A Reliability Assessment of Railway Track Buckling under Extreme Heatwaves

Minh N. Nguyen[a], Xiaoming Wang[b] & Chi-Hsiang Wang[c]

[a]*Land & Water Division, Climate Adaptation Flagship, Commonwealth Scientific & Industrial Research Organization (CSIRO), Australia*

Tel.: +61-3-9252-6290; Fax: +61-3-9252-6244; Email: Minh.Nguyen@csiro.au

[b]*Ecosystem Sciences Division, Climate Adaptation Flagship, Commonwealth Scientific & Industrial Research Organization (CSIRO), Australia*

Tel.: +61-3-9252-6328; Fax: +61-3-9252-6249; Email: Xiaoming.Wang@csiro.au

[c]*Ecosystem Sciences Division, Climate Adaptation Flagship, Commonwealth Scientific & Industrial Research Organization (CSIRO), Australia*

Tel.: +61-3-9252-6221; Fax: +61-3-9252-6249; Email: Chi-Hsiang.Wang@csiro.au

Note: This is the post-print version of the paper. The paper has been published online by the *Journal of Rail and Rapid Transit*, SAGE publications, UK, at http://intl-pif.sagepub.com/content/226/5/513

The paper should be cited as:

Minh N Nguyen, Xiaoming Wang, and Chi-Hsiang Wang (2012) A reliability assessment of railway track buckling during an extreme heatwave, *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol.226, Number 5, September 2012. doi:10.1177/0954409712441743, SAGE publications, UK

Abstract

This paper presents a reliability assessment of railway track buckling under extreme heatwave events. Monte-Carlo simulation is used to estimate the track buckling failure probability. The effects of important predictor parameters such as the effective buckling lengths and buckling modes of the rails, as well as the rail temperatures at the time of installation and during a heatwave are taken into account in the simulation. The result shows that the buckling failure probability of railway tracks in a specific type of buckling in Melbourne under an extreme heatwave similar to the event of January 2009 is about 2/100,000 in average, which is a good estimate of the number of the track segments buckling in such type observed in the Melbourne railway network. The assessment demonstrates a science-based approach for reliability assessment for railway track buckling failures in heatwaves.

Keywords: reliability, railway track, buckling, climate change, heatwave, Monte-Carlo simulation

1. Introduction

Railway networks are essential transportation infrastructure for Australian cities. Structural buckling failures of railway tracks due to extreme heatwaves had been one of the major causes of service disruption of the networks, as observed in the heatwave event of January 2009 in Melbourne, Australia, during which the daily maximum temperatures exceeded 43°C for 3 consecutive days. In addition, climate change research indicates a future of more frequent and more intense extreme heatwaves in Australia; assessment of heatwave hazard to the rail track buckling failure is needed for future planning and management of railway network services.

This paper presents a reliability assessment of the Melbourne railway track buckling under extreme heatwaves similar to the event of January 2009. The buckling failure probability is estimated by Monte-Carlo simulation where the effects of the effective buckling lengths and buckling modes of the rails, as well as the rail temperatures at the time of installation and during the heatwave are taken into account. The aim of the study is to establish a science-based approach, i.e. through numerical simulation to assess the risk of railway track buckling under heatwaves. The results would assist the planning and management of railway network services to cope with future changing climate.

2. Steel Rail Buckling

An extreme heatwave of long duration may cause structural failures to railway tracks. A recent example was the buckling of railways in Melbourne during the extreme heatwave event in January 2009 [1, 2].

The buckling of railway tracks occurs as a result of excessive thermal stress in the tracks. As temperature increases, thermal expansion occurs, mainly elongating the length of the tracks. There may be thermal expansion joints between adjacent tracks to accommodate the thermal expansion. However, when the temperature increases to a level higher than the expansion joints can accommodate or, even worse, the tracks were fully connected by welding, compressive stress starts to build up along the tracks. As a consequence, track buckling occurs when the compressive stress exceeds its critical buckling capacity, which depends on the track material, effective buckling length, cross-sectional geometry, and configuration of the rails.

The track elongation δ_T (m) due to a temperature change ΔT (°C) can be estimated by

$$\delta_T = \alpha \, L \, \Delta T \qquad (1)$$

where L is the track length, and α is the thermal expansion coefficient. For steel, $\alpha = 12 \times 10^{-6}$ m/m°C.

