

Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east United Kingdom[†]

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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 United Kingdom with extreme high temperatures becoming an increasingly frequent occurrence. The result is that the number of buckles, and therefore delays, expected *per* year will increase if the track is maintained to the current standard. This paper uses a combination of analogue techniques and a weather generator to quantify the increase in the number of buckles and rail related delays in the south-east of the United Kingdom. The paper concludes by assigning a cost to the resultant rise in delays and damage before making recommendations on how these effects can be mitigated. Copyright © 2008 Royal Meteorological Society

KEY WORDS railway; buckle; climate change; delay minutes

Received 3 July 2008; Revised 22 September 2008; Accepted 8 October 2008

1. Introduction

Although the rail network is a robust infrastructure (Eddowes *et al.*, 2003) and weather conditions in the United Kingdom are rarely as extreme as in other countries, smooth operations can still be affected by even minor weather-related influences. It is estimated that present-day adverse weather conditions cause 20% of all unplanned delays on the UK rail network (Thornes and Davis, 2002). Delays are measured in ‘delay minutes’ which are defined as the total number of minutes delay to passenger and freight trains (when compared to the timetable), where the cause of delay is directly attributable to Network Rail (Network Rail, 2008). Thornes and Davis (2002) estimate that the weather is the cause of 5 million delay minutes *per* year. Network Rail reported around 3 million weather related delay minutes in 2007 (Network Rail, 2007). The difference in the two sources can be attributed to Thornes and Davis’ estimate including delays indirectly caused by weather. Hence, it is important to be able to anticipate impacts and cope with them for the safe and efficient running of the service.

There is a growing consensus that over the next century, the climate of the United Kingdom is going to undergo significant change. Winters will become milder and wetter, whereas summers will be hotter and drier

(Hulme *et al.*, 2002). Furthermore, it is anticipated that there will be a general trend towards more extreme weather (Hulme *et al.*, 2002). These weather extremes have the potential to cause increased problems on the rail network. The result is that weather related problems (e.g. buckling, flooding due to inadequate drainage, sudden earthworks failure, scour at the base of bridges and damage to overhead wires; Eddowes *et al.*, 2003) will occur with increasing frequency on the network. The scope of the present paper is to consider the potential effect of climate change on increased incidences of rail buckles and other rail-related damage caused by extreme high temperatures. The area of study chosen for this research is the south-east region of the United Kingdom. The rationale for this is that the south-east is already the region exposed to the highest temperatures in the United Kingdom and so will show the worst-case scenario of climate change.

2. Baseline railway buckling in the United Kingdom

Before the predicted impacts of climate change on weather patterns in the United Kingdom can be applied to railway operations, the impact of existing weather on network performance must be reviewed and analysed. This section outlines a background to railway buckling followed by an analysis of the Network Rail Alterations Database where all buckles and other heat related defects are recorded.

2.1. Background

A buckle is defined as any track misalignment serious enough to cause a derailment (ORR, 2008). Although

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[†] This paper was published online on 19 November 2008. Some errors were subsequently identified. This notice is included in the print and online versions to indicate that both have been corrected, 5 December 2008.

railway track is pre-stressed to withstand a reasonable temperature range (Chapman *et al.*, 2006, 2008), extremes of temperatures can cause both jointed track and continuously welded rail to buckle due to the forces produced by the metal expanding. However, a rail subjected to high temperatures will rarely buckle spontaneously. Instead, it is the disturbance caused by a train that is a common contributor. To overcome this, speed restrictions are introduced at certain rail temperature thresholds to reduce the stress on the rail and therefore reduce the risk of a derailment (Table I). A further threshold exists in the United Kingdom at an air temperature of 36°C where blanket speed restrictions are imposed regardless of rail temperature. A general rule of thumb is used in the industry to convert between air and rail temperatures (Hunt, 1994):

$$T_{\text{air}} \approx \frac{2}{3} T_{\text{rail}} \quad (1)$$

where T_{air} and T_{rail} are the temperatures (°C) of the air and the rail, respectively.

