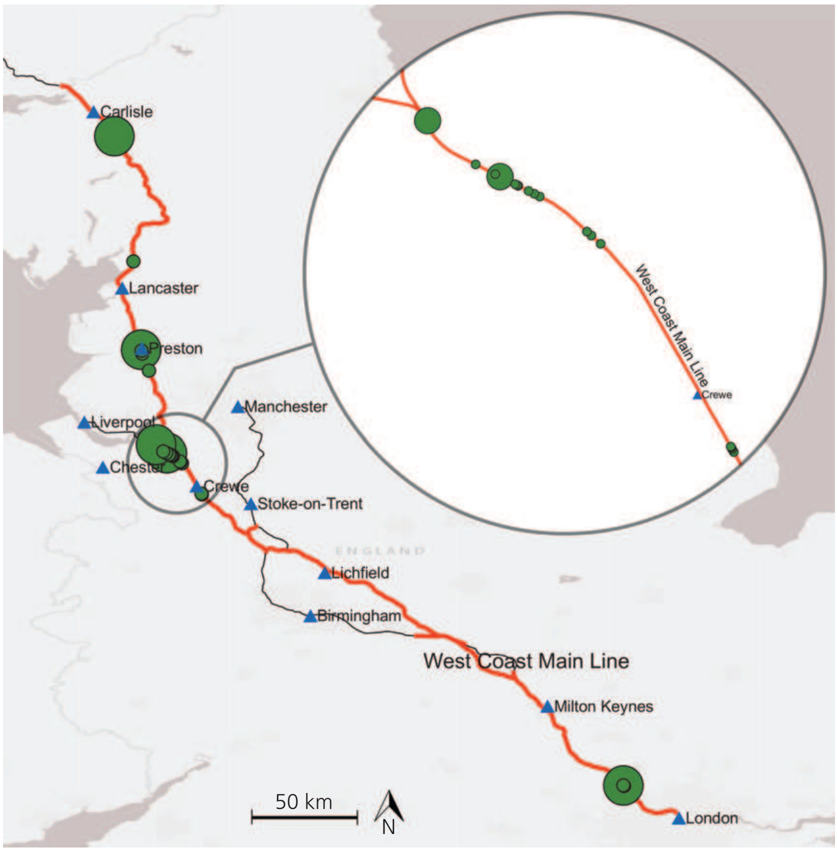

Figure 4. Distribution of RCF sites and underbridge locations. The size of the shaded circles indicates an underbridge within ±40 m of the RCF site (small, 0; large 1). The enlarged area (10× zoom) highlights the section of line with 67% of RCF sites

whole data set, it was found that 47% of the RCF sites had long slides within ±40 m. Of these, 78% occurred within the highlighted area, in which long slides occurred within ±40 m at 55% of the RCF sites. This supports a locational correlation between these two factors, which is further explored in Section 3.2.2.

3.1.3 Momentary slides and RCF

RCF sites at which momentary slides occurred within ±40 m are indicated with a filled circle in Figure 6. It was found that 37% of the RCF sites had momentary slides within ±40 m. Of these, 55% occurred within the highlighted area, for which momentary slides occurred within ±40 m at 30% of the RCF sites. This suggests locational correlation between these two factors and this is explored further in Section 3.2.2.

3.2 Moving-window correlation quantification

3.2.1 Underbridges and RCF

Figure 7 shows the proportion of 80 m analysis windows that contained RCF sites and each of the four categories of low-adhesion events discussed in Section 2.1.1. In the figure, quantification is on a positive/negative basis for the existence of RCF or low adhesion at a location and does not distinguish the number of occurrences within an analysis window. The presence of underbridges is indicated, with data plotted relative to the respective baseline values for each RCF or adhesion category for the whole line. The baseline case is included in the plot as a visual reminder, with unity representing the proportion of analysis windows that contained each type of event when considering the whole line, whether or not the analysis window included an underbridge. Analysis windows with underbridges present were just under 10% of the total line length considered.