The compressive load P_T (N) due to a temperature change ΔT (°C) in a track fully constrained at both ends can be computed by

$$P_T = \alpha \, \Delta T \, EA \tag{2}$$

where A (m^2) is the cross-sectional area of the track; E is the Young's modulus of the track material. For a steel rail, $E = 200$ GPa $= 2 \times 10^{11}$ N/m^2.

The critical buckling load P_{crit} (N) for a straight and axially loaded bar is defined by

$$P_{crit} = \pi^2 EI / (kL)^2 \tag{3}$$

where I (m^4) is the moment of inertia of the track cross-sectional area about its weak axis, which is often the vertical axis; k is the effective length factor depending on the type of the constraint at the rail's ends. For both ends fixed, $k = 0.5$; for both ends pinned, $k = 1.0$; for one end fixed and one end free, $k = 2.0$.

Buckling of a rail segment occurs when the compressive load P_T due to thermal expansion exceeds the buckling capacity P_{crit}; i.e.,

$$P_T - P_{crit} > 0 \tag{4}$$

3. Reliability Assessment

This section shows an example for assessing the probability of buckling failure for rail segments installed in the Melbourne railway network under heatwaves similar to that occurred in January 2009, during which there was a stretch of three days with maximum temperatures exceeding 43°C.

3.1 Assumptions

From observations of the rail system and the rail buckling, as shown in Figure 1, the following parameters are assumed:

- The rails are of 50 kg type, commonly used for branch rail lines. From AS 1085.1 [3], the geometric properties of the rail cross section are:
  - Area: $A = 6.45 \times 10^{-3}$ m^2
  - Cross-sectional moment of inertia about the weak axis (vertical): $I = 3.26 \times 10^{-6}$ m^4
- The rails are continuous; i.e. no thermal joints between adjacent tracks. The rails therefore have fixed along-the-length constrains at both ends. This is based on the fact that the tracks were interconnected by welding in Melbourne railway network.
- The rail material is steel. The Young's modulus $E = 2 \times 10^{11}$ N/m^2. The thermal expansion coefficient is $\alpha = 12 \times 10^{-6}$ m/m°C.

Monte Carlo simulation technique is used for failure probability estimation. The probability distributions for the temperature change ΔT, the buckling length L, and the effective length factor k are assumed as follows:

- For the temperature change ΔT:
  - During the heatwave, at the time the maximum air temperature reached 43.6°C, it is assumed that the rail temperature reached 61°C to 66°C. This is based on an estimate that the rail temperature was 17°C higher than the air temperature or 1.5 times the air temperature [4]. The rail temperature is higher than the air temperature due to the high thermal conductivity and diffusivity of rail steel. It is therefore assumed that the rail temperature during the hot spell follows a normal distribution with a mean value of 63°C and a standard deviation of 1°C.

- At the time of construction, the rails were laid at the rail neutral temperature and constrained to prevent buckling. The neutral temperature is a temperature between expected hot and cold maximums of the region. It is generally selected either at 75% of the expected maximum temperature of the region or 22°C less than the maximum expected rail temperature [4]. The expected maximum temperature of the Melbourne region is 45°C. The neutral temperature is therefore in the range of 33°C to 44°C. It is therefore assumed that the rail neutral temperature follows a normal distribution with a mean value of 38°C and a standard deviation of 2°C.
- The temperature change ΔT is the difference between the rail temperature and the neutral temperature. As the rail temperature and neutral temperature are normally distributed, the temperature change ΔT also follows a normal distribution with the mean value of (63°C – 38°C) = 25°C and a standard deviation of $(2^2+1^2)^{1/2}$ = 2.2°C.

- For the type of buckling observed in Figure 1, it is assumed and estimated that:
  - The mean rail length subject to single-buckling mode is 2.5 m. It is thus assumed that the rail length L follows a normal distribution with a mean of 2.5 m and a standard deviation of 0.4 m.
  - The rail buckling form suggests that the effective length factor k may vary from 0.5 to 1.0. It is thus assumed that k follows a normal distribution with a mean of 0.8 and a standard deviation of 0.1.

3.2 Numerical Results

Since no existing probability models describe the distribution of buckling capacity expressed in Equation (3), the rail failure probability due to buckling can only be estimated accurately by Monte Carlo simulation. For this purpose, a railway network assumed to contain one million segments of steel rail tracks was investigated. The track lengths and temperature changes were distributed probabilistically as discussed in Section 3.1. For each of the one-million rail segments, occurrence of buckling failure was determined according to Equation (4). A Monte Carlo simulation program in MATLAB [5] was developed using the library-functions available in its Statistics Toolbox. The computer time for simulating a sample of size one million on a PC of 8 GB-RAM with 2.7-GHz Intel Core i7 processor was less than 40 seconds. Figure 2 presents the histograms of simulated compressive load and buckling capacity.