2.2. Network Rail alteration database

The alterations database (ADB) is a record of all incidents that have caused delay minutes on the railway in the United Kingdom. Network Rail runs and maintains the railway infrastructure in the United Kingdom and delay minutes incurred due to problems with this infrastructure are their responsibility. The ADB is ultimately a field record of incidents. Often the incident descriptions are subjective in nature but are also inconsistent due to an individual's interpretation of a problem. As a result, extracting specific causes of delay minutes can prove difficult, particularly with regard to buckled rails. This became evident during this research when it was discovered that the number of buckled rails recorded in the rail-related delays section of the ADB is significantly less than the number reported by Hunt *et al.* (2006) for the same period. Upon inspection it appeared that buckles were also being recorded under different descriptions in the ADB. Terms such as 'rail defect' and 'cracked rail' were both likely alternatives and are a consequence of the subjective definition of a railway buckle (e.g.

ORR, 2008). For this reason it was decided also to analyse the 'rail related delays' section of the ADB as a more complete record of heat related incidents. However, there is a danger that this will include emergency speed restrictions and events that are not associated with hot weather such as broken fishplates (metal plates used to bolt two rails together in jointed track). Network Rail is aware of the inaccuracies in the ADB and has modified the training and documentation associated with recording events causing delay minutes (formerly Rail Track standard RT/E/C/18302). The new standard went in to full industry use from 30 April 2006.

2.3. Relationship between maximum temperatures and rail-related delays

Observed weather data from the UK Met Office were used to analyse possible weather-based delays recorded in the ADB (although this study is focussed on 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. For the south-east, the station located at Heathrow airport is considered most representative and was the weather station used for this analysis. Therefore, to ascertain how high temperatures influence events that cause delay minutes on the railway, the recorded weather data (i.e. the maximum temperature on the day of the incident) from Heathrow were compared with the content of the rail-related incidents from the ADB. Two separate analyses were conducted for the south-east region, firstly for buckles (Figure 1) and secondly for all rail-related delays, including buckles (Figure 2).

The threshold at which a rail may buckle is highly dependent on the condition of the track. Based on Table I and Equation (1), track in good condition would not be expected to buckle until ~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 25°C. This is clearly evident in Figure 1 which shows 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. Similarly, Figure 2 shows that there is clearly an increase in the average number of delay minutes on days when the maximum daily temperature exceeds 27°C. An interesting feature shown in Figure 2 is a clear decline in the number of reported incidents in the temperature ranges 28–30°C, 31–33°C and post 36°C. This is attributed to buckle harvesting. This occurs 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 (Chapman *et al.*, 2006). An additional increase in delays can also be noted

Table I. UK Critical Rail Temperature (CRT) values for standard track in good and poor states of repair (Ventry, 2002; Chapman *et al.*, 2008). Two extreme cases are provided, but a continuum exists between the illustrated examples.

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

SFT, stress free temperature is the temperature at which track is laid and is normally 27°C in United Kingdom.

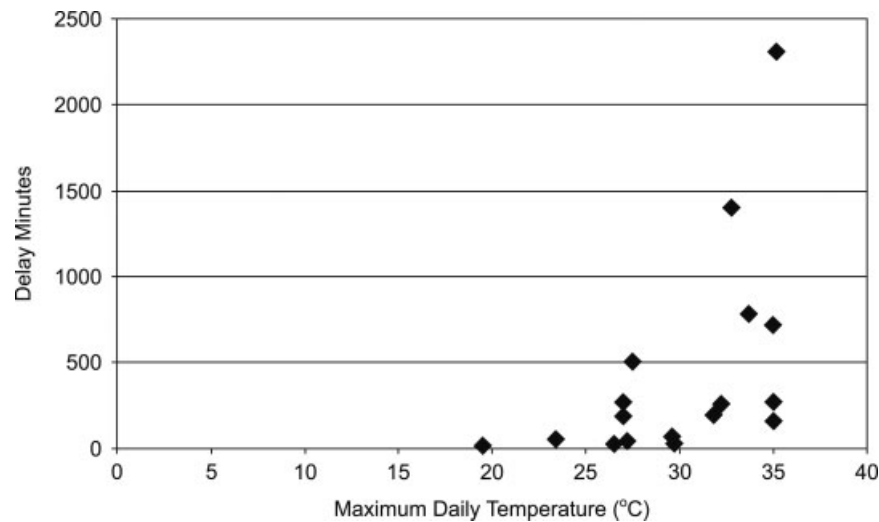


Figure 1. Number of delay minutes attributable to 'buckle' events recorded in the ADB for London and the south-east and the maximum temperature reached on the day of occurrence. [Correction made here after initial publication.]