As shown in Figure 7, when there were no underbridges in the analysis window, the occurrence of RCF and momentary slides was just slightly below the baseline. When the analysis window contained a single underbridge, the occurrence likelihood of RCF and momentary slide events increased to 1·3 times the baseline. When there were multiple underbridges within the analysis window, the percentage of cases that also contained a momentary slide event increased to 1·9 times the baseline. For both categories of long slides, the likelihood of their occurrence in the same analysis window as an underbridge was close to the baseline. When the severity criteria were not applied to

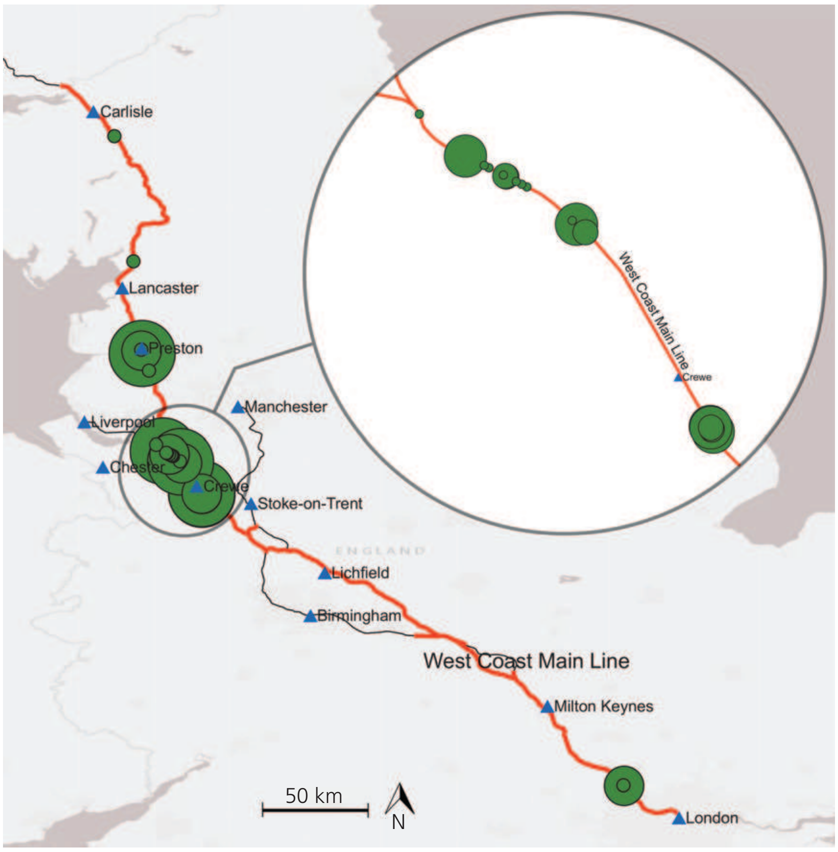

Figure 5. Distribution of RCF sites and long slides. The size of the shaded circles indicates the number of long slides within ±40 m of the RCF site (small, 0; medium, 1 or 2; large, 3+). The enlarged area (10× zoom) highlights the section of line with 67% of RCF sites

the low-adhesion events, the likelihood of their occurrence in the same analysis window as an underbridge was almost identical to the baseline.

Figure 8 shows the average number of RCF or low-adhesion events that occurred per analysis window, which gives a slightly different picture than the positive/negative approach used in Figure 7. All the results are relative to the baseline, the average number of events per analysis window that occurred when considering the whole line. The average number of RCF sites that occurred increased to 1·2 times the baseline when an underbridge was present. Taking the mean of the two categories of momentary slide, the number of events that occurred increased to 1·3 times the baseline in the same analysis window as a single underbridge. This further increased to 1·4 times the baseline when there was more than one underbridge. The average number of long slides increased to 1·1 times the baseline in the same analysis window as a single underbridge, but then decreased to 0·7 times the baseline when there was more than one underbridge. Without the severity criteria applied to the low-adhesion events, the average number that occurred in the same analysis window as a single underbridge increased to 1·2 times the baseline, further increasing to 1·6 times the baseline when there was more than one underbridge.

Of all the analysis windows that contained underbridges, 8% had multiple underbridges. Given that bridge sites made up just under 10% of the total line length, multiple bridge sites therefore make up only 0·8% of the line length. The limited number of analysis windows that matched this condition meant that no RCF sites met this criterion. However, the increase in both RCF site likelihood (on a positive/negative basis as in Figure 7) and the average number of sites per analysis window with a single underbridge (Figure 8) demonstrates the influence that an underbridge has on increasing RCF-type defects.

Without application of the severity criteria, the number of analysis windows that contained any type of slide event was 85% of the total number. This meant that when considering the likelihood of occurrence on a positive/negative categorical basis (Figure 7), the baseline analysis window was already likely to show positive, this measure being insensitive to the number of events. The increase in the average number of slide events indicated in Figure 8 (i.e. quantified on a continuous rather than categorical basis) better demonstrates the correlation of these events with underbridge locations.