To obtain the distribution for the number of failed rail segments in one-million segments, a total of 1,000 simulation runs, each with one-million segments, were then carried out. The result is shown in Fig. 3. It was found that the number of buckled segments ranges from 7 to 40, with an average of about 23. The distribution of the number of buckled segments can be reasonably modelled by a binomial distribution with a mean of 22.8 and variance of 22.3, as shown in Figure 3. This result is in line with the theory of a simulation-based reliability method described in [6].

It is therefore estimated that the buckling failure probability of a 2.5-metre steel rail segment in the type of buckling observed in Figure 1 under a heatwave condition such as the event in Melbourne, January 2009, is about 23/1,000,000, ie. approximately equivalent to 2/100,000. The Melbourne railway network has a total length of about 270 km, which can be divided into more than 100,000 rail segments of length 2.5 m. With a buckling failure probability of 2/100,000, it is therefore anticipated that the number of rail-segment buckling similar to that in Figure 1 is around 2. This agrees with the number of buckled segments observed in the Melbourne railway network in the January 2009 heatwave: one case was reported between Jolimont and Flinders Street Stations (Figure 1), and another at Holmesglen on the Glen Waverley train line [1, 7].

3.3 Discussions

Besides the assumptions made in Section 3.1, for ease of computation and a lack of data for some parameters the following are implicitly assumed as well in this study:

- The effects of solar radiation and heat build-up in the rails during the long hot spell were neglected. The rail temperature could be even higher and un-evenly distributed due to these factors. These could cause an increase of the compressive load and a reduction of the buckling capacity of rails.
- Likely deficiency in local track structure conditions was neglected; for example, drainage may cause weakening of rail foundation, and ballast strength may vary along the rail route.
- The rail critical buckling capacity was computed by assuming the rail to be a straight and axially loaded bar. In reality, some curved rails are laid (Figure 1), and local track misalignments may exist that induces eccentric load on the rails. These rails therefore would subject to bending moments, resulting in decreases in critical buckling capacity.
- For a buckled rail section as shown in Figure 1, it is assumed that the lateral constraints of the rail (usually in the form of spikes or clips located at about every 0.5 m along the rail) had failed due to degradation of rail fastening system, such as deterioration of old timber sleepers, corrosion of rail spikes, etc.; and/or poor maintenance practice.

Nevertheless, through this work, the need for reviewing the design and construction of railway tracks for adaptation to changing climate is identified as follows:

- Reviewing and revising rail construction procedure, where rails were laid at its 'neutral temperature' (Section 3.1), to cope with increasing average, and larger variability, of temperature in the projected changing climate.

- Reviewing and improving rail performance by improved or new construction configurations or designs of rail joints to accommodate the thermal expansion.

- Emphasizing the importance of proper maintenance for railway tracks, and the use of more durable materials for sleepers, spikes, etc.

- Using new materials for rails, which are less sensitive to changes of temperature. Premium materials should be used in consideration of wheel and rail contact mechanics in relation to wear and fatigue properties of the current rail steel. This use may result in significantly higher construction or replacement costs. However, a better performance of the rail network would be a beneficial trade-off in the long term, in particular with more intensive and more frequent heatwaves projected for the region under the changing climate.

4. Conclusions

Extreme heatwaves can cause serious breakdown of railway networks due to a number of reasons, including the buckling of rail tracks, as observed during the heatwave of January 2009 in Melbourne, Australia. A reliability assessment of railway track buckling under extreme heatwave events has been undertaken using Monte Carlo simulation. Uncertainties of the effective buckling lengths, the buckling modes, the rail temperature at the time of installation and the rail temperature during a heatwave have been taken into account. The buckling failure probability of railway tracks in Melbourne determined in this study agrees with the number of buckled segments observed during the heatwave of January 2009. This agreement is an important proof of concept for this approach. The assessment has therefore demonstrated a reliability-based assessment approach for railway track buckling failures under heatwaves, which can be further developed into a framework to assist railway authorities in planning and management of railway network services.