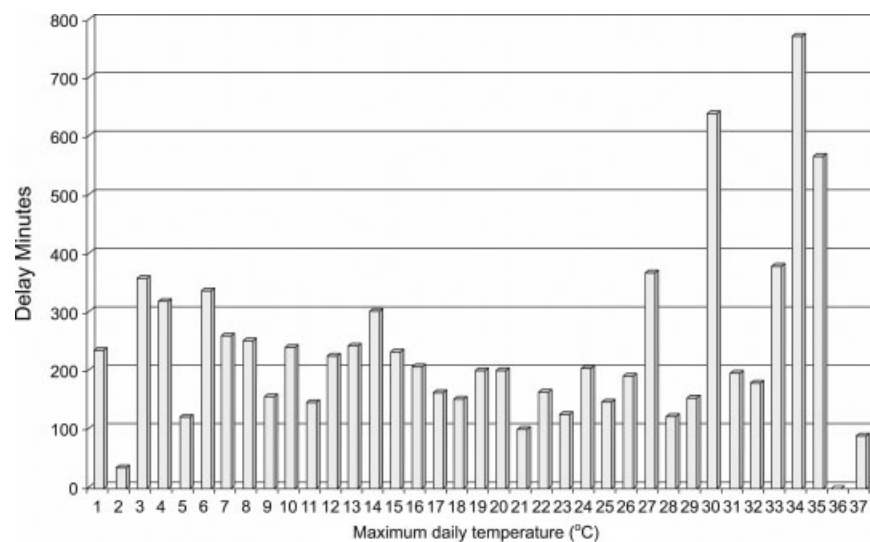


Figure 2. Average delay minutes *per day* for maximum daily temperatures in the range 1–37°C.

at lower temperatures. Cold weather poses an alternative set of problems for the rail network such as frozen points, and damaged rails due to tension cracking (the opposite of buckling where the rail contracts).

3. Weather analogues: the 2003 heatwave

The use of analogues (e.g. Feenstra *et al.*, 1998) can provide a useful starting point to study the impact of climate change on the railway network. The aim of this methodology is to find an occasion in the past which could be considered representative of the 'normal' situation to be faced in the future. One recent event which stands out as an analogue for future climate change is the heatwave experienced during the summer of 2003. August 2003 was an exceptionally hot month in Europe and caused a great deal of damage in many sectors of industry and society (Burt, 2004). This extreme weather

can clearly be detected in the ADB where 137 railway buckles were reported compared to the long-term average of 30–40 *per annum*.

Hunt *et al.* (2006) provide an estimate for the additional costs incurred due to the exceptional weather experienced that summer. From the period between 14 May and 18 September 2003, 165 000 delay minutes were considered attributable to heat-related incidents. This figure is significantly higher than for the summer of 2004 which is considered 'normal' with only 30 000 delay minutes recorded. The difference between the 2 years is largely attributed to the exceptionally hot conditions during August 2003. The cost of the 130 000 additional delay minutes was estimated to be in the region of £2.2 million, which gives an average outlay of £16.70 *per* delay minute. However, this figure is conservative. It 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; i.e. in the south-east of the United Kingdom (including London). Here, the number of passengers would be considerably higher than the UK average and the majority of travellers would be commuters. Ultimately, the average cost *per* minute would be markedly more, possibly double if not treble the quoted figure.

An analysis of the cost of weather related seasonal delays performed by Rail Safety and Standards Board used a notional value of £50 *per* delay (Eddowes *et al.*, 2003). The evident limitations of deriving a cost based solely on average train and passenger profiles indicates that using the value of £50 cost *per* delay minute will produce more realistic costing.

Overall, the 2003 analogue provides a useful case study into how climate change may affect the railway network. Indeed, by considering recent projections, the summer of 2003 may be considered 'normal' by 2050. Such estimates can be provided by weather generators based upon UK Climate Impacts Programme (UKCIP) data (e.g. Kilsby *et al.*, 2007). However, they also provide the opportunity to model the situation in much more detail.