When considering the categories of momentary slides and long slides, the numbers of analysis windows that contained

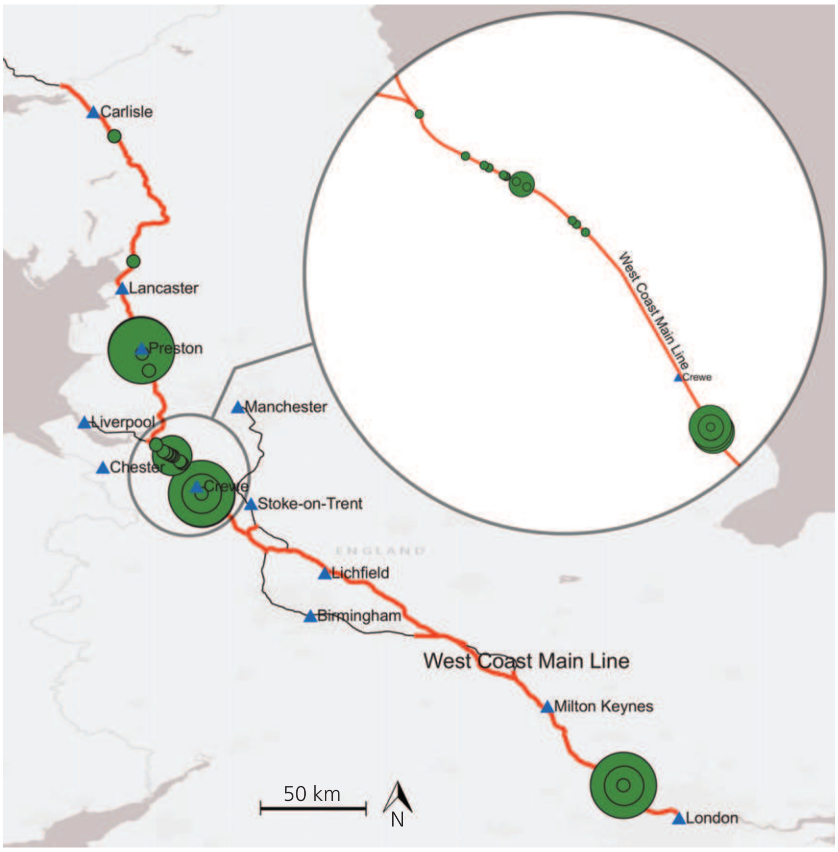

Figure 6. Distribution of RCF sites and momentary slides. The size of the shaded circles indicates the number of momentary slides within ±40 m of the RCF site (small, 0; medium, 1 or 2; large 3+). The enlarged area (10× zoom) highlights the section of line with 67% of RCF sites

these types of events were, respectively, 12% and 29% of the total number. These lower proportions permitted the likelihood (positive/negative) analysis in Figure 7 to demonstrate correlation of these events with bridge location.

The large increase in momentary wheel slide likelihood (Figure 7) and the average number of events per analysis window (Figure 8) when multiple underbridges were in the same analysis window supports a process where numerous stiffness changes and increased instances of track misalignment within a short section of line lead to momentary slide events, with the wheelset not able to accommodate the sudden changes in track alignment.

No correlation was found between the likelihood of long slides and underbridge locations. This was expected as the stiffness changes associated with underbridges are local and would not affect the adhesion level over 800 m of track, the criterion for a 'long' slide. The underlying cause of the negative correlation in the number of long slides that occurred in the same analysis window as multiple underbridges (Figure 8) cannot be confirmed with the available data. However, one observation is that a key influence behind this correlation would be the proportion of underbridges within heavy braking areas such as on the approach to stations or signals since a long slide would only be likely during braking. The different responses to the presence of an underbridge for the momentary and long categories of events support the hypothesis that they have different causes. In future work it may be useful to include locations dominated by braking as a factor in the analysis.

3.2.2 Low adhesion and RCF

The locational correlation between RCF sites and low-adhesion events is shown in Figure 9. For sites without RCF, the data were almost identical to the baseline values for the whole line. Without the severity criteria applied to the low-adhesion events, the likelihood of their occurrence (positive/negative basis) in the same analysis window as a site of RCF increased to 1·1 times the baseline. Filtering the adhesion data, the likelihood of a momentary slide occurring within the same analysis window as RCF was 2·4 times the baseline considering an average of the MD and MT categories. The likelihood of long slides occurring within the same analysis window as a site of RCF was 1·5 times the baseline when taking the LD and LT categories together.

