Quantifying the Effects of High Summer Temperatures due to Climate Change on Buckling and Rail Related Delays in the UK.

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Abstract

Extreme high temperatures are associated with increased incidences of rail buckles. Climate change is predicted to alter the temperature profile in the UK; according to these predictions extreme high temperatures will become a more frequent occurrence. The result is that the number of buckles expected per year could increase if the track is maintained to the current standard. This paper quantifies the increase in the number of buckles and rail related delays and assigns a cost to the resultant rise in delays and damage.

1.1 Introduction

It is estimated that present-day adverse weather conditions cause 20% of all unplanned delays; this is equivalent to 5 million delay minutes [13]. Although the rail network is a robust infrastructure [6] and weather conditions in the UK are rarely as extreme as in other countries, smooth operations can still be affected by even minor weather-related influences. It is important to be able to anticipate these impacts and cope with them for the safe and efficient running of the service.

Climate Change models predict that the weather in the UK is going to change. It is anticipated that there will be a general trend towards more extreme weather [7]. Winters will become milder and wetter, whereas summers will be hotter and drier. These weather extremes have the potential to cause increased problems such as rail buckling, flooding due to inadequate drainage, sudden earthworks failure, scour at the base of bridges and damage to overhead wires [6].

1.2 The Aim of the Project

The aim of the whole project is to establish the severity and geographical distribution of the impacts of Climate Change on the UK's rail network by quantifying the potential change in frequency and severity of weather-related damage. The content of the project has been developed from the identified risks to the railway network, posed by climate change [6]. These include increased risks caused by high temperatures, reduced impact of extreme cold weather and the increasing severity and frequency of extreme storms causing flooding and earthworks failure.

1.3 Scope of paper

The scope of this paper will be to consider rail buckles and other rail-related damage caused by extreme high temperatures. In the UK, the South East is one of the regions exposed to the highest temperatures and so will show the worst-case scenario of the impact of hotter weather in the UK.
RSSB has highlighted heat-related damage, particularly buckles, as an area of future vulnerability due to Climate Change [6]. A track buckle is defined as any track misalignment serious enough to cause a derailment [12]. This definition demonstrates how serious a rail buckle can be to safety on the railways, and why the RSSB has highlighted a possible increase in rail buckles due to climate change as a notable issue. The definition also reveals the subjective nature of a rail buckle; this may explain why Network Rail has fewer recorded in their field records (called the Alterations Database) than are documented in other sources and literature (discussed further in section 3.1). In addition, the definition elucidates the importance of other "rail related delays" being included in the analysis. Network Rail is aware of the inaccuracies in the ADB and has modified the training and documentation associated with recording events causing delay minutes, which was formerly Rail Track standard RT/E/C/18302. The new standard went into full industry use from 30th April 2006.

The aim of this paper is to establish the change in severity of rail buckles and other rail-related delays, caused by the predicted increase in hot days due to climate change for the South East region of the UK, resulting in the following objectives.

- To quantify the impact of current (baseline (BL)) weather on the rail network in the South East, leading to the identification of critical thresholds for buckled rails and rail-related delays

- To apply these thresholds to the rail network under future regional weather scenarios to establish the future impacts of climate change on the network
- To quantify the costs incurred due to an increase or decrease in frequency and/or severity of rail-related incidents, caused by temperature in those regions

Railway track is "designed to withstand a reasonable (temperature) range" [2]. Extremes of temperatures can cause both jointed track and continuously welded rail (CWR) to buckle due to the forces produced by the metal expanding. However, a rail subjected to high temperatures will rarely buckle spontaneously; the disturbance caused by a train is a common contributor, hence, speed restrictions are introduced at certain rail temperature thresholds to reduce the stress on the rail. Table 1 shows the rail temperatures that normal track, in good and bad states of repair, becomes vulnerable to damage and the actions taken to mitigate damage. The "good" and "bad" states of repair represent the extremes of the spectrum; a continuum exists between depending on the track condition. Blanket speed restrictions are also imposed in the UK regardless of when the forecast air temperature exceeds 36 °C The relationship between ambient air temperature and associated rail temperature is roughly defined in equation 1 [8].

