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The hottest July day on the railway network; insights and thoughts for the future

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Title: The hottest July day on the railway network; insights and thoughts for the future

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Abstract

The 1st July 2015 was the hottest July day on record (37.5°C recorded at Heathrow) in the UK, and record-breaking temperatures were recorded across England. This short-duration heatwave (30/06-01/07/2015) affected railway services both directly, by causing asset failure or malfunction; or indirectly, by necessitating the use of emergency speed restrictions (ESRs) to reduce the likelihood of track-buckling. Incidents caused by heat and lightning were recorded across the British railway network and knock-on delays affected rail travel in regions where extreme weather did not have a direct impact. In total, 23,700 delay minutes were attributed to ESRs; 12,800 to heat; and, 4,000 to lightning incidents. Attributing specific incidents to extreme weather is problematic, and it is likely that the actual number of incidents caused by the extreme weather on 30/06-01/07 was far greater. Indeed, there were nearly 220,000 delay minutes on 30/06-01/07; all regions experienced more than twice the daily average delay minutes on one or both days, costing an estimated £16 million to the national economy. Incidents on critical routes (e.g. London North Eastern connecting London and Scotland) or near critical transport nodes such as Manchester Piccadilly caused the longest delays. Under future warmer climatic conditions, heatwaves and extreme temperatures

are projected to occur more frequently and the railway operator has several measures to adapt or update existing infrastructure in order to reduce the impact of heat and lightning. Alternative solutions such as low-cost sensors for real-time condition-monitoring or green infrastructure for increased asset resilience should also be considered.

1.1 Introduction

Extreme weather, such as prolonged rainfall, intense rainfall, heatwaves, strong winds, and storm surges can cause numerous problems for railway infrastructure, resulting in delays and disruption for passengers and freight customers. In recent years, there have been several high-profile extreme weather events. For example, in February 2014, an 80 metre section of track that formed part of the London to Penzance railway line, including the platforms at Dawlish station, was severely damaged by high seas, heavy rain, and strong winds (Network Rail, 2015a). This damage left the southwest peninsula of the UK without a critical rail route for 2 months which severely impacted the local economy and society, and incurred costly repairs for Network Rail (Dawson *et al.,* 2016). In June 2012, intense summer storms caused flooding and landslips that closed sections of both the East Coast and the West Coast Mainlines which connect London to Scotland, as well as regional services across the UK. Initially the impacts of track closures were localised but these quickly became national as the knock-on effect of local delays and the severing of both mainlines between London-Scotland affected rail travel across the country. In total, the June 2012 storms incurred over 10,000 weather-related delay minutes with the impacts lasting until mid-July (Jaroszweski *et al.,* 2015). In December 2015, a succession of winter storms took their toll on the rail network: trees felled by Storm Barney damaged overhead cables in northwest England; heavy rainfall associated with Storm Desmond left the West Coast Mainline track under 2 metres of floodwater at Carlisle disrupting travel between London and Scotland for several days; heavy rainfall from Storm Eva caused several landslips and line closures between Carlisle and Newcastle as well as severe flooding at Kirkstall, West Yorkshire; and finally, flooding from Storm Frank damaged the Lamington Viaduct in Scotland which led to disruption and closures on the West Coast Mainline between Carlisle and Glasgow (Network Rail, 2015b; 2016a). Network Rail estimates that weather costs the infrastructure owner and operator between £100-200 million each year although this is likely to be an underestimate because attributing individual equipment failure to extreme weather is not always possible, and these figures do not include the operational costs of actually managing a weather event (Network Rail, 2015c). Costs also do not include the wider social or economic impacts of the disruption of rail transport. For example, Network Rail estimated the cost of repairing the track at Dawlish at £35 million (HoCTC, 2015); but the wider economic impact of the rail disruption on tourism, fishing, and other industries in Devon has been estimated between £60 million and £1.2 billion, with individual business losing between £100 to £1,000 per day of line closure (DMF, 2015).

Following the recent succession of relatively cool summers in the UK, the impact of heatwaves and extreme heat on the railway infrastructure has become relatively minimal in comparison to other extreme weather events such as prolonged rainfall, intense rainfall, strong winds, and storm surges. It has therefore received little attention in press reports or in industry climate change adaptation reports (e.g. Network Rail, 2015d). However, previous warm summers such as 1995 and 2003 clearly show that heat severely impacts railway infrastructure (Thornes, 1997; Hunt *et al*., 2006). Heat impacts upon railway assets in a variety of ways (Palin *et al*., 2013; Ferranti *et al.*, 2016). For example, the heating of rail track in direct sunshine can lead to thermal expansion and consequential buckling of the rail. Track buckling is more likely to occur in combination with the additional energy of a passing train, and for this reason emergency speed restrictions are used in hot weather conditions to slow down trains and thus reduce the risk of buckling and potential derailment. The reported incidence of rail buckles is higher during warmer summers such as 1995 and 2003 (Hunt *et al*., 2006) and the use of temporal analogues shows that the number of buckles and the associated financial costs are predicted to increase in the future under warmer climatic conditions (Dobney *et al.,* 2009; Dobney *et al.,* 2010). Extreme heat can also cause overhead lines that transmit electricity to the trains to expand and sag causing de-wirement of the pantograph. The pantograph connects the train to the overhead line and therefore the electricity supply needed to power the train; de-wirement leaves the train without power. The incidence of overhead line sag was also projected to increase in a future warmer climate (Palin *et al.,* 2013); following this study Network Rail introduced new policy requiring the use of auto-tensioned fixings for the overhead lines, this should significantly reduce the occurrence of line sag in the future. Signalling assets can also malfunction on warmer days and indeed signalling failures account for 57% of reported heat-related incidents between 2006 and 2013 (Ferranti *et al.*, 2016). Telecommunications assets, particularly those within lineside cabinets or location cases are also sensitive to heat; the temperature within a location case can be much warmer than ambient temperature, and can also change much more rapidly (Rail Corp, 2012), leading to the equipment overheating. Higher temperatures may also:

reduce the opportunity for track maintenance which cannot be done on days when ambient temperatures are above 21°C, or predicted to exceed 25° in the subsequent three days; increase the risk of lineside fires; and, increase the risk of rail employees suffering from heat stress during routine outdoor work (Palin et al., 2013). Finally, higher temperatures can also cause passenger discomfort, for example in overcrowded or poorly ventilated trains, or in glazed buildings and shelters; and may also lead to increased alcohol use by passengers leading to more aggressive behaviour, slips, trips and falls (RSSB, 2015a).

Extreme heat therefore impacts railway services either directly, by causing asset failure or malfunction; or indirectly, by necessitating the use of emergency speed restrictions (ESRs) to reduce the likelihood of track-buckling. Both cause delay and disruption for passengers and freight customers, and incur financial costs for Network Rail who are required to make payments via the Schedule 8 system to compensate the train and freight operating companies for poor performance (ORR, 2015). There is also an additional financial cost associated with repairing the broken or faulty asset, and with managing the incidents and consequential delays. As the Dawlish example clearly shows, delays also have a wider impact on regional and national economy and society. Despite this, there is little empirical research into the observed impact of extreme heat on the railway infrastructure (Koetse and Rietveld, 2009). Accordingly, this study provides a detailed assessment of the impact that a short-duration heatwave had on the UK's railway network. It examines the fault incidents recorded by Network Rail on 30th June to 1st July 2015; the latter was the hottest day recorded in UK history.

1.2 Synoptic Situation

The 1st July 2015 was the hottest July day on record in the UK (Kendon *et al.,* 2016). A maximum temperature of 36.7 °C was recorded at Heathrow at 14:13 UTC (Weather, 2015a), and record-breaking temperatures were recorded at several other weather stations across the UK (Figure 1 and Table 1; BADC, 2016). The previous maximum temperature for July was 36.5 °C at Wisley, Surrey on 19th July 2006, which was the highest recorded UK temperature since the record-breaking heatwave in August 2006 (Kendon *et al.*, 2016). From late June until September 2015, much of mainland Europe experienced heatwave conditions (Mekonnen *et al.,* 2016). The heat experienced on 30th June and 1st July in the UK was associated with hot air that was advected northwards from Spain (Kendon *et al.,* 2016). The heat began building during the last week of June and peaked in the early afternoon on the 1st July, before cooler air and a thundery trough advanced from the west during the middle to late afternoon (Weather, 2015b; 2015c). This created thundershowers with lightning and hail in most of Great Britain (except for the south-east), particularly in the northeast (Weather 2015c).