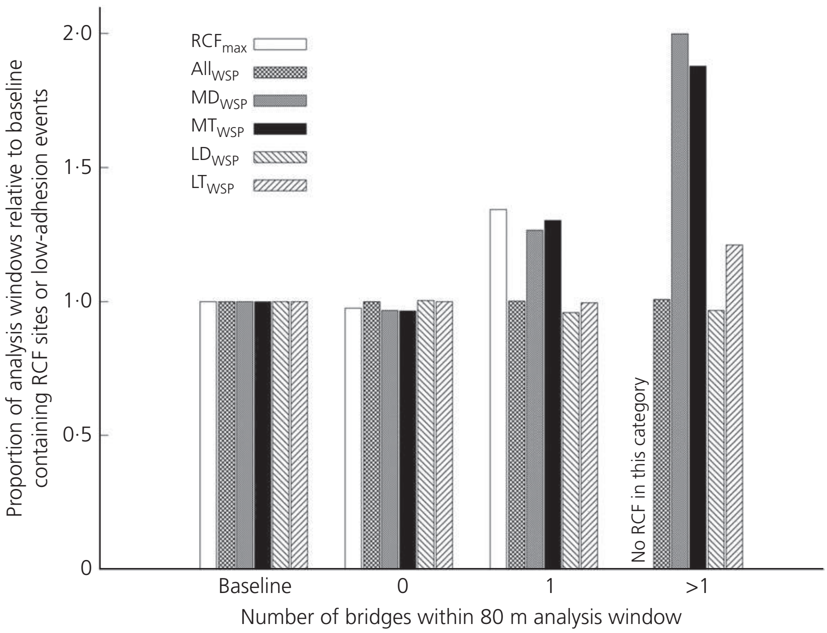

Figure 7. Comparison of the proportion of analysis windows that contain RCF sites or low-adhesion events that occurred in the same analysis window as an underbridge with the baseline. All_{WSP} represents adhesion event data without filtering by severity criteria

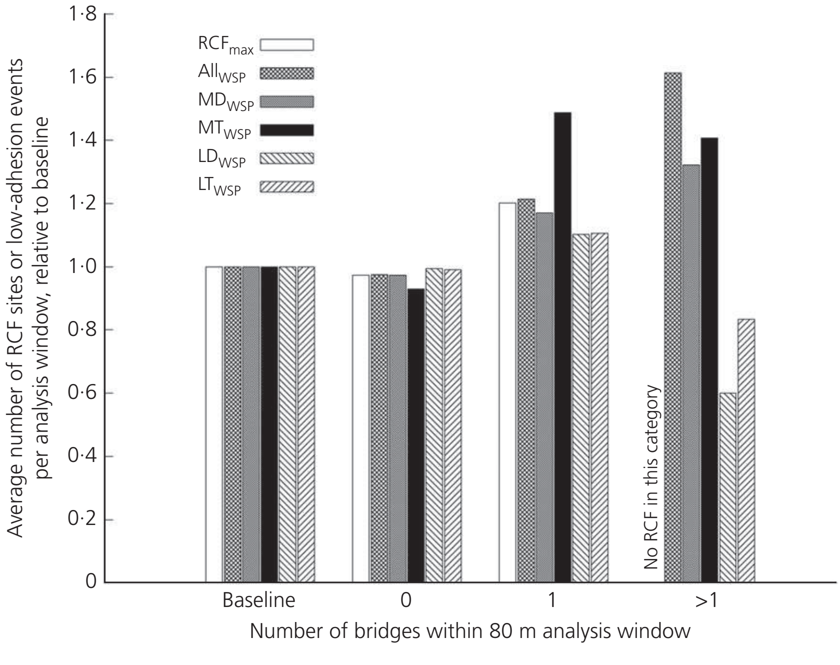

Figure 8. Comparison of the average number of RCF sites or low-adhesion events that occurred in the same analysis window as an underbridge with the baseline. All_{WSP} represents adhesion event data without filtering by severity criteria

Figure 10 shows how the average number of low-adhesion events is correlated with the presence of RCF. Without the severity criteria applied to the adhesion events (ALL_{WSP} in the figure), the average number of events that occurred in the same analysis window as a site of RCF increased to 2·3 times the baseline. The average number of momentary slide events that occurred within the same analysis window as RCF was 1·3 times the baseline, taking the average of the MD and MT categories. The average number of long slides that occurred within the same analysis window as RCF was 0·7 times the baseline