Nevertheless, this study made use of a number of assumptions due to insufficient knowledge of the railway track conditions and lack of performance data. While the number of buckled segments in the analysis agrees with observations, it is preferable that more predictor variables be included so as to result in a more realistic rail network model. It is also noted that only the buckling mode similar to that shown in Figure 1 was assessed. Other modes of buckling may also occur in the railway network during the heatwave. Improvement of the results in this study and proposition of adaptation strategies to extreme heatwaves for railway networks are possible when relevant data available from the railway industry/authorities, such as the variability of track geometry and track strength, are integrated into the model to refine its predictive capability in the future.

Acknowledgements

The authors would like to express their appreciation to CSIRO Sustainable Cities and Coasts Theme, Climate Adaptation Flagship, and Land and Water Division for the support to this work.

References

1 Ham L. (2009) Tracks buckle and so does rail system, *The Age*, January 29, 2009, http://www.theage.com.au/national/tracks-buckle-and-so-does-rail-system-20090128-7s0h.html (accessed February 2012).

2 Wikipedia (2011), *Connex Melbourne – 2009 Heatwave Issues*, http://en.wikipedia.org/wiki/Connex_Melbourne, (accessed February 2012)

3 Standards Australia (2002), AS-1085.1-2002: Railway track material – Steel rails, SAI Global, Australia.

4 Yates A. and Mendis P. (2009), *Handbook – Climate Change Adaptation for the Railway Sector*, Australian Security Research Centre, ISBN 978-0-9804337-2-2, Australia.

5 Mathworks (2011), *MATLAB – the Language of Technical Computing*, Version R2011b, Mathworks Australia, http://www.mathworks.com.au/products/matlab/index.html (accessed February 2012).

6 Ayyub B. and Mccuen R. (1995), *Probabilistic Structural Mechanics Handbook – Theory and Industrial Application*, *Chapter 4: Simulation-based Reliability Method*, C. Sundararajan, Eds., pp. 53-69, Chapman & Hall, New York.

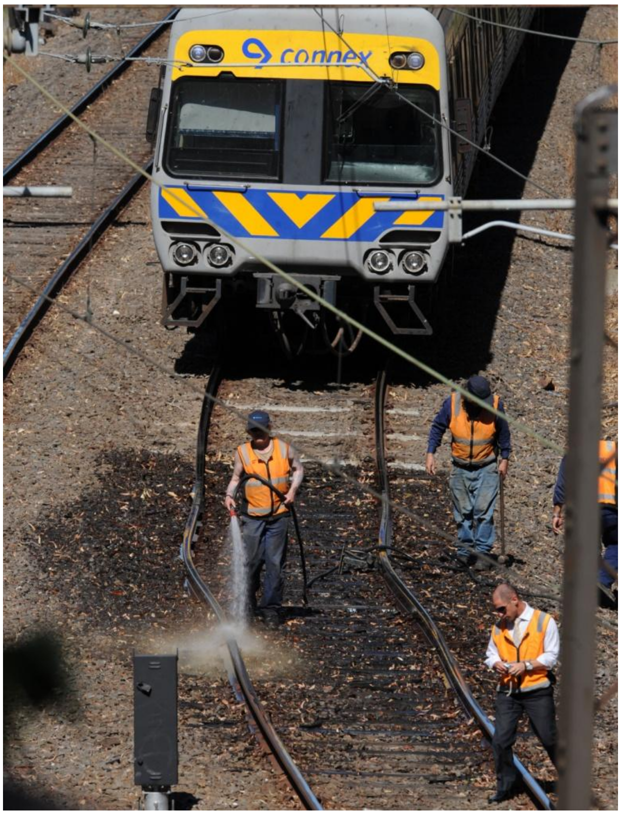

Figure 1: Buckling of a railway track during the January 2009 heatwave in Melbourne (Joe Armao/Fairfax Syndication)

