

The future cost to the United Kingdom's railway network of heat-related delays and buckles caused by the predicted increase in high summer temperatures owing to climate change

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Abstract: Climate change predictions suggest a trend towards hotter drier summers in the UK. At extreme high temperatures the railway network is prone to dangerous, damaging, and expensive rail buckles. In order to reduce the risk of a rail buckle, emergency speed restrictions are introduced which can be costly. This article presents a quantification of the effects of higher summer temperatures due to climate change on the UK railway network. A combination of analogue techniques and a weather generator are used to establish trends between heat-related delays and temperatures. Costs are assigned to the change in frequency and severity of delays and evidence-based recommendations are made for future operations. The results demonstrate that the costs incurred as a result of the hot summer of 2003 will become typical in the 2050s (high emissions scenario) and 2080s (low emissions scenario). If no changes are made to maintenance regimes, it is estimated that the total costs of heat-related delays will eventually double to nearly £23 M during extreme summers.

Keywords: climate change, delay minutes, railway, buckle

1 INTRODUCTION

Extreme weather conditions and the operability of many modes of transport can be infamously incompatible. Railways are a robust form of transport [1]; however, a range of extreme and sometimes even minor weather conditions can affect operations [2]. In the UK, a delay that is related to a failure of the infrastructure is attributable to Network Rail and is known as a 'delay minute'. Approximately 20 per cent (circa. 5 million) unplanned delay minutes per year are related to weather [3].

Climate change is predicted to significantly alter weather conditions in the UK; summers will become hotter and drier and winters will become warmer and wetter. Furthermore, extreme events such as heat-waves and winter storms may also become more

prevalent [4]. It has been shown that higher summer temperatures due to climate change will significantly increase the cost of heat-related delays in the south-east of the UK [5]. Although London and the south-east are frequently highlighted as being the UK region most prone to increased heat, it is assumed that similar, although less extreme temperature changes will occur across the rest of the country [4]. The aim of this article is to extend the work presented in Dobney *et al.* [5] by refining the methodology and presenting results for a UK-wide study on the effects that hotter summers may have on railway network operations.

1.1 The nature of heat-related delays in the UK

The railway in the UK is a vital transport network with many lines heavily used and approaching full capacity. These demands, and associated difficulty of access, can leave the network under-maintained and prone to problems. Heat-related delays in the UK can be caused by a number of infrastructure failures triggered as a result of high ambient temperatures. For example,

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diesel engines can overheat, as can electrical line-side equipment such as points and signals. Line-side fires are an additional hazard during prolonged periods of drought. However, a major impact of high rail temperatures is the railway buckle. A rail buckle is defined by Ellis [6] for the Rail Accident and Investigation Branch (RAIB) as 'a sudden, short and un-designed bend in the track caused by a lack of lateral resistance, poor track maintenance and (generally) high rail temperatures. They have the potential to derail a train'. Extremely hot temperatures cause the metal of the rail to expand, resulting in a deformation of the track due to high compressive forces. Although continuous welded rail (now standard across the UK) is pre-stressed to withstand a reasonable temperature range based on the UK climate, if the temperature is extremely high, the track incorrectly stressed, or just in poor condition (Table 1), then buckles are more likely to occur. However, a rail will rarely buckle spontaneously; an additional energy input being required and is usually from a passing train. It is for this reason that emergency speed restrictions are enforced on days where there is a risk of rails buckling. Although the result is significant delays on the network, a delay is considered to be a better option than a buckled rail, certainly from a safety perspective.

The threshold values shown in Table 1 can be converted to air temperatures using a 'rule of thumb' formula between rail temperature and ambient air temperature, such as is shown in equation (1) [7], where both temperatures are measured in degrees centigrade (°C)

$$\text{Trail} \approx \frac{3}{2} \text{Tair} \quad (1)$$

Hence, well-maintained track should theoretically not be considered vulnerable to a buckling incident until ~39 °C and upwards (ambient air temperature); a temperature so far unrecorded in the UK [8, 9]. However, as buckles are a frequent summer occurrence in the UK, it can be assumed that large sections of the UK railway network are either incorrectly stressed or in need of maintenance.

Table 1 UK critical rail temperature values (relating to the rail temperature (Trail) see equation (1)) for standard track in good and poor states of repair [2, 10]. Two extreme cases are provided, but a continuum exists between the illustrated examples

Track condition	On standby	Impose 30/60 mile/h speed restriction	Impose 20 mile/h 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 the temperature where no thermal forces are acting upon the rail. In the UK, it is normally 27 °C.

All heat-related delays are recorded in the Network Rail alterations database (ADB), which is discussed in detail in section 2.1. The ADB is essentially a field record of incidents. It includes: the date the incident was discovered as well as the cause/nature of the incident along with a start and end location along the line the incident occurred on. To establish the impact that baseline climate has on heat-related delays in the south-east UK, Dobney *et al.* [5] linked the ADB with observed weather data from London Heathrow weather station. Heathrow is considered the most representative station for the south-east from the World Meteorological Organization's (WMO) list of weather stations, comprising the regional basic synoptic network.