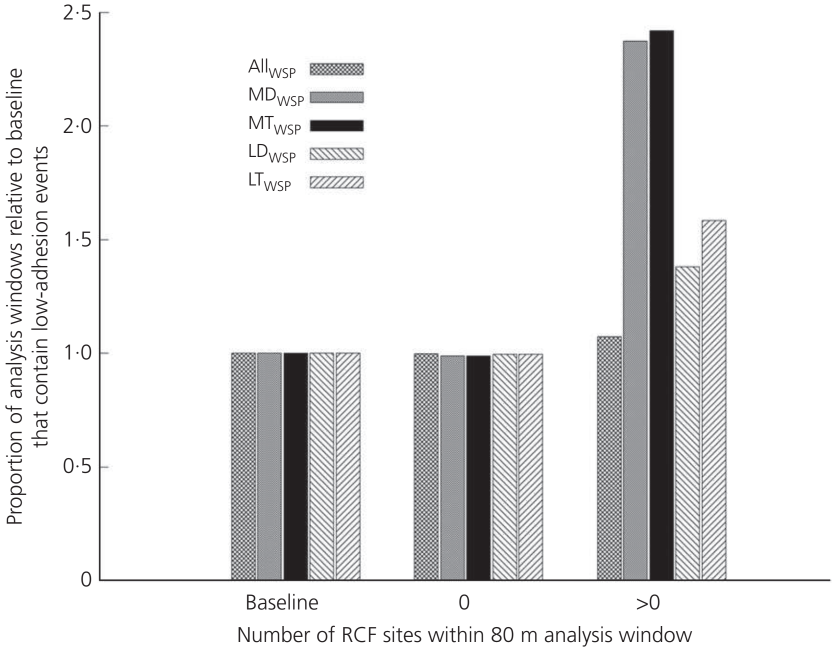

Figure 9. Comparison of the proportion of analysis windows that contain low-adhesion events in the same analysis window as a RCF site with the baseline

when taking the average for the LD and LT categories. As indicated by the subscript WSP in the figures, these slides all occurred under braking and were detected by WSP activation on the train.

Without application of the severity criteria, the number of analysis windows that contained low-adhesion events was 85% of the total number, making the binary method of quantification insensitive and leading to only small changes in the

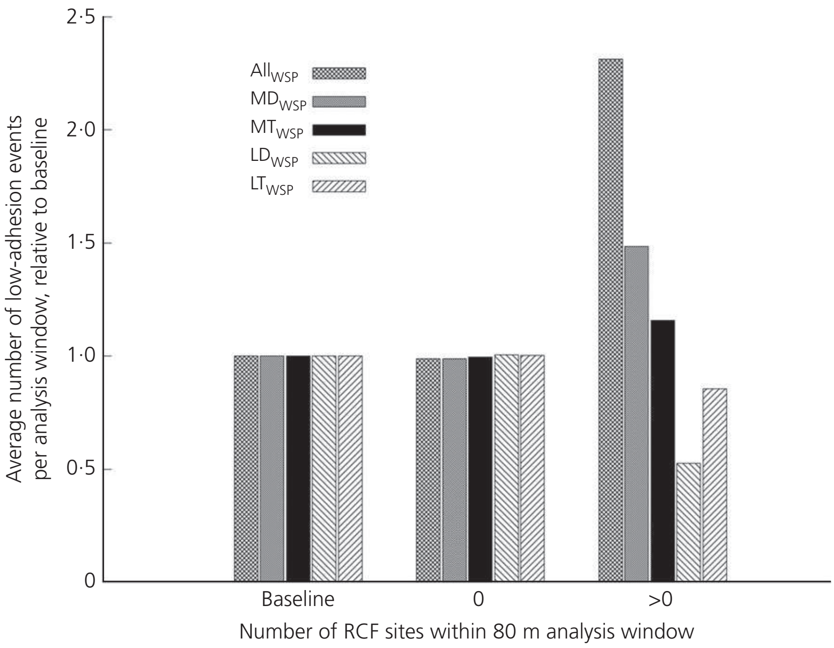

Figure 10. Comparison of the average number of low-adhesion events in the same analysis window as a RCF site with the baseline