$$T_{air} \approx \frac{2}{3} T_{rail} \qquad \textbf{(1)}$$

Track condition	On standby	Impose 30/60mph speed restriction	Impose 20mph speed restriction
Good condition	SFT + 32	SFT + 37	SFT + 42
Inadequate ballast	SFT + 10	SFT + 13	SFT + 15

[SFT = stress free temperature (normally 27 °C in UK)]
Table 1: UK Critical Rail Temperature (CRT) values for standard track in good and poor states of repair [2, 14]

1.4 UK Rail GIS
For the purpose of this study it is necessary to have available a detailed, interactive map of the network in the South East. ArcMap is the most appropriate software for the level of detail required for this project. It is used to build geographical information systems (GIS), which summarise, map and manage spatially referenced data by using layers that show different themes of information. For the purpose of this study features such as the number of lines on a route and critical infrastructure have been mapped. Additionally, a regional weather profile can be mapped; areas that have been exposed to high temperatures (for example) can be highlighted and based on UKCIP data, and the future predicted heat profile of each region can be mapped.

1.5 Structure of the Report
The costs incurred during a recent extreme hot period are summarised in section 2. The impact on rail operations due to high temperatures for existing weather and infrastructure is analysed in section 3. Section 4 demonstrates the impact that more extreme high temperatures could have on the UK's rail network. The information documented in the case study is instrumental in quantifying, costing and verifying the rail-related impacts of climate change, which is discussed in section 5.

2 The 2003 Heat Wave
August 2003 was an exceptional month during an unusually hot summer in Europe and caused a great deal of damage in many sectors of industry and society [1]. For the railways the damage caused was the worst seen since summer 1995, where there were a similar number of buckles, 137 in 2003 and 133 in 1995, compared with the average 30 – 40 per annum

2.1 Cost of the hot summer 2003.
The report on the costs of the hot summer of 2003 [9], calculates an estimate for the additional costs incurred due to the exceptional weather experienced that summer. From the period between 14th May and 18th September 2003 165,000 delay minutes (defined in section 3.1) were considered attributable to heat-related incidents. During the same period in 2004 only 30,000 delay minutes occurred. The summer of 2004 is considered "normal" and the difference between summer 2004 and summer 2003,

i.e. 130,000 excess delay minutes, is largely attributed to the exceptionally hot conditions during August 2003.

The cost of the 130,000 additional delay minutes caused was £2.2 million, which gives an average "price" of £16.70 per delay minute. This figure is based on UK-wide averages used to derive the cost of a delay minute based on train-related delays. It does not include the cost of materials or labour for infrastructure repairs. In addition, the majority of buckles would occur where the temperature is highest, in the SE and London, where the number of passengers would be higher and the distribution of travelling purpose would lean towards workers and commuters, meaning the average cost per minute would probably be significantly more.

3 Impact of existing weather on railway operations

Before the predicted impacts of climate change on weather patterns in the UK can be applied to railway operations, the impact of existing weather on network performance must be reviewed and analysed. Two essential sources of data were used to perform this analysis: Network Rail's alterations database (ADB) and UK Meteorological Office recorded weather data. These have been combined to ascertain the impact that hot days have had on the network. The ADB data available is for the whole of the UK, from 2001 to 2006, inclusive.

3.1 Network Rail's alteration database.

The alterations database (ADB) is a record of all incidents that have caused delay minutes on the railway in the UK. Network Rail runs and maintains the railway infrastructure in the UK and delay minutes incurred due to problems with this infrastructure are their responsibility. Network Rail Delay Minutes are defined as the total number of minutes' delay to passenger and freight trains, where the cause of delay is attributed to Network Rail.

The ADB is a field record of incidents; the incident descriptions are subjective in nature but are also inconsistent due to individual interpretation of a problem. As a result extracting specific causes of delay minutes proved difficult, particularly with regard to buckled rails. This came to light because the number of "buckled" rails recorded in the rail-related delays section of the ADB is significantly less than the number reported in the 'Analysis of the hot summer 2003' report by the Department for Transport (DfT). This suggests that buckles were being recorded under different descriptions, "rail defect" and "cracked rail" are both likely alternatives.

As a result, all causes of delay minutes were analysed from the rail-related delays section of the ADB. This included other rail-related delays that are associated with high temperatures, for example, emergency speed restrictions and events that are not associated with hot weather - broken fish plates for example.