Dobney *et al.* [5] showed that buckling can occur in the south-east region of the UK within the temperature range of 18.7–35.2 °C with more severe buckles occurring at temperatures >25 °C and the most severe at >30 °C [5]. In an average baseline year, these heat-related delays cost £4.84 m (based on £73.47 per delay minute [11]), compared with £6.0 m estimated from the findings of Hunt *et al.* [12]. Based on the simulated weather data for the UKCIP02 medium high emissions scenario, it was estimated that the predicted cost of delay minutes caused by buckled rails and heat-related delays would double every 30 years. This suggests a need for changes in stressing, track, and ballast maintenance regimes to improve track condition in order for the frequency and severity of future rail buckles to be at an acceptable level.

1.2 Track structure and the role of ballast

The nature of long metal rails is that in varying temperatures they expand and contract, hot weather causes the rail to expand creating a high compressive force which can cause the rail to buckle. In continuous welded rail (CWR) the effects of heat-induced expansion is combated by stretching and extending the running rail at the time of installation. It is fixed at a set tension that relates to a stress-free temperature (SFT) of 27 °C [13]. However, if the temperature is consistently very hot then the rail can be vulnerable to buckling, particularly if the track is inadequately supported by the infrastructure (see Table 1).

The track, ballast, and substructure provide a means for safe and stable transit for rolling stock. The quality of the ride and the propensity for the track to buckle are reliant on the support offered by the running rail, the sleepers, the ballast, and the underlying geology. Well-constructed ballast supports the track longitudinally to maintain the pre-stressed rail and laterally, which supports against the heat-related expansion that causes buckles. Vibrations and movement of a passing train are absorbed into the track foundation and surrounding earth, this can lead to pumping of

sub-soil into the ballast, which reduced the adhesion between the ballast particles.

Ballast degrades as the rough, angular surfaces become worn at the contact points through the constant loading and unloading from passing trains. As contact points become less stable the ballast settles from the vibrations caused by passing rolling stock; these processes reduce the stability and support offered by the ballast. Maintenance of ballast comes in two main forms: tamping and stone blowing. Tamping is a process where the track is lifted up, the ballast stones are shuffled round, and the track re-laid. This reforms more stable bonds between rough edges of the ballast stones; however, tamping should not be performed when the track may be exposed to heat in the near future. It takes time for the ballast to form a cohesive mass again; if the ballast is not stable enough buckles can occur. Stone blowing adds fresh ballast in order to renew and strengthen the contact between the ballast pieces. Pandrol clips that fasten the running rail to the sleepers are also important in preventing the rail from buckling; if the support is inadequate the running rail can buckle off the sleepers.

2 DATA ACQUISITION

Dobney *et al.* [5] made future predictions for the Network Rail defined south-east region; this work

was extended to include other Network Rail regions. This was initially based on the EU regions (Fig. 1(a)), which is the template for the Network Rail areas; however, after a preliminary investigation of the data available from the ADB, it was discovered that there was insufficient raw data to support valid statistical trends in all areas. Hence, it was decided to merge regions based on a similar climate, geographical location, and strength of data. Upon inspection, the best approach was to split the UK into four regions; these are shown in Fig. 1(b).

2.1 The alterations database

The ADB is a field record of incidents causing delays that occur on the railway network. Delays are recorded in different sections depending on the nature of the delay, categories like 'flooding', 'snow/ice', and 'earth-slip', although the system for recording incidents was updated in 2007. In Dobney *et al.* [5] only the rail-related delays section (including buckles) of the ADB was available to analyse the impact of heat due to baseline weather. The ADB does not include details of how specific incidents are discovered; in general faults can be discovered through both manual and automated techniques. Buckles are defined as 'a bend in the track' that 'have the potential to derail a train' [6] and are obvious enough to usually be manually detected and assessed. Track misalignments may cause a 'rough