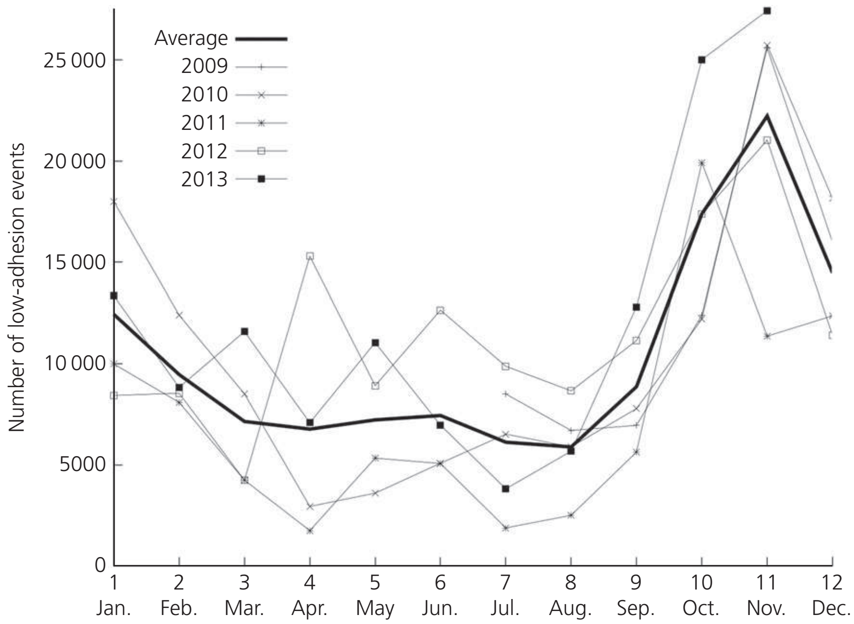

Figure 11. Number of wheel slide events occurring per month; these refer predominantly to momentary WSP events, not to safety-critical events such as signals passed at danger

likelihood results for RCF correlation in Figure 9. The change in the average number of low-adhesion events that occurred per analysis window shows much greater sensitivity. For momentary slides, the increase in both the likelihood (Figure 9) and the average number of events per analysis window (Figure 10) when coincident with RCF supports the hypothesis that a locational correlation exists between momentary slides and RCF sites, although this is not a causal link.

For longer slides, Figure 10 shows a reduction in the number of events when coincident with RCF, even though Figure 9 showed an increase in likelihood of occurrence on a positive/negative basis. The reason for the reduction in the number of long low-adhesion events when coincident with RCF could not be established from the data, but it is notable that the trend to increased likelihood (Figure 9) is much weaker for long slides than for momentary slides. It is possible that, although the data filtering applied helped to reveal the strong correlation between momentary slides and RCF locations, it also removed some potentially useful data on longer slides. The data visualisation for long slides in Figure 5 reveals that over three-quarters of the long slide events occurred in one geographical area. The binary analysis showing a positive correlation between long slides and RCF locations is most representative of this highly concentrated area, whereas the quantified analysis (showing a negative correlation) would better represent the rest of the area in which there was limited coincidence of long slides and RCF sites.

It is important to consider that although a single RCF crack would be classed as ‘heavy’ if having a visible surface crack length over 20 mm and ‘severe’ if over 30 mm (Railtrack, 2001), these cracks rarely occur in isolation but more often in significant quantity, giving them more potential to influence adhesion over a prolonged section of track. Together with the geospatial differences, this indicates that additional factors not captured in the quantified analysis need to be considered in order to obtain a deeper understanding of the links between long slides and RCF.

3.3 Temporal analysis

Building on the geospatial analysis, temporal analysis was conducted to assess both yearly and daily patterns in low-adhesion events. The monthly temporal analysis (Figure 11) highlighted periods during the year when wheel slide events occurred. It should be noted that these events refer predominantly to momentary WSP events, not to safety-critical events such as signals passed at danger. There was some variation between years, as would be expected since weather conditions are a key determinant of adhesion conditions, however, the behaviour for each year was similar and was represented well by the monthly average of the data (the dark line in Figure 11). Taking the mean of the data for each month took account of the fact that the data sets for 2009 and 2013 did not cover every month in those years. It was found that the 3-month autumn period (October to December) contained the greatest proportion of the yearly total of low-adhesion events (40–45%), with occurrence peaking in November. This is in line with the general understanding for the UK that low adhesion is a problem in the autumn. However, Figure 11 also shows that 55–60% of wheel slide events were distributed throughout the remaining 9 months of the year. Therefore, although fewer events occur per month, a greater number of events in total occur outside the autumn period.

In addition to the through-year analysis, an hourly temporal analysis was undertaken using two approaches.