This short-duration heatwave was different from the recent heatwaves in 2003 and 2006 for two reasons. Firstly, it remained warm overnight on the 30th June leading to high temperatures early in the day on the 1st July (Kendon *et al.,* 2016). For example, the overnight minimum temperature at Heathrow (21:00-09:00 UTC) was 20.7 °C; the maximum temperature was 32.5 °C (BADC, 2016). Secondly, unlike the heatwaves experienced in 2006 and 2003, record-breaking temperatures were observed across the length and breadth of England. For example, the temperature recorded at Stonyhurst in Lancashire broke the previous maximum temperature record from 1976 by 1.1°C (Weather, 2015a). Figure 1 shows the maximum temperature recorded on 30th June and 1st July 2015 at weather stations which are part of the Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Dataset (1853-current) (BADC, 2016). It highlights those weather stations where long-term (> 50 years) temperature records were broken on 1st July 2015 (Kendon *et al.,* 2016).

2 Data

Network Rail is responsible for the performance and management of the majority of Great Britain's railway infrastructure, upon which different passenger and freight operating companies run their trains. The infrastructure includes over 20,000 miles of track, and thousands of signalling and telecommunications assets. For management purposes the railway network is separated into several Routes as shown on Figure 2.

Information on asset performance is collected by Network Rail using a variety of systems and procedures and stored in several different databases. Information from two separate databases; FMS (Fault Management System), and TRUST (Train Running System on TOPS (Total Operation Processing System)), are used in this study. FMS and TRUST were developed separately, and were designed for different purposes, and therefore there are differences in the type of information recorded in each databases. As faults and/or delays are independently recorded in either FMS or TRUST, some incidents can appear only in FMS; some incidents can appear only in TRUST; and, some incidents do appear in both datasets. FMS records fault history details at national level, and integrates and connects several legacy Network Rail databases developed for different asset types (Network Rail, 2008). FMS contains information on asset type, location, and includes a free text description of the fault written by the person who dealt with the specific incident, that may attribute the fault to specific weather phenomena. TRUST is also a legacy system designed to monitor the progress of trains and tracking delays. The system compares the times at which trains arrive, depart or pass specific locations and compares them with the schedule in order to retrospectively calculate any delay minutes, and associated delay costs (Network Rail, 2016b). TRUST is an operational database that can be freely downloaded (http://www.networkrail.co.uk/data-feeds/). In general, unlike FMS, TRUST data does not include detailed information on the failed or faulty asset, nor does it contain specific information about the fault or failure such as the free text description in FMS. In contrast, unlike TRUST, FMS does not contain information on delay costs or minutes. Those incidents which do appear in both datasets can be retrospectively cross-related for analysis purposes.

Although neither TRUST nor FMS were designed for meteorological analysis, or for use in weather impact studies, both databases contain data that can, with careful processing, be applied for these purposes. For this study, weather-related incidents were identified from the free text column in FMS using an adapted algorithm developed for a previous study (Ferranti *et al.,* 2016). The algorithm was used to search for weather-related key words and phrases recorded in the database such as: buckle, temp, expansion, hot, thermal, weather, storm, high, light, etc. Those incidents selected by the algorithm were carefully examined by eye to remove erroneous or ambiguous data. Particular care was taken to differentiate between those incidents which were caused by heat, and preventative speed restrictions that are used to minimise the impact of track-buckling under hot weather conditions. Weather-related incidents from TRUST were provided by Network Rail following their own propriety analysis to investigate the impact of weather on the railway infrastructure (Network Rail, 2015c. Finally, FMS and TRUST datasets were cross-related using ID numbers, and also spatially joined using GIS in order to identify common incidents and prevent duplication.

A comparison period is useful to contextualise the impact of the extreme weather on 30/06-01/07. For example, the number of incidents from the heatwave event could be compared with TRUST and FMS data for the same time period for the previous year, or previous years (2006-2013). However, Ferranti *et al.* (2016) demonstrated that the resilience of railway infrastructure to heat increases through the summer season with each incremental hot day as heat-vulnerable equipment is repaired or replaced. Thus comparing 30/06-01/07 with incident rates from previous years is counter-intuitive because the heat-resilience of the infrastructure will vary depending upon each years' antecedent weather conditions and the general condition of the infrastructure at that particular time. The heatwave event could also be compared with a mean daily incident rate from 2016; again this does not take into account the increased heat-related failure rates in the early summer season (see further, Ferranti *et al.,* 2016) and would also include a typically higher daily incident rates due to other weather phenomena in winter. After consideration, a 5 week period from 15th June to 19th July 2015 was selected (excluding the heatwave event). This period reflects normal operations during June and July 2015 in the two weeks before and after the week containing the short-duration heatwave event. The UK was not subjected to any other heatwaves during this 5 week period; indeed the months of June and July were slightly cooler than the 1981-2010 average (Kendon *et al.,* 2016). This 5 week period is not a 'baseline' or a 'control period' per se, simply a comparison period to contextualise the impact of the extreme weather on 30/06-01/07. FMS data from 15th June to 19th July 2015 is incomplete or missing for 4 routes: Anglia, Wales, Western Thames Valley, and Western West (Figure 2).

3. Results

3.1 Impact of extreme weather on railway infrastructure

Figure 3 shows the total number of incidents recorded in the Network Rail FMS and TRUST databases between 15th June and 19th July 2016. Both datasets show a weekly pattern with a reduced number of incidents recorded at the weekend, and a clear increase in the number of incidents on during the heatwave event. For FMS this represents a 66% and 54% increase compared to the daily average weekday mean during the comparison period. In TRUST, more than 84,500 and 105,500 delay minutes were recorded on 30th June and 1st July respectively, which represents increases of 84% and 130% increase compared to the daily average weekday mean. It is important to note that the difference between the percentage increases relate to the differences in the types of data recorded by the two datasets and should not be directly compared. Both FMS and TRUST datasets clearly show that this was not a typical day on the railway network and that heat and the other extreme weather on 30/06-01/07 severely impacted the railway infrastructure. Indeed, this was the worst summer day in terms of performance since 2008, and affected a greater number of train operating companies than previous episodes of extreme heat (Network Rail 2015e).

Figure 4 shows the location of incidents attributed to extreme weather from both FMS and TRUST. Incidents which are common to both datasets are shown only once and are denoted by the key. On the 30th June there were 79 incidents attributed to extreme weather, predominantly heat. These were mainly located in England in Routes (Figure 2): London North Eastern (39%); London North Western - South (13%); London North Western - North (11%); and Wales (11%). Scotland was least impacted by the extreme weather. On 1st July, 67 incidents attributed to extreme weather were reported in central and eastern England, and in Scotland too: London North Eastern (43%); London North Western - North, London North

Western - South, Scotland, and Kent (9% each). There was also more lightning fault incidents than on the previous day (22%), especially in northeast England.

Figure 5 shows the preventative ESRs introduced to reduce the risk of track-buckling and potential derailment; 67 were issued on 30th June and 50 on 1st July. Although the 1st July was a warmer day, curiously more ESRs were actually listed in FMS and TRUST on the 30th June than on 1st July. Whether there were fewer ESRs declared on the 1st July or whether this is an artefact of Network Rail reporting or recording procedures is unclear.

3.2 Impact on the extreme weather by asset type (FMS)

As explained in Section 2, attributing incidents to extreme weather is only possible when weather-related descriptions are provided in the incident record. However, as there is no other obvious reason for the high number of incidents observed on 30/06-01/07 it can be assumed that the majority of extra incidents shown in Figure 3.1a are due to the extreme weather. Figure 6a and 6b shows the breakdown of all FMS incidents by asset type on the 30/06-01/07 as compared to the period between 15th June and 19th July (Figure 6c). On both days, and over the longer averaging period, the greatest number of incidents is associated with track and signalling assets. Indeed the distribution of incidents across the different asset classes is broadly similar for 30/06-01/07 and 15/06-19/07 suggesting that all asset types were impacted by the weather, and that the extreme weather did not disproportionately impact any particular asset type.

Table 2 compares the average number of FMS incidents per day (calculated from the 15/06-19/07 period excluding the heatwave event) with the number of incidents on 30/01 and 01/07 for sub-assets classes. This further shows that the extreme weather impacted a broad spectrum of asset types, although four asset sub-classes in particular (Table 2a): Operational Property (building), Traction Power (electrification & plant); Lineside Equipment (signalling/electrification & plant/telecoms) and Track Circuit (signalling); appear to have been more severely impacted by heat. Correspondence with Network Rail has indicated that Automatic Warning Systems are considered particularly sensitive to heat; although there were slightly more incidents associated with Automatic Warning Systems on 30/6-01/07 they do not appear to have been disproportionality impacted when compared to other asset sub-classes (Table 2b).