3.2 Met Office Weather Measurements

Observed weather data from the UK Met Office has been used to analyse possible weather-based causes of events resulting in delay minutes. In this case, the interest lies is the maximum daily temperature and the impact on rail-related delays, specifically buckles.

The World Meteorological Organisation has a list of weather stations comprising the regional basic synoptic network (RBSN), which are considered to be regionally representative in the UK. For the South East, the station located at Heathrow airport is considered most representative and the necessary meteorological data was obtained from the British Atmospheric Data Centre (BADC).

To ascertain how high temperatures influence events that cause delay minutes on the railway, the recorded weather data from Heathrow was compared with the content of the rail-related incidents from the ADB. This approach was two fold:

1. Compare all rail "buckles" with the corresponding maximum daily temperature on the day the event was recorded;
2. Compare all rail-related delays with the corresponding maximum daily temperature on the day the incident was recorded.

The methods and results are described in the following sections.

3.3 Analysing "buckles" in the South East and London

The threshold at which a rail may buckle is highly dependant on the condition of the track. Based on table 1 and equation 1, track in good condition would not be expected to buckle until after ~39°C ambient air temperature. However, for track in bad condition the track is at risk at ~25°C. Therefore, inspection of the temperature on days when buckles and rail-related delays have occurred should demonstrate that more severe and higher frequency events should occur when the temperature reaches upward of 25ºC. Figure 1 shows the results of comparing the temperature data from Heathrow and all recorded events labelled "buckles" in the ADB in the SE and London.
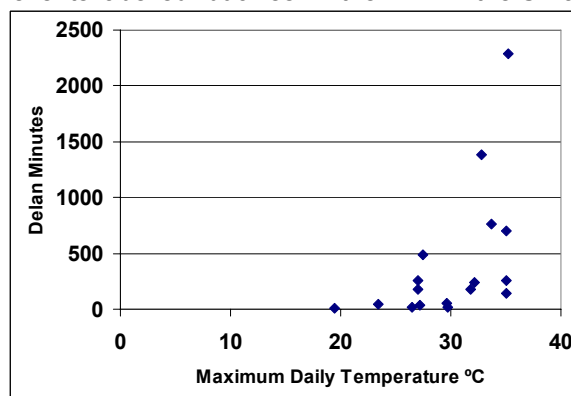

Figure 1: Number of delay minutes attributable to "buckle" events recorded in the ADB for London and the SE and the maximum temperature reached on the day of occurrence.

This indicates that the majority of severe "buckles" occur when the maximum daily temperature is over 27°C, with the severity tending to increase as the daily maximum temperature increases.

3.4 Analysing Rail Related Delays in the South East

Figure 2 shows that there is clearly an increase in the average duration of incidents on days when the maximum daily temperature is 27°C upwards. The 'dips' in average delay minutes at the upper end of the scale 28-30°C, 31-33°C and post 36°C may be due to buckle "harvesting". This is when the critical rail temperature is exceeded for the first time that year and a number of buckles occur. After this point, additional buckles are not expected unless temperatures exceed the previous maximum [3].

There is also an increase in average severity at the lower end; this is most likely due to the impact of cold weather on rail-related delays; damaged rails, frozen points and the like. The temperatures in Figure 2 are maximum daily temperatures, if the maximum temperature on a day is very low there is a likelihood that the minimum temperature would reach below 0°C. This can cause damage such as tension cracks in the rail and points failure, both can result in sizeable delays. These features will be considered in a later phase of the project.
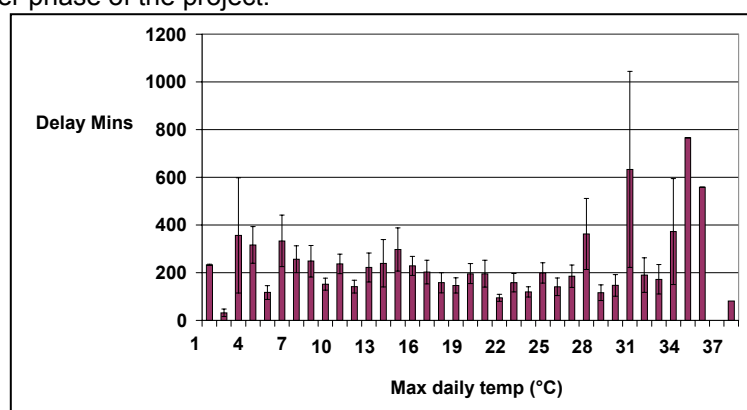

Figure 2: Average delay minutes per day for maximum daily temperatures in the range 1°C to 38°C, showing variability bars for each 1°C interval.