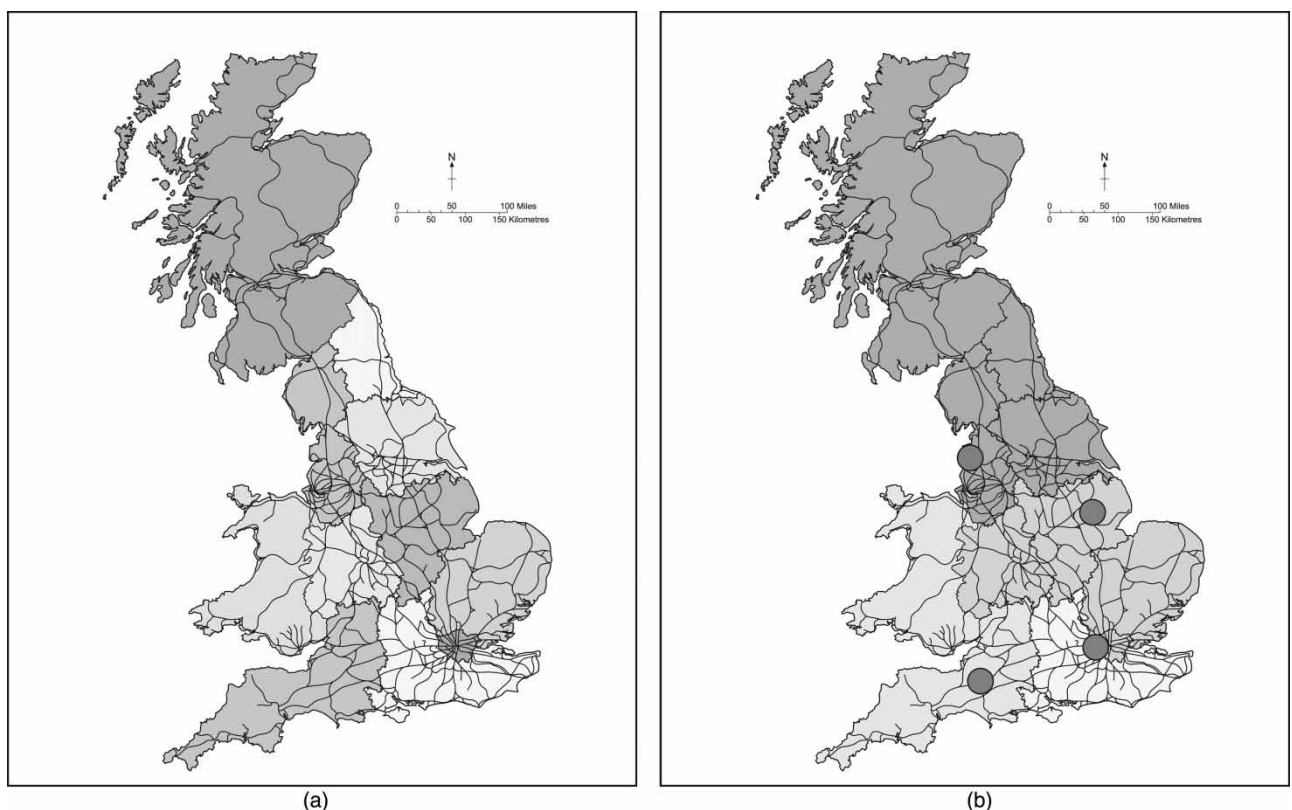


Fig. 1 (a) Map of the UK divided into the EU-defined regions. (b) Map of the UK divided into combined EU regions, with corresponding weather stations

ride' that is often reported by vehicle drivers. However, it is apparent that the RAIB [6] definition of a buckled rail is open to personal interpretation by the staff responsible for logging the incident in the field. This assessment was corroborated by a poor correlation of reported buckling incidents between the ADB and Hunt *et al.* [12]. Consequently in Dobney *et al.* [5] all incidents in the 'rail-related delays' section of the ADB were included in the subsequent analysis for baseline heat-related delays.

In this article additional sections of the ADB were analysed, which allowed for incidents that were specifically heat related to be investigated. The sections of the ADB available for this article were 'rail-related delays' (broken, cracked, twisted, buckled, and flawed rail) and 'weather' (severe weather affecting infrastructure, including heat, snow rain, ice, etc.). Furthermore, the analysis was also restricted to the months of May to September (inclusive). However, the addition of the weather-related delays section of the ADB did not change the discrepancy in the number of buckles between the ADB in Dobney *et al.* [5] and those reported by Hunt *et al.* [12]. It was suggested by Dobney *et al.* [5] that buckles were being recorded under descriptions such as broken or cracked rail; however, there was insufficient evidence to prove this was solely a heat-related problem, so no descriptions of failures of this nature were included in this study.

2.2 Baseline weather data

Baseline weather data were sourced from a list of regionally representative weather stations from the

WMO and accessed via the British Atmospheric Data Centre. One weather station was selected for each combined region, based on the strength of correlation with the other EU regional weather stations and a centralized geographical location in the combined region. One exception to this is the north region, which is much larger than other regions. In order to best represent the region, the station is located centrally in terms of the main centres and intercity lines, which tend to be more southerly (relative to the Highlands of Scotland). Trends were then derived between the baseline weather and the ADB.