Finally, Figure 7 shows the impact that heat and lightning had on the different asset types by region for the 30/06-01/07 period. Approximately 50% of reported heat and lightning incidents occurred in the London North Eastern route (see further Figure 4), where the extreme weather impacted all asset types. Signalling and telecoms assets appear particularly sensitive to lightning (Figure 7b); all asset types are vulnerable to extreme heat and the greatest number of incidents are recorded on signalling assets. This is consistent with previous heat impact studies (Ferranti *et al.,* 2016).

3.3 Impact of extreme weather on delay minutes and costs (TRUST)

The TRUST system compares train running with the scheduled timetable and incidents from this database can be examined in terms of delay minutes and delay costs. Costs are taken from Schedule 8, the process by which Network Rail compensates train operators for unplanned service disruption that is caused by Network Rail and other train operators. Figure 8 shows the total delay minutes for each Route for all incidents recorded in TRUST starting on the 30th June and 1st July. Over the two-day period the greatest number of delay minutes were recorded on the London North Western Route (60,310 minutes) followed by the Southeast (Sussex and Kent; 43,763 minutes), and London North Eastern (37,731 minutes) (Table 3). In terms of the magnitude increase, the Western Route experienced the greatest increase in daily average delay minutes on 30th June, and the London North Western Route on 1st July (Table 3). With the exception of Scotland, every Route experienced more than twice the daily average delay minutes on one or both days of the heatwave event showing the extreme weather impacted across the whole of the railway network in England and Wales.

Figure 8 also shows the delay minutes associated with weather-related incidents from TRUST comprising heat incidents, lightning incidents (1st July only), and ESRs. It should be noted that although ESRs are commonly blanket speed restrictions and therefore affect a whole line or even a broader area, for attribution purposes they are located on a particular track section on the affected routes. For heat or lightning incidents the point locations represents the point or track section where the incident occurred. The number of delay minutes due to ESRs was greater on the 30th June, and were distributed across incidents of varying size in central, southern and eastern England. ESRs that accrued a large number of delay minutes included track sections in: Reading (3,200 min); London Paddington to Ladbroke Grove (2,200 min); Stoats Nest Junction to Earlswood, on the Brighton mainline between London and Brighton (2,000 min); and Salford Crescent to Bolton, a major route in Greater Manchester (1,500 min). There were fewer delays due to ESRs on the 1st July, even though in terms of maximum temperatures this was the hotter day. Large delays were experienced again at Reading (1,500 min) and Three Bridges (4,000 min) which is a major junction on the Brighton mainline. Although the recorded delay minutes was notably less on the 1st July, the cost of the ESRs were approximately the same on both days (Table 4).

The mostly impactful incident in terms of delay minutes (6,900 min) and costs (£302, 000) was a heat-related track fault that occurred between Stowmarket and Ipswich in Anglia on 30th June; this was ongoing until 5th July 2015. On the hotter 1st July, heat was less of a problem, however lightning caused several incidents in north-eastern England that led to considerable delays, for example at Northallerton (1,200 min; £45,800) and between Alnmouth and Morpeth (1, 800 min; £224,200) on the East Coast Mainline that connects London and Scotland.

The magnitude of delay minutes attributed to a particular incident depends up the duration of the incident, and also the usage of the track section along which the delay occurred. For example, although Network Rail can potentially repair an electrical failure near Waterloo in six minutes, this can still result in a total delay of three hours (Network Rail, 2013). Incidents that occur along less frequently used sections of the railway network generally impact fewer trains and therefore accrue less delay minutes. This is demonstrated in Figure 8. The majority of ESRs had a duration of one day, but some (e.g. those at Reading) accrued a far greater number of delay minutes for they occurred along more critical sections of track, and therefore impacted a far greater number of trains. Similarly the lightning incident at Northallerton on 1st July is recorded as lasting only 4 minutes in the TRUST database (14:57-15:01), however because it occurred on the LNE mainline, which is a critical transport route, it impacted upon a total 89 trains travelling between stations including: Kings Cross, London; Glasgow; Manchester; Liverpool and Newcastle (Figure 9a). The first recorded delay attributed to the lightning strike at Northallerton began at 14:08 and the last was at 21:55.

3.4 Limitations of the study

It is important to note that the actual impact of the extreme weather on 30/06-01/07 is probably far greater than described here. It has already been acknowledged that the than those presented in Sections 3.1 to 3.3 because the extreme weather may not have been noted as a causative factor, not least because weather may not have been the obvious cause of the incident (Network Rail, 2015c; Ferranti *et al.,* 2016). For example, Figure 3 shows more than 500 extra incidents were recorded in the FMS database on 30/01-01/07 (as compared to the weekday average), however only a quarter of these extras incidents (124 incidents) can be directly attributed to heat, lightning or heat-related ESRs (Figures 4 and 5).

Secondly, the financial impact goes far beyond those Schedule 8 costs derived from the TRUST database. Schedule 8 costs *do not* include the actual cost of repairing or replacing the faulty asset, or the additional costs that Network Rail or the train operating company may accrue in order to manage the incident (Network Rail 2015c). Moreover, they do not account for any socio-economic impacts that a train delay may have on passengers or business; the National Audit Office estimates that every train delay minute costs the national economy £73.47 (2007 costs) (NAO, 2008). There were nearly 220,000 delay minutes on 30/06-01/07 which equates to an estimated cost of £16 million to the national economy.

Another major limitation is the absence of robust data to examine the impact that extreme weather, particularly extreme heat may have on passengers and staff. Extreme heat can cause passenger discomfort or illness in overcrowded or poorly ventilated trains, or in glazed buildings and shelters, and can sometimes be associated with an increased alcohol use by passengers causing more minor accidents (RSSB, 2015a). This is problematic when the trains are running to schedule, but delays (either due to the extreme weather, or unrelated incidents) can further exacerbate the impact of extreme heat. For example, on 1st July there was a problem with a pantograph and the overhead lines on a track section of near Manchester Piccadilly Station. Manchester Piccadilly is a critical transport node that connects: national services between London and Scotland; regional services travelling east-west; and, local transport across the city of Manchester. Delays following this incident consequently propagated across much of the railway network, impacting 611 trains from 15:31 on 1st July until 15:11 on the 2nd July; in total 19,000 delay minutes are attributed to this single incident (Figure 9b). This incident was not attributed to extreme weather but media reports indicate that extreme heat exacerbated the frustration and discomfort experienced by passengers. For example, Manchester Evening News described the inside of carriages 'stifling' with passengers on the train 'close to fainting' after a power loss left the train unable to move and the air-conditioning unable to operate (MEN, 2015). Indeed, the risk to passengers from high temperatures on public transport is listed as a research priority in the 2017 Climate Change Risk Assessment (CCRA, 2016).

Finally, this analysis has not linked specific asset incidents or failure to meteorological data, for instance to try to identify a threshold failure for specific asset types (e.g. Network Rail, 2014; Network Rail 2015c). Although, high-resolution meteorological data is available for the UK (e.g. Figure 1) and interpolation can be used to derive approximate temperature in areas without direct measurement (e.g. Figure 4 and 5), the temperatures of railway assets, such as track, overhead lines, or communication units can vary significantly over even small distances. The variations in temperature will depend upon the specific location, the type of asset, and will probably be different from the temperature recorded at the nearest weather station. For example, Chapman *et al*. (2006) measured a temperature range of 39°C along a short section of track, and overhead lines have been measured at 10°C warmer than the nearest meteorological station (RSSB, 2015b). Moreover, the location of the fault provided by Network Rail may not be exact, and may represent the mid-point of a track section, along which the fault occurred, rather than the exact location of the asset. Accordingly, there is little merit linking asset incidents with temperature measurements (e.g. to develop temperature thresholds for specific assets), and it is not appropriate to make comparisons on infrastructure resilience between different regions or Network Rail Routes. For example, lightning was recorded in other regions of northern England and Scotland on 1st July 2015, but the railway impacts were mainly observed in northeast England. This does not indicate that infrastructure in northeast England is less resilient to lightning; lightning strikes in other regions may not have taken place near railway assets. By their design, Network Rail fault databases do not included weather impacts that do not cause a fault. This information would be necessary to compare infrastructure resilience across region. There is a need to develop better monitoring solutions on the railway to link asset faults with local weather conditions in order to facilitate these types of weather impact studies.