4. Modelling the impact of climate change

UK Climate Impacts Programme (UKCIP) co-ordinates research on climate change prediction models in the United Kingdom. The models are based on four different future CO₂ emissions scenarios: low; medium-low; medium-high and high. These scenarios are derived from 'storylines' based on key drivers of emissions from the Intergovernmental Panel on Climate Change (IPCC). For each of these scenarios there are future changes predicted for three time slices: 2011–2040 (called the 2020s); 2041–2070 (called the 2050s); 2071–2100 (called the 2080s). For the total duration of these time slices the cumulative carbon emissions for each scenario are: high –2189 GtC; medium-high –1862 GtC; medium low –1164 GtC; low –983 GtC (GtC = gigatonnes of carbon, where 1 tonne of carbon yields 3.67 tonnes of CO₂). For each period there are four 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.

4.1. Environment Agency Rainfall and Weather Impacts Generator (EARWIG)

Weather generators produce an unlimited time series of stochastic weather data based on the baseline climate measured at a set location (Hutchinson, 1987). Their main application has been in climate impact assessments, however more recent work has seen them used to develop climate change scenarios (e.g. Semenov and Barrow, 1997). EARWIG (Environment Agency Rainfall and

Weather Impacts Generator) is a weather generator that uses observed baseline weather as well as the future climate change predictions (from UKCIP02) to produce daily weather records, which can then be used to generate probability distributions. Weather series are produced at a daily time resolution, based on two stochastic models, firstly rainfall (*via* a Markov chain) and secondly other climate variables dependent on rainfall. A full description of EARWIG is available in Kilsby *et al.* (2007) and therefore will not be provided here.

For climate change studies of this nature there are several advantages to using a weather generator. Firstly, a probability distribution of annual/monthly/weekly weather can be determined, allowing the estimated probability of a specific temperature threshold being exceeded to be readily calculated. Secondly, the data sets produced are internally consistent; this means that there are fewer discrepancies when comparing the same threshold across different time series or baseline/emissions scenarios. Although EARWIG was developed for agricultural and water systems management, it should have the potential to be used for other climate change impact assessments (Kilsby *et al.*, 2007). As this has not been tested, a quick comparison study was conducted to compare the baseline data of Heathrow (1961–1990) with an EARWIG ensemble run for the same period (Figure 3). The correlation between the two data sets is acceptable with an R^2 value of 0.96. The temperature distributions are particularly similar for the higher extremes of temperature with an R^2 value of 0.997 for temperatures greater than 21 °C, which are the data of relevance in this paper.

4.2. Results

EARWIG can be used to simulate weather distributions for baseline weather, all emissions scenarios and all time series. However, in the interests of conciseness, just 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 United Kingdom (IPCC, 2000). Figure 4 shows the generated distribution of frequency of maximum daily temperature in days *per* year for the medium high emissions scenarios.

4.3. Costs to the railway network

As expected, 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 delays to the railway (Figure 4). What is now pertinent is to consider the potential future cost of these weather related delays. In order to assess the future costs incurred due to buckling the following sources of information have been combined:

1. average cost of £50 *per* delay minute as derived in 3;
2. average number of rail-related/buckling events expected *per* day in the south-east (0.77). (This figure