3 METHODOLOGY: BASELINE CLIMATE

In order to analyse all heat-related delays (including buckles), a filter was applied to the ADB to extract delays described under the terms 'buckles', 'heat', and 'temperature'. These were then grouped into 1 °C intervals based on the date of the incident and the corresponding maximum daily temperature from the representative weather station. The maximum, minimum, mean, and standard deviation (SD) were then calculated for the data in each 1 °C interval. On initial inspection it was apparent that the mean and SD were skewed by a high number of very minor incidents. Relating back to the ADB it was considered that these very minor delays were unreliable; for all regions there were a significant number of delays causing zero minutes and repetitions of minor delays was also common. To reduce the effect of this skew, any incidents from the raw data that fell below the intercept of the minimum trend line were eliminated from the analysis. Figure 2

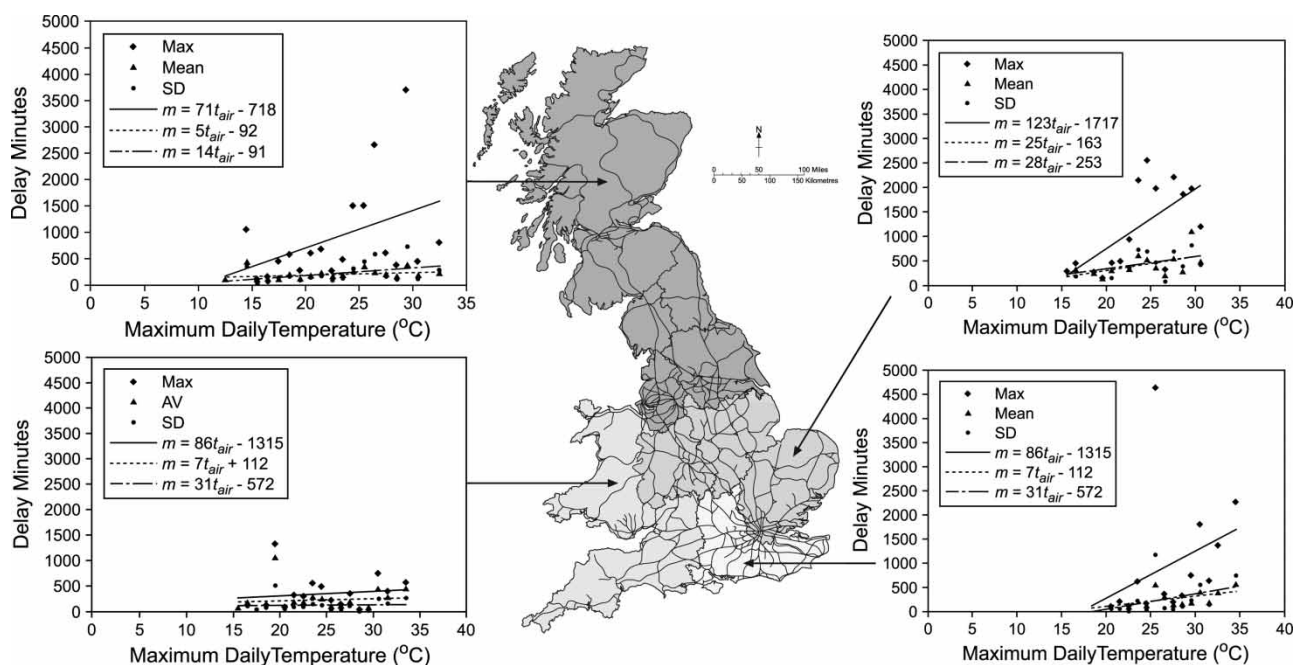


Fig. 2 Maximum, mean, and SD trends in delay minutes of all heat-related incidents from the ADB against the maximum daily temperature on the date of discovery for all regions

shows the trend lines for the maximum, mean, and SD for all regions after removing the minimum values.

3.1 Reliability of trends

Table 2 shows the R^2 and p -value data for the gradient of all trend lines for each region. The initial analysis shows that the relationship is only significant in the Midlands region at the 95 per cent level. However, in all regions the removal of one or two data points that were clear outliers immediately improved the significance of the trends, leaving the majority of relationships significant at the 95 per cent level and all within 80 per cent. However, it was decided to leave all the data in the analysis as there is no justification for the removal of any data points based on the available data in the ADB. These apparent outliers can be explained through considering both the nature of the railway network and the limitations of the available data for this study. For example, one important factor pertaining to the severity of an incident (in delay minutes) is the location on the network. For example, a buckle in the south region that caused over 4000 delay minutes at $\sim 26^\circ\text{C}$ happened between Waterloo and Clapham Junction in Central London. This demonstrates that a severe rail buckle that occurs on one of the busiest lines in the country on a week day will have an enormous impact when compared with a similar buckle on an infrequently used line.

There is also a clear example of a lack of data availability in the northern region where there are a series of heat-related emergency speed restrictions occurring at $\sim 15^\circ\text{C}$. These all have quite high delay minutes associated with them (~ 500 – 1000). It is likely that these are not heat-related delays but are being misreported in the ADB. Alternatively, the damage may be heat related but discovered/recorded days after the event occurred. These delays significantly alter all the trend lines in the north region and are thought to be the main cause of poor trend significance.

This analysis is also limited by the problem of buckle harvesting [14]. This occurs when a new maximum temperature is reached in any summer period. Any failures will then occur producing a spike in delay minutes. If the same temperature is reached again over the next few weeks, then fewer delays will be experienced as the sections of track prone to failure at that temperature have already been harvested.