4 Climate Change Predictors
4.1 UK Climate Impacts Programme (UKCIP)

UKCIP co-ordinates research on climate change prediction models in the UK. The models are based on 4 different future emissions scenarios: low; medium-low; medium-high and high. For each of these

scenarios there are future changes predicted for three "time slices": 2011 – 2040 (called the 2020's); 2041 – 2070 (called the 2050's); 2071 – 2100 (called the 2080's). For each time period there are 4 different categories of statistics that have been calculated: changes in annual averages; changes in seasonal averages; changes in monthly averages and changes in the frequency of some extreme events.

4.2 EARWIG: Environment Agency Rainfall and Weather Impacts Generator
EARWIG is a weather generator that uses observed baseline weather and future climate change predictions (from UKCIP) to produce daily weather records, which can then be used to generate probability distributions. There are several advantages to using EARWIG:

1. Absolute expected maximum and minimum values can be produced accurately
2. A probability distribution of annual/monthly/weekly weather can be plotted, allowing the estimated probability of a specific threshold being exceeded to be calculated. In this case the probability of the threshold(s) for buckling being exceeded can be ascertained for baseline and future temperature scenarios. Giving an idea of increase/decrease in frequency and severity.
3. The data sets produced are internally consistent; this means there are fewer discrepancies when comparing the same threshold across different time series or emissions scenarios.

4.3 Calibrating EARWIG with recorded weather data.
To calibrate EARWIG it was necessary to compare real weather data with simulated data, where both data sets come from the same location. Simulated data was produced by EARWIG for the co-ordinates of the Heathrow weather station. Data was gathered from Heathrow weather station, both for the time period 1969-1999 (baseline time slice), the results of comparing the two datasets is shown in Figure 3.
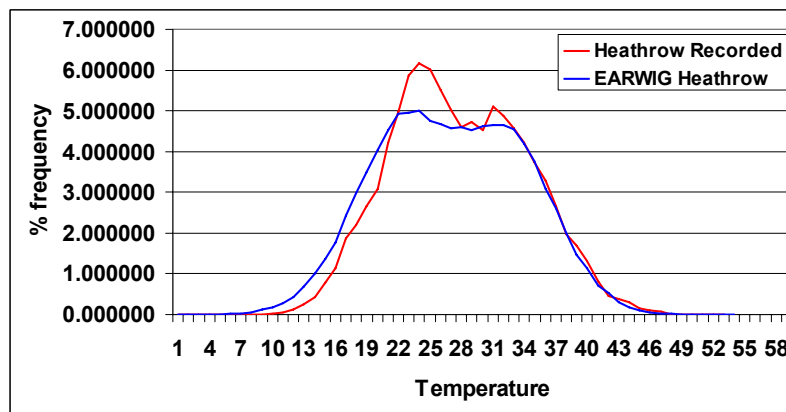

Figure 3: the % frequency that temperatures (in 1°C increments) occur for simulated and actual recorded data at Heathrow, for baseline weather.

The correlation between the two data sets is very good. Particularly for the higher temperatures which is the data of relevance in this paper.