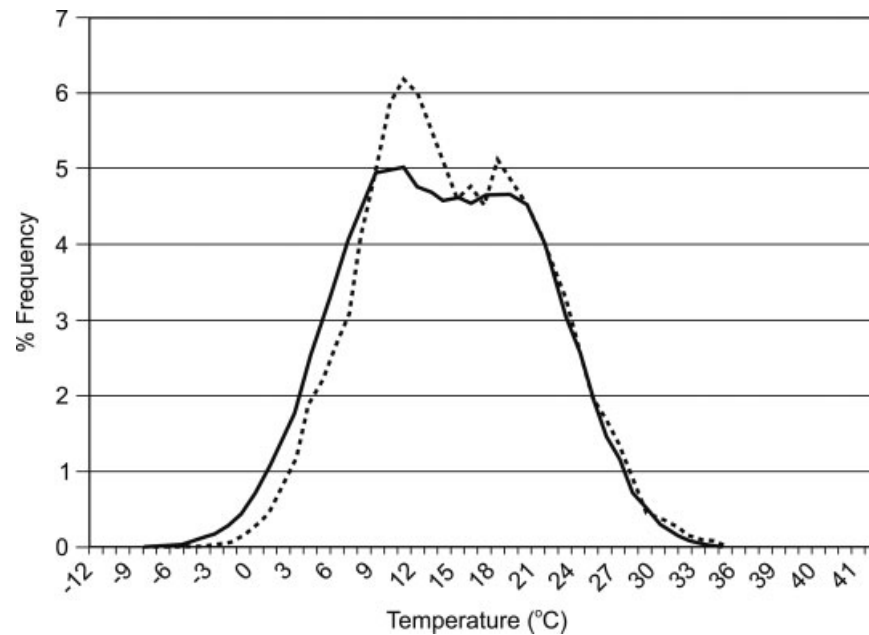


Figure 3. Percentage frequency that temperatures (in 1°C increments) occur for EARWIG simulated and actual recorded data at Heathrow, for baseline weather. - - - Heathrow Recorded; — EARWIG Heathrow. [Correction made here after initial publication.]

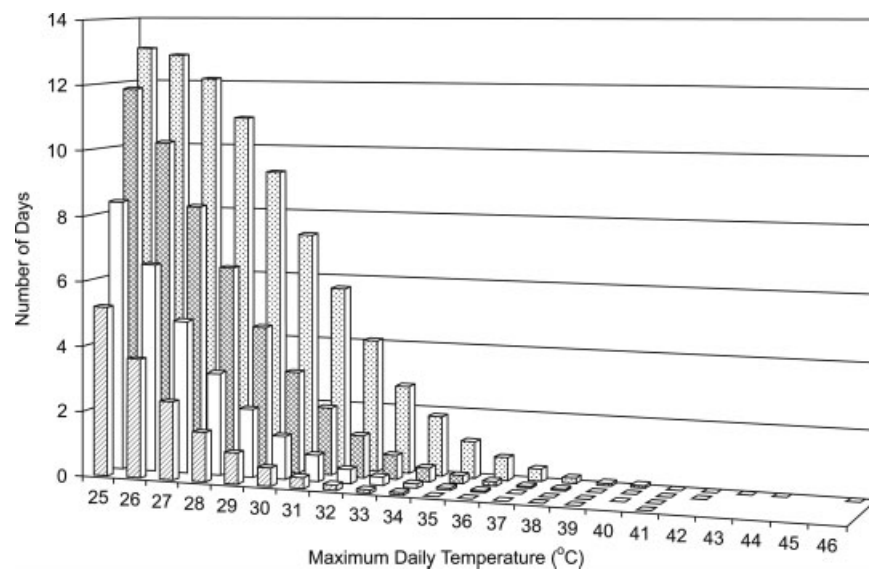


Figure 4. Number of days *per* year that the maximum daily temperature is predicted to reach each 1°C interval. Assumes the medium high emission scenario and all time series. ▨ 2080 MH; ▩ 2050 MH; □ 2020 MH; ▤ BL. [Correction made here after initial publication.]

is derived from the total number of rail-related incidents from the ADB, divided by the period of time (in days) from May to October for 2001–2006.);

- the average delay duration of an event on a day when the maximum daily temperature reached a certain temperature (Figure 2);
- the number of days expected to reach each maximum daily temperature (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 from

Equation (2) to the data in Figure 2:

$$m = 42t - 923 \quad (2)$$

where m is the estimated delay minutes and t is the maximum daily temperature. A linear relationship was chosen over the standard exponential relationship between temperature and buckling frequency (Hunt, 1994) to provide a more conservative estimate when dealing with high, unfamiliar, temperatures;

- each predicted time series is for 30 years 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;