Overall, if more ADB data were available the resolution of regions could be reduced and apparent outliers would not be such an infrequent occurrence, thus having a more predictable effect on the final results. However, the results from removing outliers showed that the main body of data is reliable, and that in the context of the research and network operations there is no justification for removing these outliers which are a significant contribution to overall delays and costs.

3.2 Weather analogues: the 2003 heatwave

The hot summer of 2003 is frequently used as a weather analogue. Studies compare the estimated cost of a 'hot' summer in the south-east to the reported costs of the 'normal' summer 2004 [5, 12]. To compare the results of reference [5] the south-east paper with the cost of the entire UK, an indiscriminate division based on the number of network rail regions was made in reference [12]. The results showed a favourable comparison; however, through the assumptions and generalizations made, these results could be considered inaccurate.

Hunt *et al.* [12] 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 to be attributable to heat-related incidents. This figure is significantly higher than that for the summer of 2004, which is considered 'normal' with only 30 000 delay minutes recorded. This information is used later to validate the estimated costs using the ADB.

4 METHODOLOGY: FUTURE CLIMATES

4.1 UK Climate Impacts Programme

The UK Climate Impacts Programme (UKCIP) is the organization responsible for producing future climate scenarios for the UK. The present 2002 models (UKCIP02) are based on four greenhouse gas emissions scenarios: low, medium low, medium high, and high. The emission scenarios run through three time slices: 2011–2040 (the 2020s), 2041–2070 (the 2050s), and 2071–2100 (the 2080s) [4]. This article focuses on the low and high emissions scenarios for all time series in order to demonstrate the extreme cases.

4.2 Environment agency rainfall and weather impacts generator

Weather generators produce spatially referenced weather data based on recorded baseline data from the corresponding location [14]. They produce an unlimited time series of stochastic weather data; this method has more recently been applied to climate

Table 2 R^2 and p -values for all trend lines in Fig. 2

Region	R^2 (%)			p -value (%) ($\alpha \leq 5\%$)		
	Maximum	Mean	SD	Maximum	Mean	SD
North	20	8	15	5.7	24.3	11.3
West	2	0.7	0.1	57.3	74.0	88.4
Midlands	43	26	21	0.7	5.4	15.8
South	12	2	16	18.2	60.5	15.6

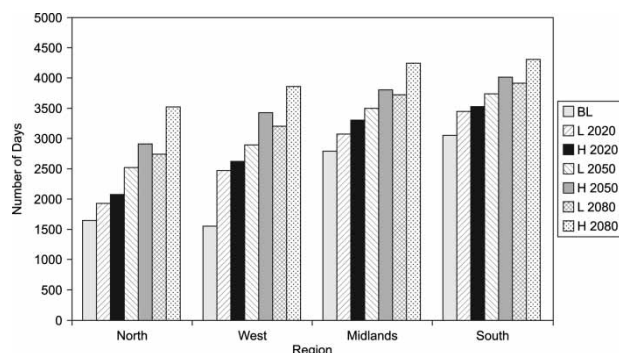


Fig. 3 Number of days in 30-year time period having a maximum daily temperature $\geq 18.5^\circ\text{C}$, simulated by EARWIG

change weather predictions (for example, see reference [15]) from UKCIP02 in this case. A full description of the environment agency rainfall and weather impacts generator (EARWIG) is available in Kilsby *et al.* [16]. The utility of EARWIG was proven in Dobney *et al.* [5] where it was used to simulate future climate trends for the south-east. It was proven that the correlation between the generated baseline temperature trends and the representative weather station was very good; R^2 value of 0.96 and for temperatures $>21^\circ\text{C}$ an R^2 value of 0.997. Having proved the accuracy of EARWIG at the baseline level, it was assumed that it would also produce internally consistent future climate predictions based on UKCIP data.

EARWIG was used to produce maximum daily temperature profiles for the low and high emissions scenarios for all time series in each region. Each regional temperature profile is based on the location of the weather station used to produce the baseline trends with the ADB. Ensemble simulations are run for each region and combined to produce a probability distribution curve of maximum daily temperatures. The probabilities can then be applied to represent the entire 30 years (Fig. 3) of each time series or a typical year within the time series.

4.3 Future projections

The approach used to make projections is based on the same assumptions as Dobney *et al.* [5]; however, changes have been made to accommodate for improved approaches in the methodology.

1. The maximum, mean, and SD trend lines represent how heat affects the railway in each region (Fig. 2). A linear relationship was chosen over the established exponential relationship between temperature and buckled rails [7]; in addition, costing calculations will use the mean trend line with variation bars. These measures provide a more conservative estimate when dealing with high unfamiliar temperatures and heat-related delays like emergency speed restrictions. Trend line values are included in Fig. 2. There are also positive and negative variations in each trend line around the gradient a , \pm variations are summarized in Table 3.
2. In order to make the quantification comprehensible, the costs are presented in yearly averages representative of each 30 year time series and low and high emissions scenario.
3. The temperature range that heat-related delays occur in each region is also given in Table 3 (labelled temperature range). The lowest temperatures that events occur at in each region are taken as the regional minimum for all future climate change weather scenarios.