5 Discussion & Conclusions

The extreme weather on 30/1-01/07 impacted upon railway assets the length and breadth of the network. Impacts included; damage to infrastructure, passenger delays, passenger discomfort, and financial costs incurred to Network Rail and the train operating companies, and the national economy as a consequence of passenger and freight delays. Heat or lightning directly impacted infrastructure assets across in England, Wales and Scotland (Figure 3) and knock on delays affected rail travel in regions where extreme weather did not have a direct impact (Figure 9). Almost all asset types were affected (Figure 6, Table 2), although certain asset sub-classes (e.g. Traction Power, Lineside Equipment Track Circuit, Operational Property) may be disproportionality affected by extreme heat and lighting. The magnitude of the impact of any particular event depends upon the time it takes for normal service to resume, and the criticality (i.e. importance) of the track section within the wider railway network. Delays that occurred following incidents on critical routes (e.g. London North Eastern that connects London and Scotland; Figure 9a) or near critical transport nodes such as Manchester Piccadilly (Figure 9b) can quickly propagate across the railway network.

The 1st July 2015 was the hottest July day on record, but extreme temperatures and heatwaves are projected to become more common and last longer in the future (e.g. Fischer and Schar, 2010; Christidis *et al*., 2015). By the 2040s the heatwave season is expected to expand from July-August to May-September, and by the 2080s, over half the UK will experience heatwave conditions at some point every year (Sanderson and Ford, 2016). This has major implications for the long-term infrastructure planning undertaken by Network Rail, and for the long-term resilience of the whole of the UK transport network. As this study shows, heatwaves, even those of short duration can have a systemic impact on the railway infrastructure. It follows that without adaptation, in a future climate with more frequent and longer duration heatwaves, the disruption and costs such as those experienced on 30/06-01/07 are likely to occur more often. Future assets must be designed to operate in a future warmer climate that experiences more high temperature extremes. In particular, care must be taken to consider infrastructure located in urban areas. Towns and cities are often warmer than the surrounding countryside due to the urban heat island effect (Oke, 1073) and assets are therefore more likely to be exposed to consistently higher temperatures. Also, urban areas represent vast concentrations of assets and people that can be affected by extreme heat (Chapman *et al*., 2013), and are often critical transport nodes meaning that any incidents and consequential delays will quickly propagate across the railway network and therefore have a disproportionately large impact. Moreover, impacts originating from incidents on the railway network can also affect other transport systems, which may also be impacted by the same weather issues.

Network Rail have recently produced a series of regional Weather Resilience and Climate Change Adaptation Plans (Network Rail, 2015f); these are summarised in Table 5. The planned actions and potential actions vary across the Routes. Anglia, located in the relatively warmer, drier and sunnier southeast of England (Mayes, 2013) plans a range of measures to reduce the impact of heat. Wessex, Kent, and Sussex Routes, despite their similar geographic location have far fewer planned or potential actions. On 30/06-01/07 the extreme heat impacted a range of assets in the London North Eastern Route (signalling, track, telecoms, building; Figure 7). This Route plans to improve air conditioning and undertake research into new methods of keeping equipment cool. Given the widespread impact of heat on the 30/06-01/07 described in this study, the planned and potential actions in Table 5 must be implemented across all regions and asset types if all heat-related impacts are to be avoided. Fundamentally, Network Rail asset policy specifies that all rail electrical equipment should operate across an ambient temperature range of -25^{o}C to 40^{o}C; the policy also states the need for air-conditioning in equipment housing. Consequently, legacy equipment that is vulnerable to heat is now being replaced with modern heat-resilient alternatives, and reliable air conditioning is made available, as part of normal asset renewal cycles. This will improve resilience to heat. In addition, the advent of digital signalling systems (such as the European Rail Train Management System – ERTMS) will remove a significant quantity of track-side signalling equipment.

This study has used FMS and TRUST to understand the impact of extreme weather, but these databases are not comprehensive, data entry is not consistent, and most importantly the databases were not designed for meteorological analysis and therefore do not collect the appropriate data. Moving forward, a better evidence base that clearly demonstrates the impact that extreme weather has on the railway infrastructure is required. It may be possible to collect more robust data which is appropriate for meteorological impact studies by modifying the recording procedures for the existing databases such as FMS to incorporate weather or climate key words in the free text columns. Data is particularly deficient on the impact that extreme heat may have on railway users and staff. Emerging techniques such as crowdsourcing, i.e. obtaining data or information by enlisting the services of a (potentially large) number of people, usually over the Internet, could be used to collect information on temperature from locations inside (e.g. on trains) and outside (e.g. at stations) on the railway network (for a review see Muller *et al.*, 2015). For example, Overeem (2013) showed how temperature data could be readily derived from smartphones. Network Rail and the train operating companies regularly use social media to communicate with rail passengers and crowdsourcing could be used to collect much needed data on the impact that all types of extreme weather is having on railway users. A better evidence base will support and guide long-term planning decisions for infrastructure and ultimately make the railway network more resilient for the future.

Network Rail may also find it useful to review their current procedures for managing heat-risk. Over 60 % of the delay costs and almost 60% of the delay minutes on 30/06-01/07 were attributed to ESRs that were introduced to reduce the chance of buckling. If the ESRs could be removed without jeopardising passenger safety, then there would be a significant improvement in service and a reduction in costs for Network Rail, especially under future, warmer climatic conditions where under current operational practice more ESRs would be required (for ESRs are introduced a specific temperature thresholds (Network Rail, 2015c), which will occur more often in a future warmer climate). Indeed, the Weather Resilience and Climate Change Adaptation Plan for Scotland notes that ESRs are often introduced too early simply because the condition of the track is unknown (Network Rail, 2015f; Table 4). Improved condition monitoring, perhaps using the Internet of Things (IoT) could offer a new approach (e.g. Chapman *et al*., 2016). Low-cost sensors that connect wirelessly to the Internet could be deployed at high-resolution to monitor the real-time temperature of tracks known to be susceptible to buckling. This could act as an early warning of the high rail temperatures associated with a higher buckling-risk and could be used as an alternative to blanket ESRs, particularly towards the end of the summer season or a heatwave event where repeated failure-harvesting had improved the infrastructure's resilience to heat (Ferranti et al., 2016).

Green infrastructure, such as strategically planted trees or green roofs or walls, could also offer an innovative solution for heat-management on the railway network. Chapman *et al*. (2006) showed that much of the spatial variation in daytime rail temperature can be explained simply by shading effects. Trees or other green infrastructure could therefore be effectively used to shade track sections at risk of buckling, or to shade heat-sensitive equipment such as lineside location cases. Embankment planting can also improve stability, drainage and ecology, and strategic planting and appropriate management would limit the impact of leaf fall during autumn (LDA, 2012).

For the future, the rail network faces the challenge of modernising an ageing infrastructure which has suffered from historical underinvestment (DfT, 2014), against the backdrop of increasing passenger and freight numbers on a network already operating near maximum capacity (Network Rail, 2013). At the same time the number of extreme weather events associated with climatic change are increasing (Fisher and Schar, 2015). This case study demonstrates how heat can severely affect railway infrastructure and disrupt services. It is imperative that Network Rail does not underestimate the potential impact of extreme heat following the recent series of mild summers and the unintentional under-recording of heat-related incidents and impacts within its different databases.