In the first approach (Figure 12), the data are presented as the total number of wheel slide events in each hour summed across each year, expressed as the percentage of the total number of wheel slide events during each year. The data used to generate Figure 12 were analysed in conjunction with weather data presented by White *et al*. (2017). This approach indicates that the highest number of wheel slide events occurred between 06:00 and 10:00 – the morning 'rush hour' period when the consequences of delay can be severe due to the high traffic density and the potential for extensive knock-ons of delays to later in the day. A small evening peak in adhesion events was also noted, although this was much smaller than the morning peak. Traffic density data (presented later in this section) show similar amounts of traffic in the morning and evening peaks, so the distribution of adhesion events cannot be explained as simply a consequence of high traffic density in the morning peak. Other factors, such as rail surface oxide formation overnight when traffic is lighter, its subsequent removal by traffic during the day or differing rates of dew formation and evaporation, are also important. Rail temperature would be expected to vary throughout the day, potentially leading to dew to form railhead ice in colder periods. However, the running temperature of wheels is raised by frictional energy dissipation at the rail–wheel contact (Ertz and Knothe, 2002; Scott *et al*., 2014). Combined with pressure melting (Bottomley, 1872; Sanz *et al*., 2004), this makes it unlikely that ice would survive to influence adhesion events.

In the second approach (Figure 13) the low-adhesion event data summed across the years 2009–2013 are presented alongside hourly data on station stops attempted each day. The station stop data are mean values from timetable information for the whole UK network on Monday 28 October 2013 and Friday 3 January 2014. The intention here was not to match station stop data to exactly the trains on which low-adhesion incidents occurred, but rather to use it as an indication of traffic density throughout the day. Using this data, a value was generated (right-hand scale of Figure 13) by dividing national station stops each hour by the number of low-adhesion WSP activations observed per hour. It should be noted that this must be interpreted carefully since the differing data sources make strict interpretation as station stops per low-adhesion incident incorrect. It is also important to reiterate that the low-adhesion events refer predominantly to momentary low-adhesion wheel slide events, not to safety-critical events such as signals passed at danger.

The normalisation in the second approach (Figure 13) shows that the time period in which an individual train had the highest chance of experiencing a wheel slide low-adhesion problem was between 03:00 and 03:59, during which the lowest number of station stops take place (nationally) per low-adhesion incident observed. The number of low-adhesion events observed was low

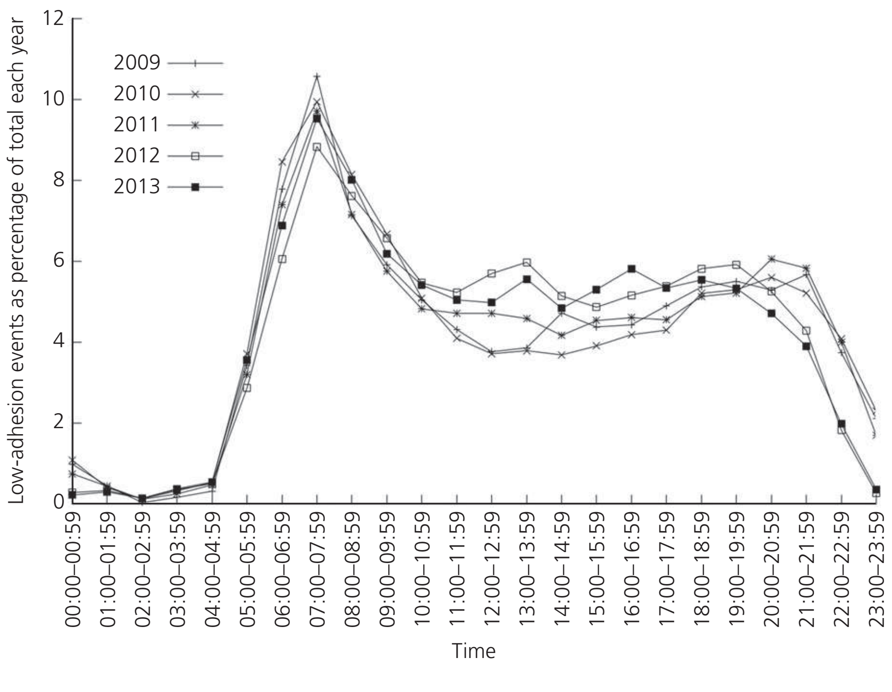

Figure 12. Number of wheel slide events that occurred per hour according to the first method (no normalisation)