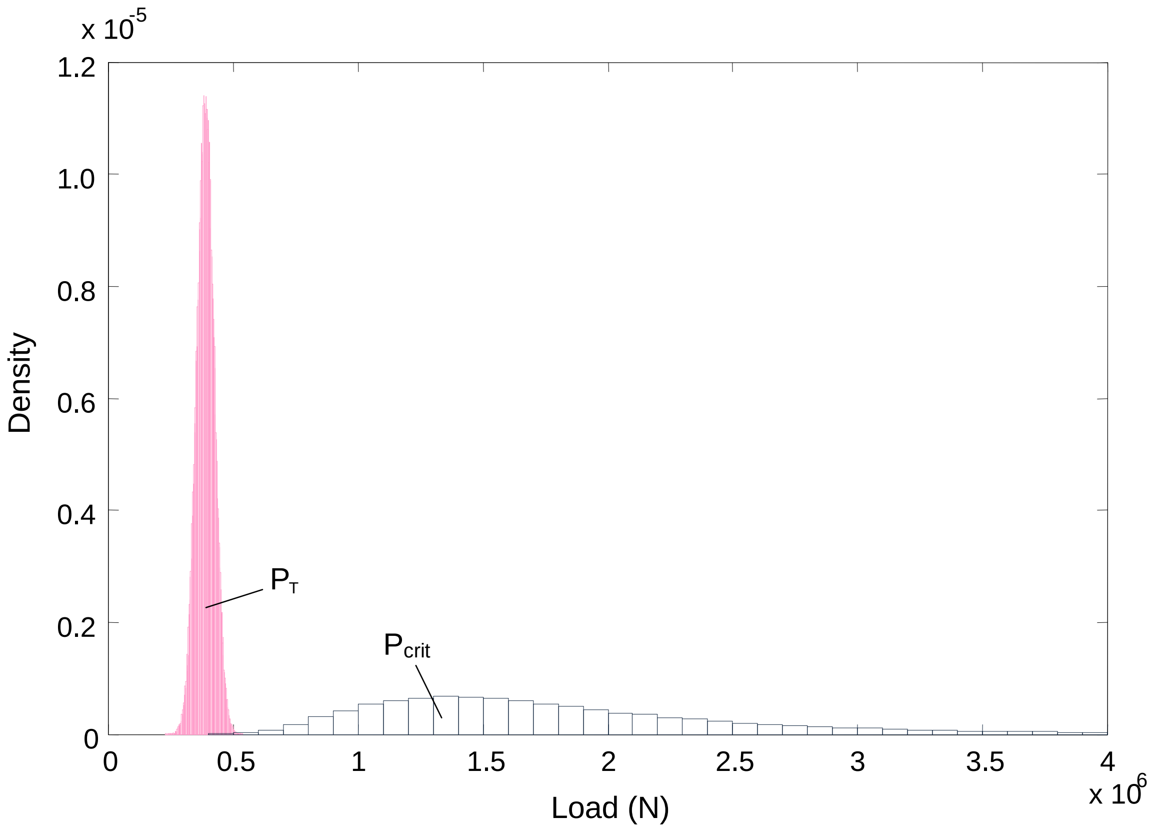

Figure 2: Histograms of compressive load and buckling capacity estimated for Melbourne railways during the heatwave of January 2009

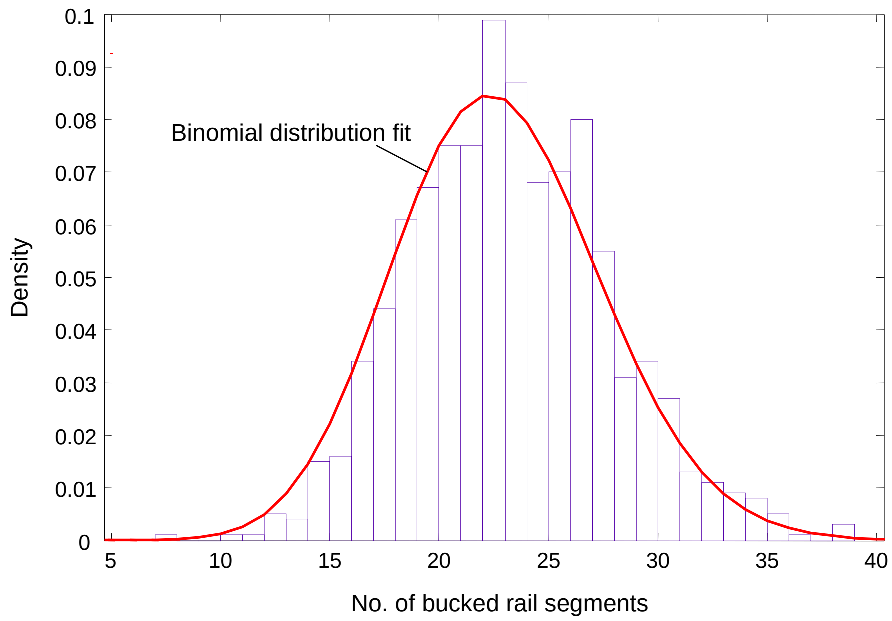

Figure 3: Probability density of the number of buckled rail segments out of 1 million segments and the distribution fit