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Figures

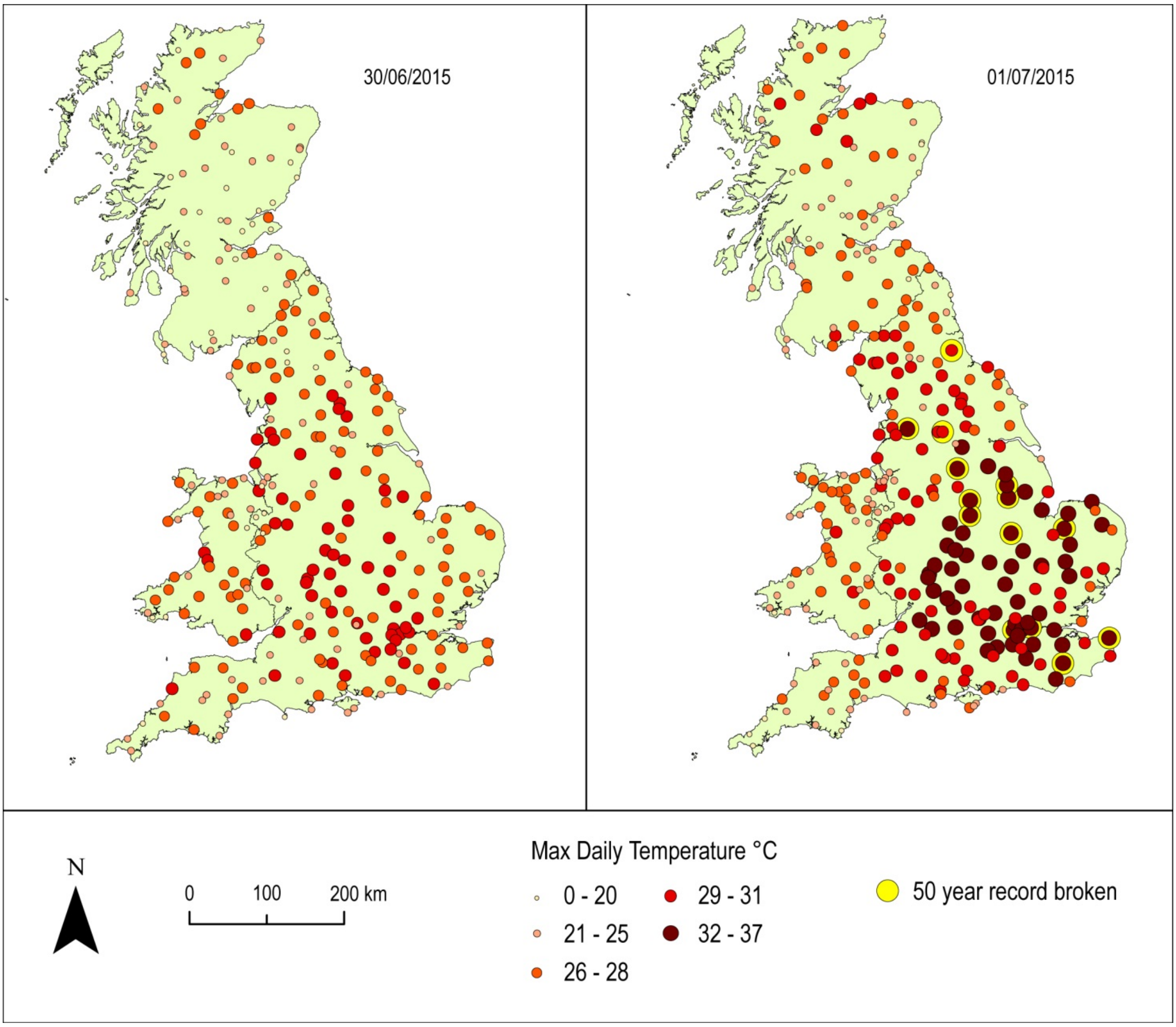

Figure 1: Temperature measurements on the 30th June and 1st July 2016. Those sites which maintain records longer than 50 years in duration and had their July maximum temperature record broken on 1st July are highlighted.

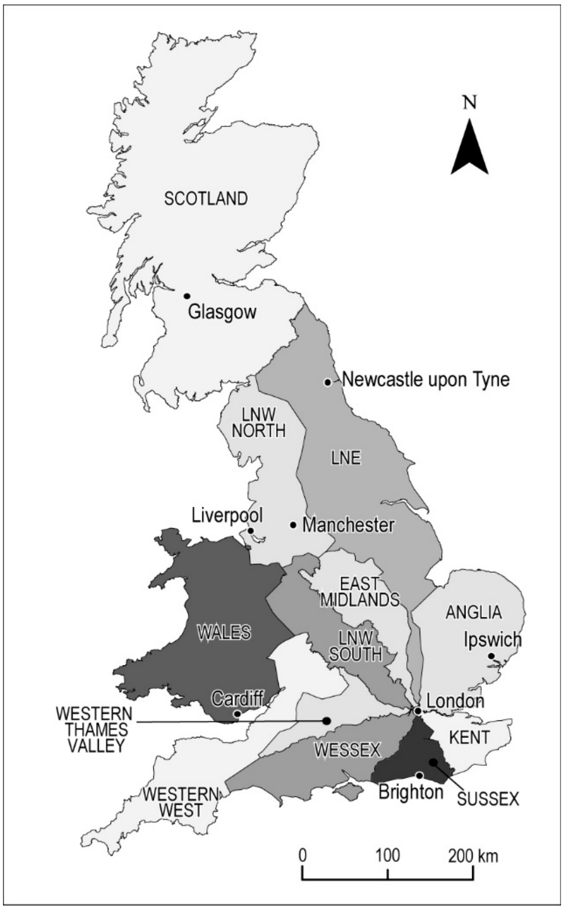

Figure 2: Network Rail operating regions in Great Britain and major towns and cities, or those referred to in text. The different Routes have been coloured different shades of grey for clarity.

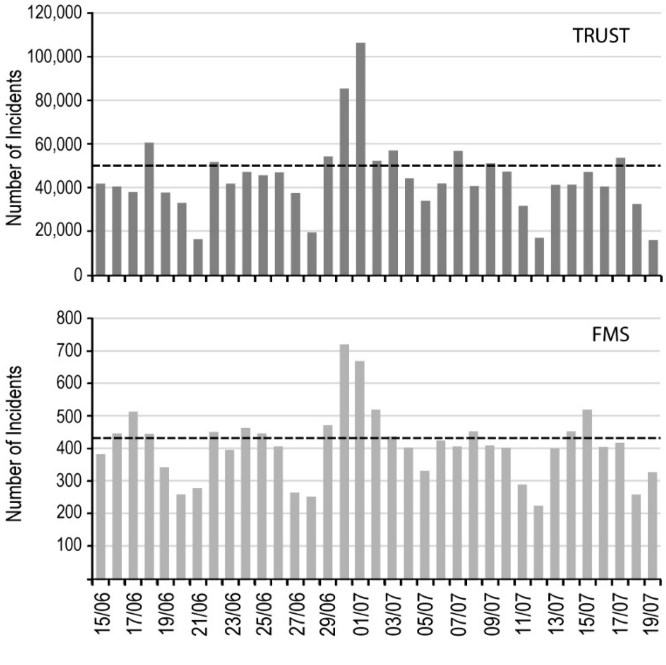

Figure 3: The number of incidents recorded in the TRUST (top) and FMS (bottom) databases between 15th June and 19th July 2016.

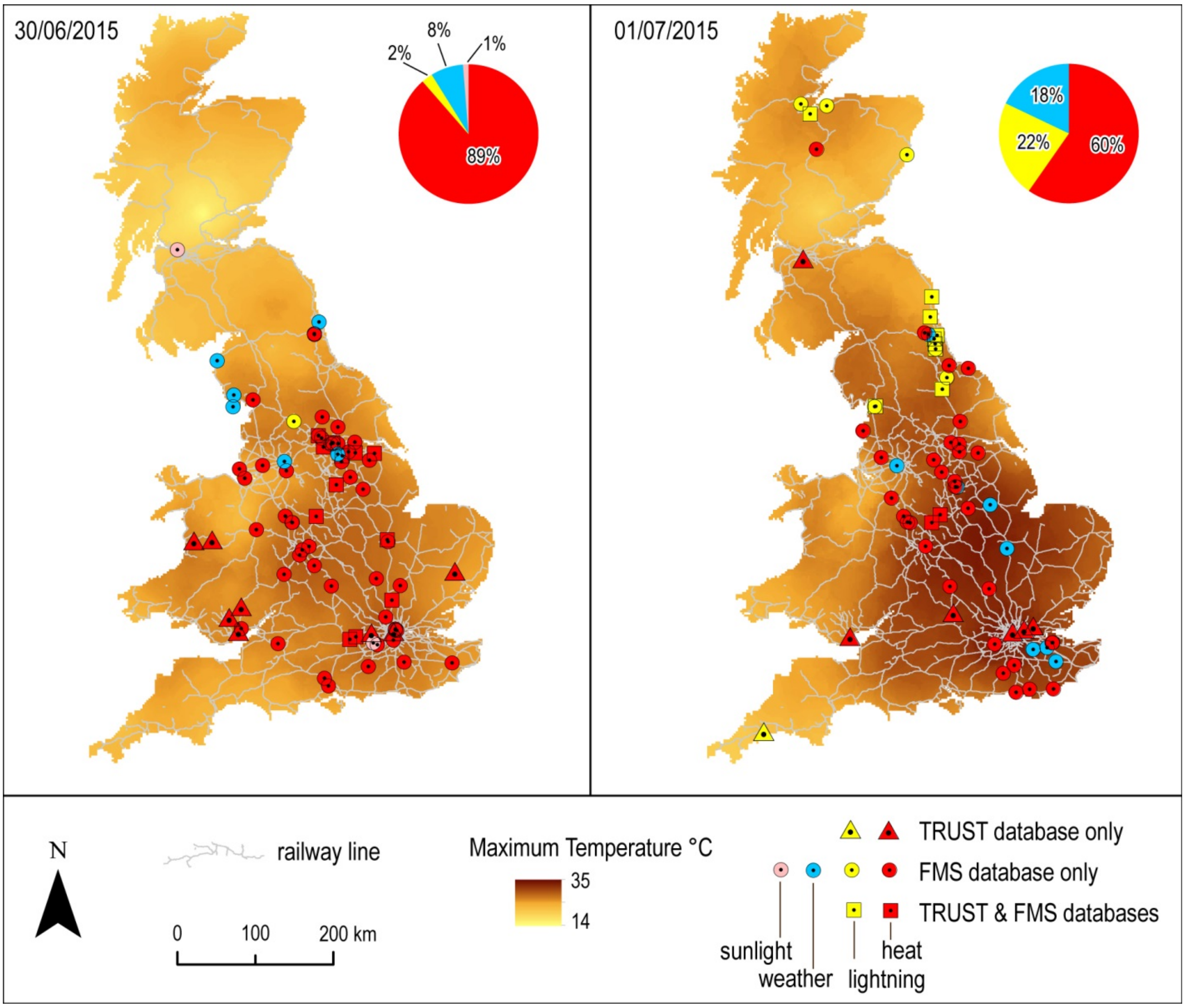

Figure 4: Weather-related incidents from FMS and TRUST on 30th June (left) and 1st July (right). The incidents overlay a temperature surface produced using kriging to interpolate between the temperature observations shown in Figure 1.