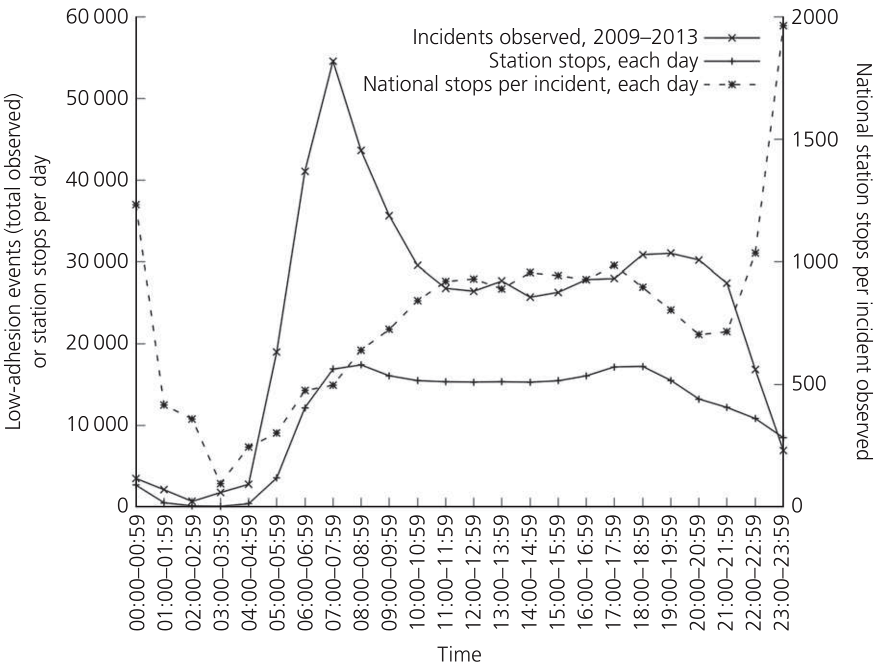

Figure 13. Number of wheel slide events occurring per hour for observed services in 2009–2013, normalised by the national number of station stops per hour

during this time (~1800) but, since traffic density is also low (indicated by ~110 station stops in that hour), each train has a higher chance of experiencing a problem than at other times of day. The figure for national station stops per observed incident rises gradually through the morning to reach a daytime plateaux by around 11:00. There was a small dip in the early evening, but the risk diminished greatly (i.e. more stops per incident) in the late evening. Normalisation of the low-adhesion data by traffic density supports the supposition from Figure 12 that traffic density is not the controlling factor since low-adhesion risk persisted through the morning peak in traffic but only marginally affected the evening peak.

4. Conclusions

Application of a moving-window filtering technique showed that there is a significant increase in RCF in the vicinity of an underbridge. Underbridge sites were characterised by an increase in RCF likelihood (i.e. the presence of any RCF) to 1·3 times the baseline, while there was an increase in the average number of RCF sites (a quantitative rather than a binary measure) to 1·2 times the baseline in the same 80 m analysis window as an underbridge. There was a strong correlation between momentary slides and underbridge locations, with an increase in the likelihood (presence/absence) of momentary slides to 1·9 times the baseline and an increase in the average number of events that occurred per analysis window (quantified basis) to 1·4 times the baseline in the same analysis window as multiple underbridges. The data showed no clear correlation between the likelihood of long slides and underbridge locations, with the likelihood of long slides remaining approximately equal to the baseline and the average number of events occurring per analysis window decreasing to 0·7 times the baseline in the same analysis window as multiple underbridges. The reasons for this decrease could not be established from the data available.

The increase in both the likelihood (2·4 times the baseline) and the average number (1·3 times the baseline) of momentary slide events per analysis window in the same analysis window as a RCF site supports the hypothesis that a locational correlation exists between momentary slides and RCF sites, although this is not necessarily a causal link. This was corroborated by geospatial distribution visualisations that presented data graphically on maps of the UK's WCML. The negative correlation between the average number (0·7 times the baseline) of long slides and RCF sites and the positive correlation between the likelihood (1·5 times the baseline) of long slides occurring and RCF sites did not support a direct locational correlation hypothesis. Geospatial visualisation in this case showed distinct differences in the level of correlation between different regions, suggesting additional factors need to be introduced into the analysis for better understanding of any correlation between long slides and RCF sites.

Temporal analysis indicated that low adhesion occurs both during and outside the autumn period and therefore cannot be solely attributed to leaf fall. With 40–45% of the yearly total of wheel slide low-adhesion events occurring during autumn, the analysis highlights that low adhesion is a problem that can affect train performance throughout the rest of the year, although at a lower rate of events per month.

When analysed in terms of the total number of incidents, it was found that the time period where low-adhesion events are most prevalent falls within the busy morning period, when the consequences of delays on passengers are the most severe. As the morning peak period may be influenced by both high traffic density and a high risk of low adhesion, a normalisation procedure based on national numbers of station stops was developed as a simple way of normalising the data for traffic density. This analysis showed that the highest risk of low adhesion for an individual train is in the very early morning (03:00–03.59). This risk was found to diminish by 11:00 (i.e. a rise in the number of station stops taking place on the network per incident observed) and the risk was found to rise only marginally in the evening peak traffic period.

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