5 RESULTS AND DISCUSSION

Future weather trend predictions show that across the UK high temperatures that cause damage and delays are going to increase. The magnitude of delays can be estimated based on the mean trend lines from the ADB analysis for each region. Figure 4 shows that the occurrence of buckled rails in all four regions shows a similar distribution to those in Dobney *et al.* [5]. Comparing the values contributing to the maximum trend line in Fig. 2 and the buckles in Fig. 4 demonstrates that the most severe consequence of high temperatures is buckled rails. The most severe buckles start to occur at temperatures $>25^\circ\text{C}$, although there are still some severe buckles occurring at $>20^\circ\text{C}$ and in the north region some minor buckles occurring as low as 15°C . This is perhaps a consequence of the representative weather station offering an *overview* of regional temperature. In a study of this scale, it is impossible to account for the local microclimate which will have a major effect on local disruption. Other possible causes are wrongly recorded descriptions or dates of events in the ADB or simply very poorly maintained track.

Table 3 Summary of regional trend data from Fig. 2

Region	Maximum $a \pm$ trend values	Mean $a \pm$ trend values	SD $a \pm$ trend values	Incident count	Average incidents per day	Temperature range of incidents
North	35	4	8	337	2.2	13.1–33
West	15	11	6	165	1.1	15.8–34.4
Midlands	39	12	18	93	0.6	16.4–31.3
South	61	13	21	120	0.8	18.7–35.2

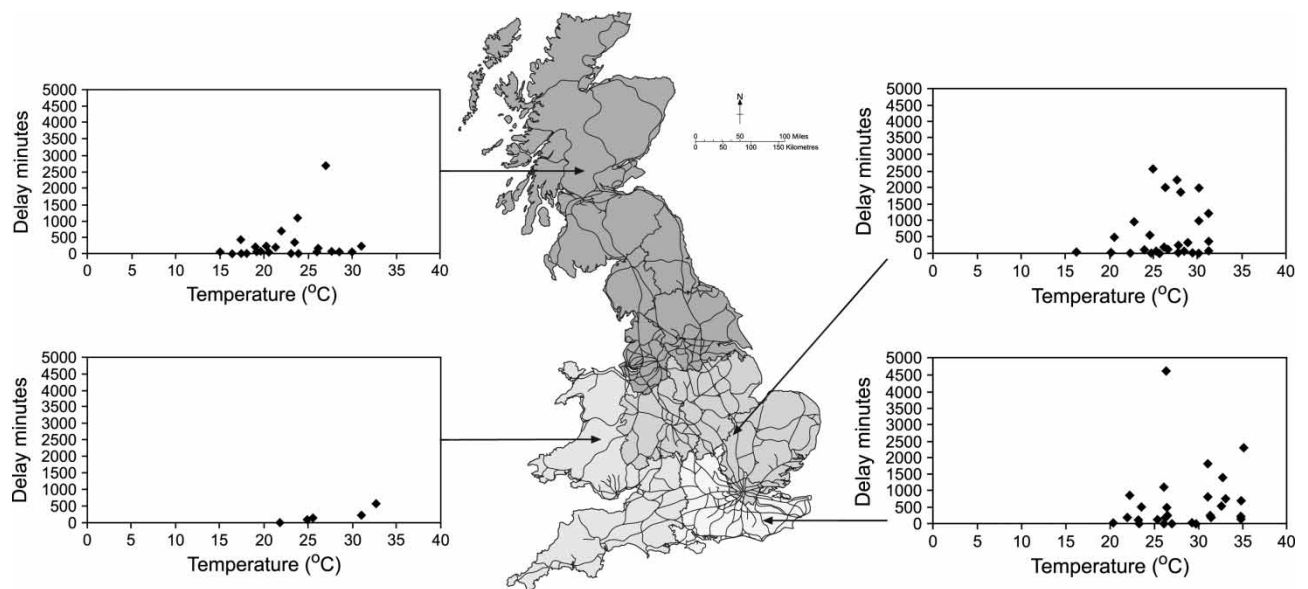


Fig. 4 Number of delay minutes attributable to 'buckle' events recorded in the ADB against the maximum daily temperature on the date recorded for each region

In order to account for the variability in the ADB data, variation bars are included in all costing calculations; this will ensure that the impact of severe buckles is not diminished.

Table 3 summarizes the data inputs for Fig. 2 and section 4.3 defines the assumptions made for establishing trends from the ADB. Applying these assumptions to the mean linear trends produces the estimated number of delay minutes for a year in each climate change scenario for each region. Equation (2) converts these into a cumulative cost, which is summarized in Fig. 5(a)

$$C = mdpc \quad (2)$$

where C is the total cost for the time series and emissions scenario, m is the delay minutes associated with a day of maximum daily temperature t (from Fig. 2), d is the number of days each maximum daily temperature is expected to occur on an average year, p is the probability that a delay minute event will happen on an average day, and c is the average cost of a delay minute £73.47 [11].