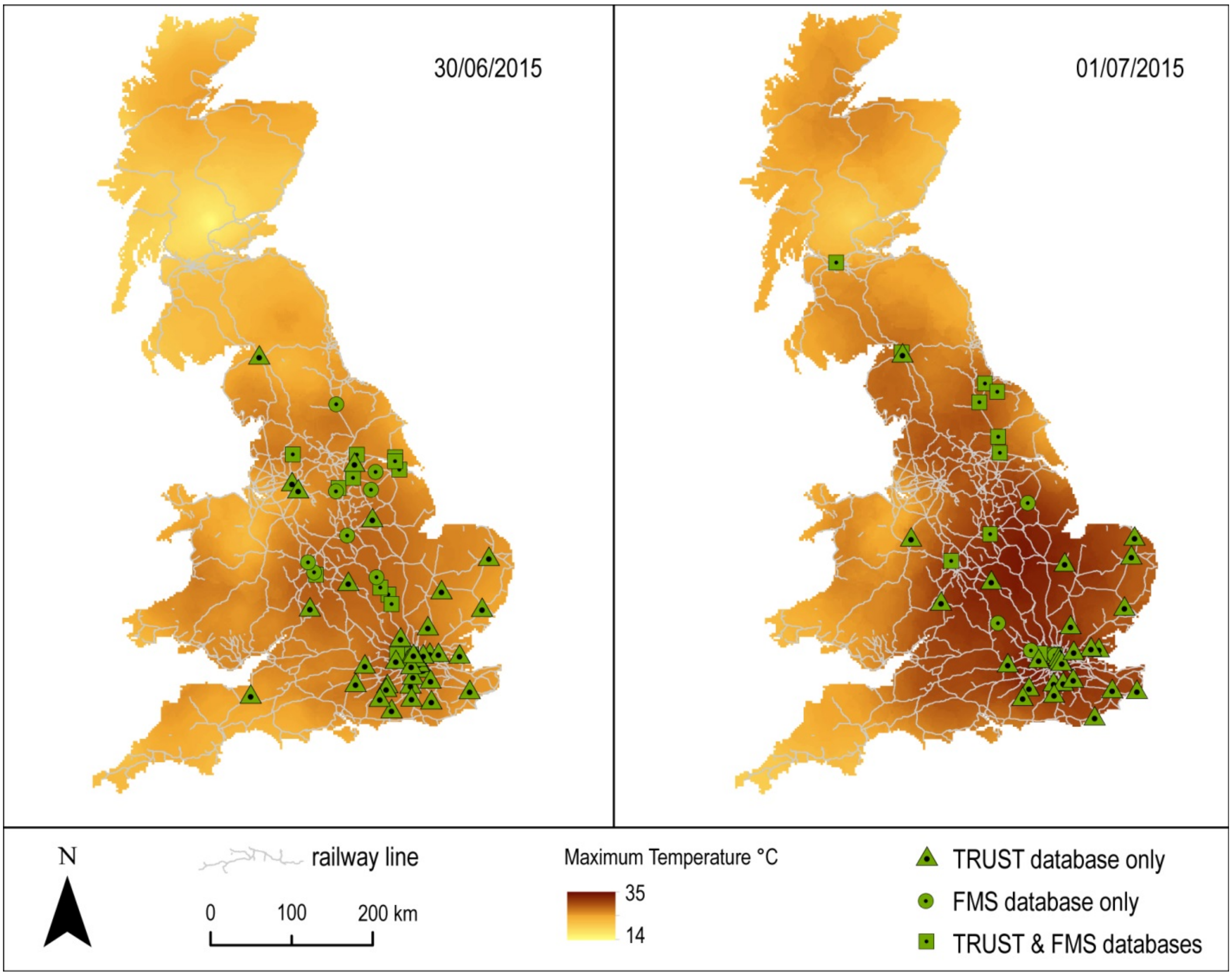

Figure 5: Emergency Speed Restrictions from FMS and TRUST on 30th June (left) and 1st July (right). The incidents overlay a temperature surface produced using kriging to interpolate between the temperature observations shown in Figure 1.

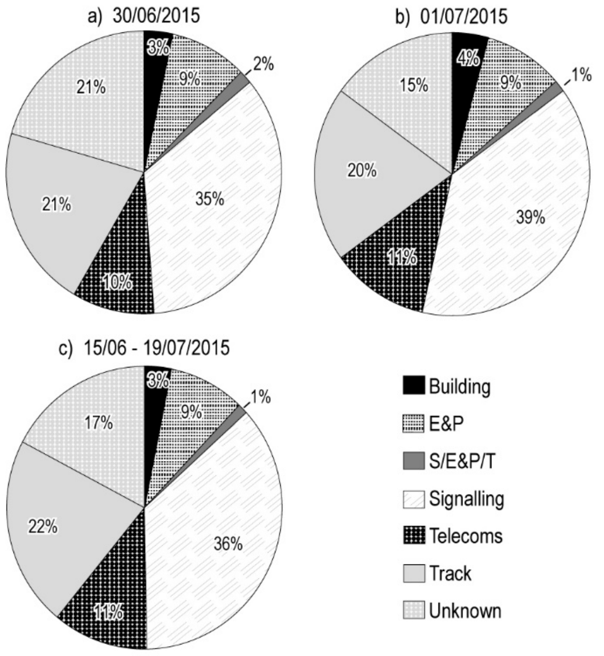

Figure 6: Breakdown of incidents by asset type; (a) 30th June; (b) 1st July; (c) 15th June to 19th July, 2016.

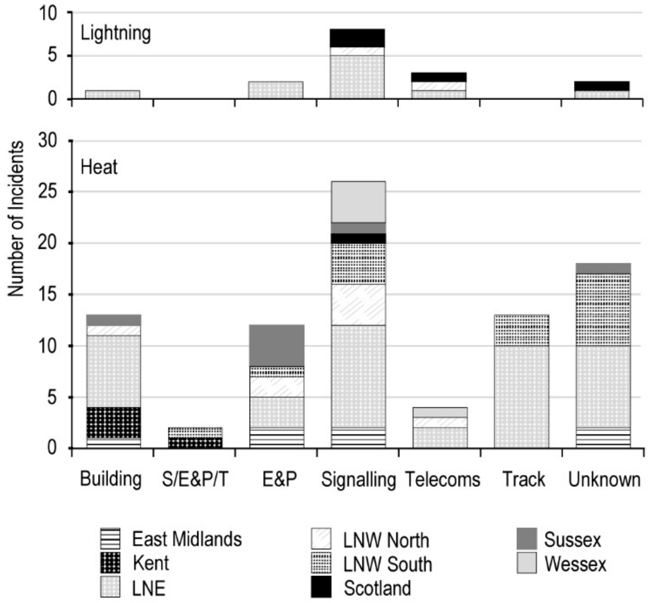

Figure 7: The total number of lightning (top) and heat (bottom) incidents on 30/06-01/07 for different asset classes and by Route (for those Routes with complete data in FMS database).