4.4 Future Predictions
EARWIG can be used to simulate weather distributions for baseline weather, all emissions scenarios and all time series. The medium high emissions scenarios will be used in this paper to demonstrate the potential impact of future temperature on buckling and rail-related delays in the UK [10]. Figure 4 shows the predicted distribution of frequency of maximum daily temperature in days per year for the MH emissions scenarios.
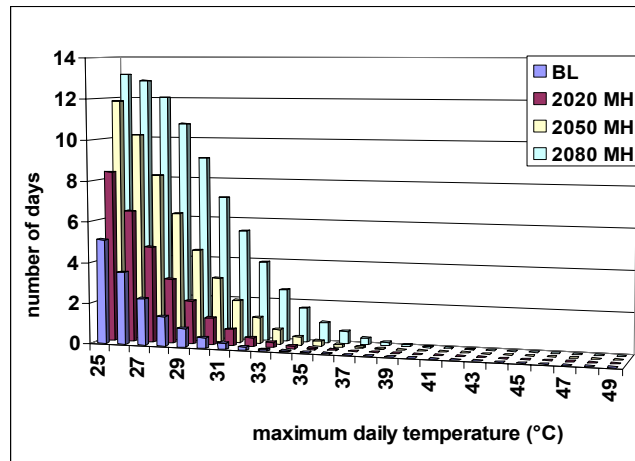
Figure 4: Number of days per year that the maximum daily temperature is predicted to reach each 1°C interval, For MH emission scenario and all time series.

It is evident from figure 4 that climate change is anticipated to cause an increase in the number of days with maximum daily temperature values that can potentially cause serious damage and delay to the railway.

5 Costing Delays

In order to asses the costs incurred due to rail-related delays the following sources of information have been combined:

- Average cost of £16.70 per delay minute, discussed in section 2.1.
- Average number of rail-related/buckling events expected per day in the South East (0.77). (This figure is derived from the total number of rail-related incidents from the ADB, divided by the period of time (in days) from May – October for 2001 – 2006.)
- The average delay duration of an event on a day when the maximum daily temperature reached a certain temperature (see figure 2).
- The number of days expected to reach each maximum daily temperature (see figure 4).

In addition a number of assumptions have been made:

- The average duration of an event on a day when the maximum daily temperature reaches 25°C or above was ascertained from a line of best fit (equation 2) to the data in figure 2. This analysis showed that the gradient of this relationship was 42 ± 18 delay minutes per °C.

$$m = 42t - 923 \qquad \textbf{(2)}$$

Where m is the estimated delay minutes and t is the maximum daily temperature.

- Each predicted time series is 30 years long and each year within the series can be considered to have, on average, the same weather profile until the next time series begins, therefore the impact of the whole duration of the time series will be quantified.
- Temperatures above 25°C can happen as early as May and as late as October, even for baseline data. The temperature profile for each time series will be taken for this 6-month period. Therefore, excluding the 6 coldest months when temperatures are not expected to reach 25°C or above.

The cost of delay minutes caused by high temperatures was calculated using equation 3, which is based on the data and assumptions discussed in previous sections. The results are plotted in figure 5.

$$C = m\,d\,p\,c \qquad \textbf{(3)}$$

Where:
C = total cost for that time series
m = average delay minutes associated with a day of maximum temperature t (from equation 2)
d = the number of days that each maximum temperature is expected to occur in each 30-year time series
p = the probability that a delay minute event will happen on that day = 0.77
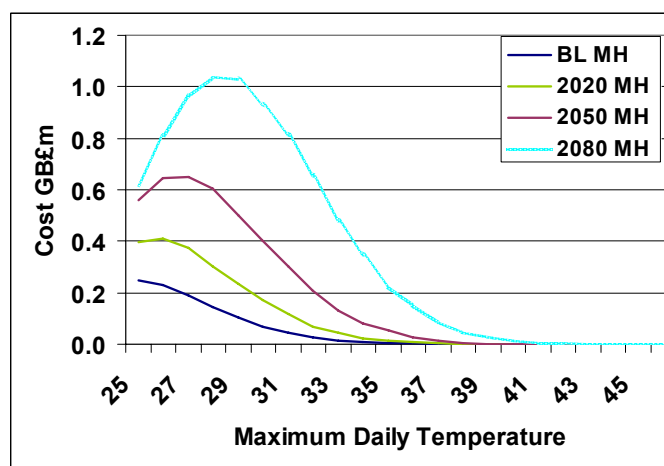
c = average cost of a delay minute (£16.70)

Figure 5: The cost (GB£m) of delay minutes caused on days when the maximum daily temperature is predicted to reach each 1°C interval associated with the medium high emission scenario in each time series.

The cumulative cost of rail-related delays and rail buckles in each time series is shown in table 2.