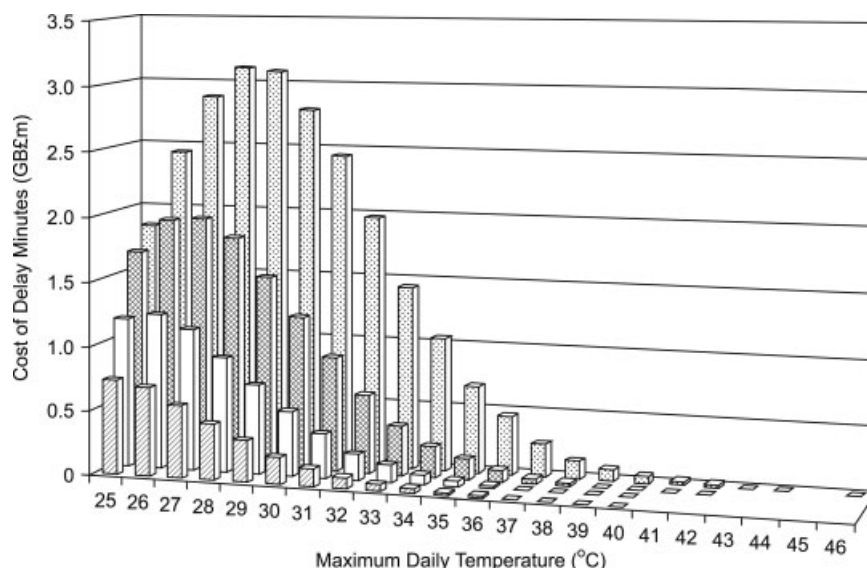


Figure 5. The cost (GBPm) of delay minutes caused on days when the maximum daily temperature is predicted to reach each 1 °C interval associated with the medium high emission scenario in each time series. [Correction made here after initial publication.]

3. temperatures above 25 °C will only occur between May and October. The temperature profile for each time series will be taken for these 6 months.

Based upon these assumptions, the cost of delay minutes caused by high temperatures are calculated using Equation (3). The results are plotted in Figure 5, whereas the cumulative cost of rail-related delays and rail buckles in each time series is shown in Table II.

$$C = m d p c \quad (3)$$

where, C is the total cost for that time series, m is the average delay minutes associated with a day of maximum temperature t (from Equation (2)), d is the number of days that each maximum temperature is expected to occur in each 30-year time series, p is the probability that a delay minute event will happen on that day = 0.77 and c is the average cost of a delay minute (£50)

To provide baseline costs for buckling, 2004 was again used as a 'normal' year (Hunt *et al.*, 2006). In 2004,

Table II. 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.

Time series	Cause of delay	Cost (GBPm)
Baseline (medium high)	Buckles	3.3
	Delay minutes	3.3
2020 (medium high)	Buckles	6.7
	Delay minutes	6.5
2050 (medium high)	Buckles	13.6
	Delay minutes	12.5
2080 (medium high)	Buckles	29.0
	Delay minutes	24.7

30 000 delay minutes were attributed to hot weather which translates to a total cost of £1.5 million pounds (based on £50 *per* delay minute). Multiplying this by the 30 years of baseline data gives £45 m as the total cost of heat-related delays nationwide. It can be assumed that much of this cost will be centred on the south-east of the United Kingdom as this is not only the most prone section to extreme temperatures, it also contains the densest section of the railway network. The exact 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 £4.1 m for temperature-related delay minutes in the south-east based on the above assumptions, this compared with £3.3 m calculated using the ABD and EARWIG simulated data.

5. Discussion and conclusions

The simulated costs shown in Table II and Figure 4 are based upon the averaged and simulated data. The cost of the predicted impact of baseline weather on a 'normal' year in the south-east (£3.3 m) is comparable to the impact of the average summer of 2004 (£4.1 m). 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.

In addition the cost associated with travelling in the south-east was almost certainly underestimated, despite using £50 as the estimate for the cost of a delay minute. Lines in this region are run close to capacity, trains are usually full and predominantly carry passengers travelling to work, making the average cost *per* passenger train-related delay minute potentially much higher than £50.

Overall, higher temperatures due to climate change are set to have a significant impact on the rail network. However, there are solutions available to make the railway network more resilient. First and foremost, ensuring the track is thoroughly maintained would reduce the vulnerability of the rail during hot weather (Table I). Furthermore, the UK rail industry will need to look at warmer climates overseas to consider how countries that operate railways in higher temperatures manage their infrastructure. For example, there may be a need to raise the stress-free temperature currently used in the United Kingdom or even to consider the approach of a seasonal re-stressing the rails for winter and summer. In summary, a change in engineering practices and regimes will be essential if the climate of the UK changes as predicted

Acknowledgements

The authors would like to acknowledge the continued support of Network Rail and Arup whose backing is invaluable to sustain this research. All climate data were made available to the project *via* the British Atmospheric Data Centre (BADC).

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