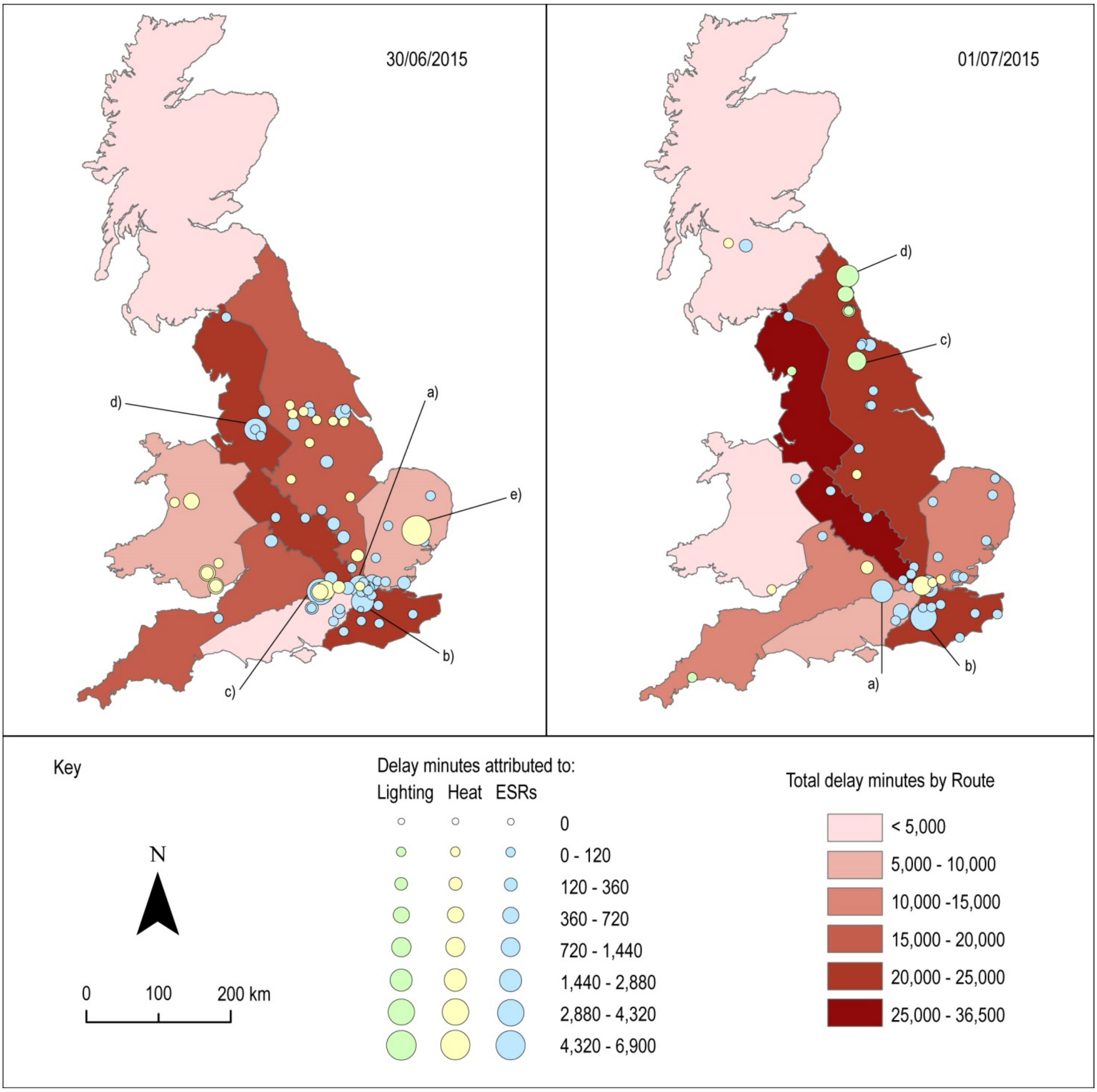

Figure 8: The total delay minutes for each Route on 30th June (left) and 1st July (right) overlain by delay minutes for incidents specifically attributed to heat or lighting, or ESRs. Incidents referred to in the text on the 30th June include: a) ESRs between London Paddington to Ladbroke Grove (2,200 min); b) ESRs on the Brighton mainline between London and Brighton (2,000 min); ESRs at Reading (3,200 min); d) ESRS between Salford Crescent and Bolton (1,500 min); and, e) heat-related track fault between Stowmarket and Ipswich. On the 1st July, incidents noted in the text include: a) ESRs at Reading (1,500 min); ESRs on the London-Brighton mainline (4,000 min); lightning incidents at Northallerton (1,200 min, see also Figure 9a); and, d) lightning between Alnmouth and Morpeth (1, 800 min).

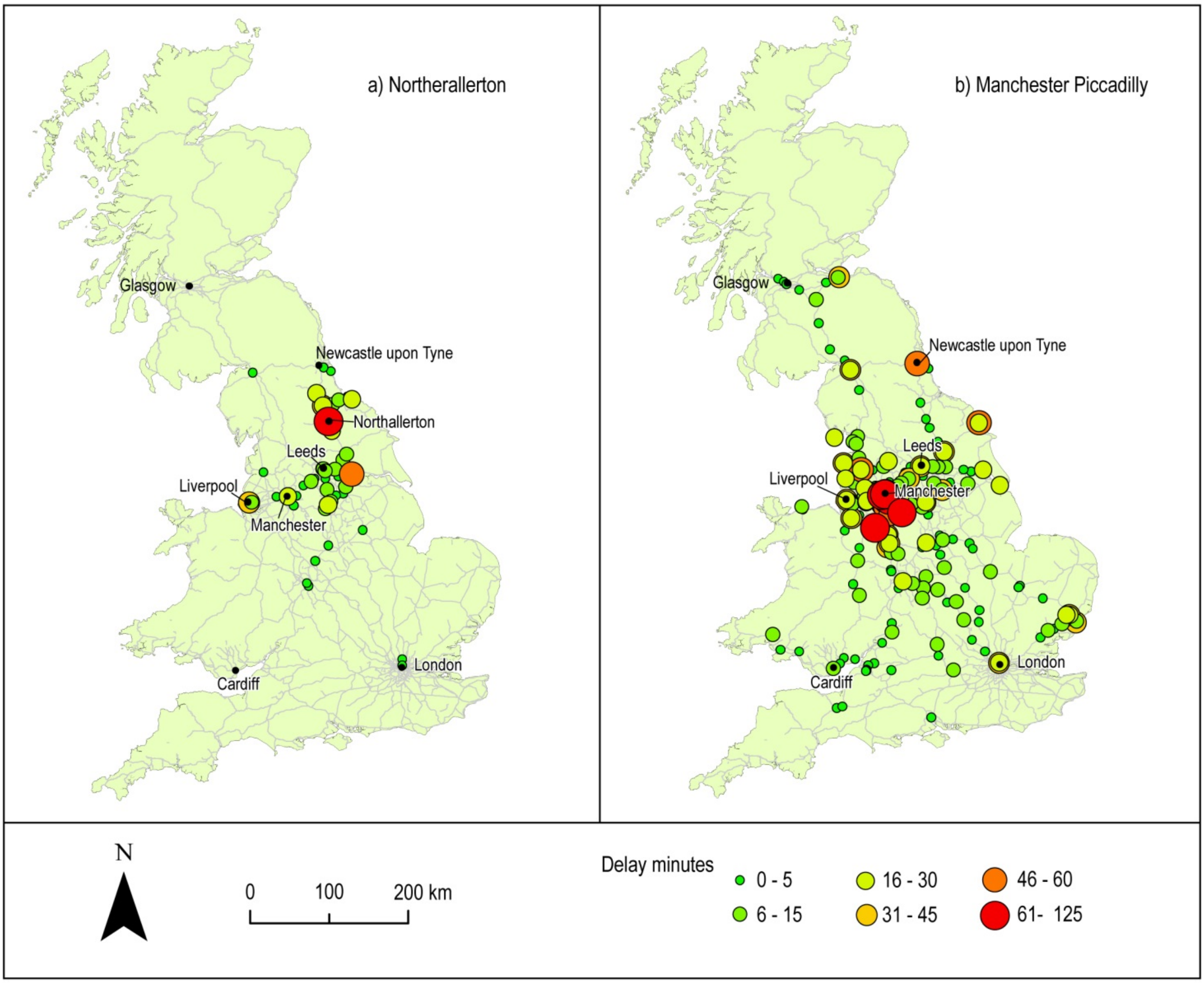

Figure 9: The delays experienced by individual trains along particular sections of track that were attributed to specific inicdents including: a) a lightning strike at Northallerton (total ~1,200 minutes); and a b) a pantograph problem close to Manchester Piccadilly (total ~19,000 minutes). Tables

Table 1: Those stations with more than 50 years of observations, for which 1 July 2015 was a record (Modified from Kendon *et al.*, 2016). See also Figure 1.