However, in order to assess the true severity of the impact of climate change on heat-related delays in each region, the cumulative costs have been normalized as a ratio to the length of rail (km) and the area of the region (km²) (Table 4). It would also be useful to normalize the results using the number of trains travelling and the total time travelled within each region. Network Rail publishes information on the number of trains operating on lines and routes as part of their annual business plan; however, the lines and routes defined by Network Rail do not correspond with the regions defined in Fig. 1(b). The results of the costs

as a ratio of the area of each region and length of rail in each region are shown in Fig. 5(b), clearly showing that heat-related delays have most impact in the south region. Up to 0.16 GBP could be spent per km of rail in each km² of land in high emissions scenario in 2080, compared with up to 0.012 GBP for the same in the north region. The disparity in relative cost should be expected to be larger when the true cost of a delay minute in each region is used in calculations. The £73.47 used in this study is the national average; it is likely that the cost in the north region will be less than this and the cost in the south is likely to be significantly more. This cost of a delay minute also does not include the price of maintenance, materials, or labour that are incurred due to an incident. As a result, there is no viable method at present of producing a full cost benefit analysis of changing future mitigation and maintenance regimes.

To provide baseline costs for heat-related delays, the delays experienced in the extremely hot year 2003 and the 'normal' summer of 2004 [12] were contrasted. In all, 2004 was considered to be a 'normal' year for heat-related delays; however, there are a number of factors that should be remembered in making this assumption. First, 2004 was a normal summer following 2003; an exceptionally hot summer. Because of the phenomenon of buckle harvesting [14], any weakened rails are likely to have buckled in the August 2003 heat-wave, so less than a 'normal' year of buckles might be expected in 2004. In addition, buckled rails are responsible for the most severe heat-related delays, which would result in an overall reduction of annual heat-related delay minutes in 2004. This can be clearly seen in the raw data from the ADB. For example, only one heat-related delay (including buckles) was recorded in