Time series and cause of delay	BL MH "buckles"	BL MH av delay mins	2020 MH "buckles"	2020 MH av delay mins	2050 MH "buckles"	2050 MH av delay mins	2080 MH "buckles"	2080 MH av delay mins
Cumulative cost GB£m	1.1	1.1	2.3	2.2	4.6	4.2	9.7	8.2

Table 2: The cumulative cost of rail-related delays and buckles occurring on days that have a daily maximum temperature greater than 25°C. Each cost is calculated for all 30 years in each time series.

5.1 Comparing the cost of summer 2004 with the cost of rail-related delays for the baseline time slice

This section aims to validate the costs shown in table 3 by comparing it with the cost of known delays incurred in a normal summer for baseline weather data. In the report, "costs of the hot summer 2003", the damage caused by the extreme heat was compared to a "normal" year; 2004. 30,000 delay minutes were attributed to hot weather this in year between mid May and late September. The cost of these 30,000 delay minutes in 2004 was £0.5m, based on £16.7 per delay minute. If it is assumed that 2004 was a "normal" or "average" year, it can be assumed that 2004 is representative of an average summer for the baseline time series. Multiplying this by the 30 years of baseline data gives £15m as the total cost of heat-related delays nation-wide, the figures calculated in table 2 are for the South East region only. The percentage of UK railway contained in the South East is not known; consequently the national cost is simply split to represent each of the regions, of which there are 11. The result is a cost of £1.4m for temperature-related delay minutes in the South East based on the above assumptions, this compared with £1.1m calculated using the ABD and EARWIG simulated data.

5.2 Discussion of results

The simulated costs shown in table 3 and figure 4 are based on a string of averaged and simulated data. By comparing the cost of the predicted impact of baseline weather in the South East (£1.1m) to the impact of the average summer of 2004 (£1.4m), the difference is not hugely significant. The difference may be attributable to missing heat-related delays that are stored in other sections of the ADB; line-side fires is one example. Also, non heat-related delays have been included in the analysis; these will have lowered the average delay minutes, therefore, reducing the overall cost. The full effect of this can be seen in the variability bars in Figure 2.

In addition the cost associated with travelling in the South East was almost certainly underestimated. Trains in this region are usually full and predominantly carry passengers travelling for work or commuting, making the average cost per passenger train-related delay minute much higher than

£16.7. Also, neither costing includes the price of labour or materials, both would add to the cost heat-related delays

Assuming a linear correlation between the maximum temperature on a day and the average number of delay minutes on that day would be considered a standard approach. However, the frequency of buckling events goes up exponentially as temperature increases [8]. Buckles can cause significant numbers of delay minutes and assuming a line of best fit more in keeping with this theory could produce more realistic figures, particularly in view of the variability shown in figure 2. However, the data collected from the ADB did not support this approach and a linear best fit produces a valid and safe agreement, particularly when extrapolating to asses the impact of such high, unfamiliar temperatures.

Future predicted temperatures are set to have a significant impact on the rail network. Based on the content of table 1, ensuring the track is thoroughly maintained would reduce the vulnerability of the rail during hot weather. It is also going to be important for the UK's rail industry to consider how countries that operate railways in high temperatures manage their infrastructure. For example, re-stressing the rails, either to a higher SFT or having different SFT for winter and summer.

6 Conclusions

Extreme high temperatures are associated with increased incidences of rail buckles; this is clearly demonstrated in figure 1. Climate change is predicted to change the temperature profile in the UK; according to these predictions extreme high temperatures will become a more frequent occurrence. By assessing the number of delay minutes caused on days when the temperature reached the threshold of 25°C or above for baseline temperature data, the impact of future temperature profiles could be determined by extrapolating the known impact of baseline data. This increase was then quantified by assigning a cost per delay minute and applying this to the predicted delays caused in each time slice. The results of the quantification are shown in figure 5 and table 2. To summarise this: increased summer temperatures are predicted to double the cost of heat-induced, rail-related delays and buckles every 30 years from baseline weather to the 2080's time slice.

The temperature at which buckles can occur is significantly reduced by poor levels of track maintenance. Based on the results of this research it has been recommended that the UK's rail industry considers a new maintenance regime in order to alleviate the impacts of high temperatures. Another approach would be to change the SFT of CWR in the UK, to either a higher SFT or to have a winter and summer SFT.

7 Acknowledgements

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