Site	Maximum temperature on 1st July 2015 (°C)	Previous max temperature in July (°C)	Date of previous maximum temperature	Length of meteorological record (years)
Durham	31	30.6	31/7/1943, 10/7/1921	133
Sheffield	33.3	31.7	31/7/1943, 10/7/1921	130
Bradford	30.9	30.6	31/7/1943, 13/7/1935	106
Cranwell	34.3	32.6	22/07/1996	93
Sutton Bonnington	33.6	32.9	19/07/2006	84
Stonyhurst	32.6	31.1	03/07/1976	75
Manston	33.6	31.4	15/07/1983	74
Goudhurst	33.3	32.8	03/07/1976	74
Waddington	33.1	32.2	12/07/1949	67
Heathrow	36.7	35.5	19/07/2006	66
Nottingham (Watnall)	33.9	32.3	03/07/1976	64
Marham	33.5	32.8	3/7/1976, 5/7/1959	58
Wittering	35.3	32.8	05/07/1959	53
St James's Park	34.7	34.4	05/07/1959	52

Table 2: The average number of incidents for different asset classes was calculated for the 5-week comparison period (15th June – 19th July) and is shown the Incident/Day column. The number of incidents for different asset classes on 30th June and 1st July is also shown, as is the magnitude increase from the average Incident/Day on these dates. The asset types are organised into four tables (a-d) by the magnitude increase of the number of incidents over the 30/6-01/07 period.

a) Asset types with more than twice the average number of incidents per day on 30th June and 1st July

Asset Name	Asset Sub Class	Incident/Day	30-Jun	01-Jul	Magnitude Increase 30 Jun	Magnitude Increase 1 Jul
Building	Operational Property	6.9	15	20	2.2	2.9
Electrification & Plant	Traction Power	5.9	19	16	3.2	2.7
Signalling / Electrification & Plant / Telecoms	Lineside Equipment	4.4	11	9	2.5	2.0
Signalling	Staff Protection	0.4	1	1	2.8	2.8
Signalling	Track Circuit	21.4	65	54	3.0	2.5
Telecoms	Supervisory Control and Data Acquisition system	0.3	1	1	3.0	3.0

b) Asset types with more than the average number of incidents per day on both 30th June and 1st July

Asset Name	Asset Sub Class	Incident/Day	30-Jun	01-Jul	Magnitude Increase 30 Jun	Magnitude Increase I Jul
Building	Structures	4.9	9	8	1.8	1.6
Electrification & Plant	Overhead Line	15.9	24	26	1.5	1.6
Electrification & Plant	Signalling Power Supply	8.0	12	16	1.5	2.0
Signalling	Automatic Warning System	3.7	6	4	1.6	1.1
Signalling	Axle Counter	4.2	6	7	1.4	1.7
Signalling	Interlocking	22.8	41	44	1.8	1.9
Signalling	Level Crossing	24.7	54	40	2.2	1.6
Signalling	Signal	42.7	53	77	1.2	1.8
Telecoms	Concentrator	2.7	3	5	1.1	1.9
Telecoms	Power	0.8	1	2	1.2	2.4
Telecoms	Radio	8.4	15	15	1.8	1.8
Telecoms	Telephone	18.0	31	32	1.7	1.8
Telecoms	Transmission Eqpt	9.6	17	17	1.8	1.8
Telecoms	Voice Recorder	0.8	1	4	1.3	5.1
Track	Track	64.6	135	102	2.1	1.6
UNKNOWN	UNKNOWN	66.8	147	99	2.2	1.5

c) Asset types with more than the average number of incidents per day on either both 30th June or 1st July

Asset Name	Asset Sub Class	Incident/Day	30-Jun	01-Jul	Magnitude Increase 30 Jun	Magnitude Increase 1 Jul
Electrification & Plant	3rd Rail	4.8	10	4	2.1	0.8
Signalling	Hot Axle Box Detector	1.2	1	4	0.8	3.4
Signalling	Monitor	7.4	10	5	1.4	0.7
Signalling	Point Operating Equipment	0.5	0	1	0.0	2.2
Signalling	Remote Control System	2.0	2	5	1.0	2.5
Signalling	Train Protection and Warning System	9.6	10	13	1.0	1.3
Track	Unknown	18.5	15	30	0.8	1.6

d) Asset types with less than the average number of incidents per day on both 30th June and 1st July

Asset Name	Asset Sub Class	Incident/Day	30-Jun	01-Jul	Magnitude Increase 30 Jun	Magnitude Increase 1 Jul
Signalling	Automatic Train Protection	0.3	0	0	0.0	0.0
Signalling	Signalling Control	0.5	0	0	0.0	0.0
Signalling	Unknown	0.0	0	0	0.0	0.0
Telecoms	Miscellaneous	0.2	0	0	0.0	0.0
Telecoms	Public Emergency Telephone System	0.2	0	0	0.0	0.0
Telecoms	Stations Information and Security Systems	2.6	0	0	0.0	0.0
Track	Unknown	18.5	15	30	0.8	1.6

Table 3: Total delay minutes for all incidents from TRUST on 30th June and 1st July 2015 and the magnitude increase as compared to the mean minutes per day for the period 15th June – 19th July (excluding the heatwave event on 30/06-01/07).

Route Name	Mean Minutes/day	Delay Minutes 30/06	Delay Minutes 01/07	Magnitude Increase 30/06	Magnitude Increase 01/07
Anglia	3,991	7,792	12,799	2.0	3.2
London North Eastern & East Midlands	7,788	16,241	20,890	2.1	2.7
London North Western	9,181	23,833	36,477	2.6	4.0
Scotland	2,414	2,630	3,948	1.1	1.6
South East	7,079	20,423	23,340	2.9	3.3
Wales	2,503	5,600	4,195	2.2	1.7
Wessex	2,742	4,040	6,871	1.5	2.5
Western	4,325	16,233	12,011	3.8	2.8

Table 4: Delay minutes and costs for those incidents attributed to weather or ESRs on 30th June and 1st July 2015

a) Delay minutes

	ESR	Heat	Lightning	Total
30th Jun	14,644	11,472	0	26,116
1st July	9,042	1,269	4,093	14,404

b) Delay costs

	ESR	Heat	Lightning	Total
30th Jun	£878,320	£527,057	£0	£1,405,376
1st July	£867,205	£83,508	£395,049	£1,345,762

Table 5: A summary of the planned actions and potential future actions by Network Rail to order to increase the resilience of the railway network to extreme heat and lightning (Network Rail, 2015f). The actions are shown for each Route where; ANG = Anglia; LNE = London North Eastern and East Midlands; LNW = London North Western; SCOT = Scotland; SE = South East – Kent, Sussex; WES = Wessex; WST = Western (Thames Valley and West). Planned actions are shown in bold (e.g. ANG), potential actions in plain (e.g. ANG**). Note that Wales does not have any planned actions or potential future actions with respect to heat.**

Weather	Asset Issue	Action	Route
Heat	All heat-related impacts	Ensure assessments of temperature resilience measures against climate change projections are specified in Route Requirements Documents	**LNW**
	Track buckling	Review current adverse weather plans	**ANG**
		Review of remote rail temperature monitoring / CRT (Critical Rail Temperature) database	**ANG**
		Continue white painting of rails.	**ANG**
		Early intervention by track maintenance	**LNW, SE**
		Additional monitoring stations to record more accurate temperatures	**SCOT**, ANG, WST,
		Upgrade track and consider increasing stress-free temperatures	**LNE**
		Research required into enhanced remote monitoring of track resistance	LNE
		Identify sites where cess support, shoulder ballast restoration, replacement of lightweight sleepers or plate support systems would be beneficial for CRT management	ANG
		Model the impact of temperature change on track performance	SCOT
	Thermal expansion at swing bridges	Review alternative measures to improve the heat resilience of swing bridges	ANG
	Clay bank desiccation	Use of 'Earthwork Watch' system for early warnings and appropriate mitigation	**SE**
	OLE (Overhead Line Equipment) sag	Remove fixed tension OLE systems	**ANG**
	Equipment/ buildings overheating	Improve air-conditioning	**ANG, SE, LNE,** SCOT
		Research required into new methods of keeping equipment cool	LNE
	Shorter working season	Assess current heat prep work banks to quantify risk to delivery with shorter working season	**WES**
Lightning	Loss of electrical systems	Ensure assessments of lightning resilience measures against climate change projections are specified in Route Requirements Documents	**LNW**
		Review current weather procedures	**ANG**
		Review benefits of lightning array protection of sensitive locations	**ANG, WES,** SE
		Utilise lightning alert and monitoring systems to assist with identification of failed assets and reduce impact on performance	**LNW**
		New or improved lightning protection systems in historically vulnerable areas, e.g. Birmingham New Street, Blea Moor (Cumbria), Cornwall, Woking to Waterloo	**SE**, **ANG,** LNW, WST, **SCOT, LNE**
		Research required into new lightning protection methods	LNE