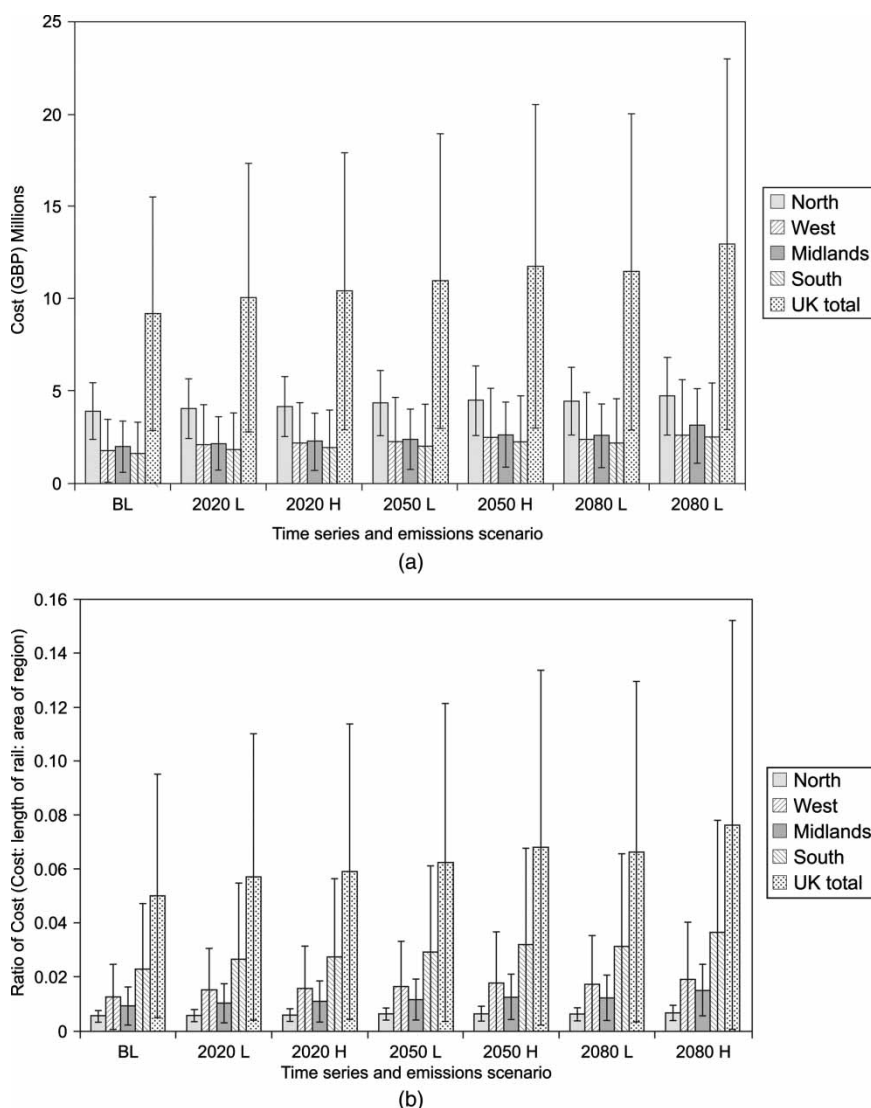


Fig. 5 (a) The annual cost (GBPm) of delay minutes caused on days when the maximum daily temperature is predicted to reach each 1 °C interval for temperatures > threshold temperature from each region (see Table 3), for time series, emissions scenarios, and regions. (b) The annual cost (GBP) (from Fig. 5(a)) of delay minutes as a ratio to the length of rail and area of the region, for time series, emissions scenarios, and regions

Table 4 Length of railway routes and area of each region

Region	Length of rail (km)	Area (km ²)
North	6800	109 000
West	3100	46 000
Midlands	4300	48 000
South	3300	21 000

the Wales region in 2004. Second, the annual average trend lines calculated for each region in this study are based on an average of 30 years of baseline weather data. During this time there will have been extremely hot and normal summers, resulting in an average of all summers in this 30-year period. From this evidence it is suggested that 2004 should be considered to be

at the lower end in severity for heat-related delays, whereas 2003 can be considered to be at the upper end. Based on 165 000 delay minutes [12] and the average cost of a delay minute being £73.47 [11], the costs of heat-related delays in summer 2003 and 2004 are estimated to be £12.1 and £2.2 m, respectively. The total cost of baseline heat-related delay minutes based on the average trend line from this study was £9.2 m with a minimum cost of £3 m and a maximum cost of £15.5 m, based on the \pm variation in the trends.

According to the future predictions for the cost of heat-related delays in Table 4, the cost of the hot summer 2003 will become an average summer in the 2050s under the high emissions scenario. For the low emissions scenario, summer 2003 will become average by the 2080s. If there is to be an extremely hot summer

Table 5 UK wide annual costs for heat-related delays, based on the average trend line from Fig. 2

	Mean – trend variation (GBPm)	Mean (GBPm)	Mean + trend variation (GBPm)
BL	3	9.2	15.5
2020 L	3.1	10.1	17.3
2020 H	3.2	10.4	17.9
2050 L	3.3	10.9	18.9
2050 H	3.5	11.7	20.5
2080 L	3.4	11.5	20.0
2080 H	3.8	13.0	23.0

the future equivalent of the hot summer 2003, according to the high emissions scenario in the 2080s the cost will be nearly double that at £23 m.

6 CONCLUSIONS AND RECOMMENDATIONS

This analysis has estimated that the cost of the predicted impact of baseline weather on an average year in the UK is £9.2 m with cooler summers costing a minimum of £3 m and extremely hot summers costing up to £15.5 m (Table 5). Using analogues, this is comparable to the impact of the extremely hot summer of 2003 and the temperate summer of 2004, which produced a range of costs between £2.2 and £12.1 m, respectively. Because of predicted climate change scenarios, this cost is set to increase to up to £23 m (at current prices) by 2080 under the worst case scenario of high emissions, based on the average trend line of real recorded data.

These costs are entirely based on the assumption that £73.47 is the average cost of a delay minute in the UK. However, the cost of delays in the south-east, London, and other major cities will be considerably more and it is in these key commuter and business travel areas that more delay minutes are caused by incidents. For this reason, it is highly likely that the costs incurred for heat-related delays could be far higher than that estimated in this article.

Overall, higher temperatures because of climate change are set to have a significant impact on the railway network in the UK. However, there are solutions available to make the railway network more resilient. First and foremost, ensuring the track is thoroughly maintained greatly reduces the vulnerability of the rail during hot weather (Table 1). 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. Indeed, there may need to be a need to raise the stress-free temperature currently used in the UK. However, in order to make an accurate recommendation, the effects of climate change on extremely low temperatures (i.e. tension cracks caused by rail shrinkage) must

first be considered. In summary, a change in engineering practices and regimes will be essential if the climate of the UK changes as predicted.

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		<i>p</i>	probability that a delay minute event will happen
		<i>p</i> -value	statistical hypothesis level (relating to α)
APPENDIX		R^2	coefficient of determination
Notation		RAIB	Rail Accident Investigation Branch
ADB		SD	standard deviation
BL		SFT	stress-free temperature
<i>c</i>		<i>t</i>	maximum daily temperature (°C)
°C		Tair	ambient air temperature (°C)
<i>C</i>		Trail	rail temperature (°C)
<i>d</i>		UK	United Kingdom
EARWIG		UKCIP(02)	United Kingdom Climate Impacts Programme (2002)
EU		WMO	World Meteorological Organization
GBP		per cent	percentage
km		2020/2050/2080	climate change prediction time series
L/H		£	pounds Sterling (Great British Pounds)
		α	significance level (relating to <i>p</i> -value)