Challenge G: An even more competitive and cost efficient railway

Improving track stability and track maintenance operations through enhanced air and rail temperature forecasts

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Summary

Modern welded track is subjected to thermal compression or traction forces because of temperature variations. These forces must remain within strict prescribed limits where track stability is kept at such a level that no deformation might happen under any possible temperature conditions at a specific location. Track stability may be further reduced by track maintenance works. Track works that may reduce track stability should therefore only be performed under a maximum temperature level. Thermal forces control is thus a critical factor to help reduce track maintenance hazards and guarantee secure train operations.

For the above reasons, a research has been conducted to deliver reasonable guesses on average rail temperature at any prescribed location or date. Given the non-deterministic atmospheric phenomenons and the random character of ensuing temperature forecasts, rail temperature predictions are to be produced with an associated probabilistic risk.

As the question was stated, two difficulties had to be overcome. The first difficulty was to derive statistical predictions from existing temperature data, while the second difficulty was to relate air temperature with rail temperature at any date or location. The whole problem had to be solved and the results should be later made available on a handheld computer. A supplementary request of the research "tender specification" stated that rail temperature predictions/risks should be issued in a real railway situation, i.e. along a railway line, in connection with existing mileposts and railway map. The computing delays should obviously be made the shortest as possible to make these predictions usable for operational real time needs.

In a first step, a statistical database has been created with past temperature recordings taken daily (minimum and maximum) on 81 meteorological stations spread across the French territory, near the main airports, over 17 years (1990 to 2007). A second step was to establish a relationship between maximum air and rail temperatures which could hold at any date or location. A collection of rail temperatures were sampled every 10 minutes at 25 places which were spread across the railway network, nearby to meteorological stations. The end challenge was to bury the whole computing engine inside a user friendly railway interface for practical use.

After some data processing of air and rail recordings, a strong relationship has been established between average air and rail week temperature. This relationship rests upon a simple physical sun energy model which can be applied to any date or world location. It is used to predict long-term rail temperature.

Results and software produced by this research have been made available to SNCF’s track maintenance services for future use. It provides them with realistic and easy to handle rail temperature predictions.
1. Overall scope

Longitudinal forces which exist inside continuous welded rails (CWR) may cause track deformations, such as buckling or chord straightening, when the temperature exceeds a certain threshold. This threshold depends on track lateral resistance, which itself varies according to track type and state.

Under normal circumstances, track is designed to support maximum temperature. However, to prevent this problem from becoming critical, during track works where track stability is temporarily decreased, appropriate provisions must be made to take into account rail temperature. Temperature must be specially taken into account when planning large scale track works.

From past or more recent studies in the field of rail temperature forecasts, it appears that this subject may be tackled either by statistical empirical methods as in [1] or by physical models as in [2].

Given the operational requirements which had to be answered, it was decided to use a mixed approach where air and rail temperatures are fitted with a simple physical model. This required building a relevant air and rail temperature database.

2. Experimental layout

To fulfill the project requirements and given the chosen methodology, an extensive measurement campaign has been performed over the operated and maintained SNCF’s railway network.

The target was to collect as much meteorological data as possible in connection with rail temperatures. Rail temperature is the key parameter to control CWR stability when maintenance operations are undertaken. Meteorological data help calibrate the forecast model.

Measurements have been performed by SNCF’s « Section Mesures » from Track Design Department.

Between 11/2005 and 05/2008, 25 measuring sites have been installed across the railway network so that much of the geographical space could be covered, nearby reference “Meteo France” stations that were currently used (to forecast survey rounds during the warm year period), in order to make the best use of the data output of these stations.

<table>
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<th>Dép.</th>
<th>Date de mise en service</th>
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<td>Montpellier</td>
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<td>11/04/2008</td>
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<td>28/02/2006</td>
<td>25</td>
<td>Le Bourget</td>
<td>93</td>
<td>30/05/2008</td>
</tr>
<tr>
<td>13</td>
<td>Rennes</td>
<td>35</td>
<td>09/03/2006</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Meteorological stations

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1 four more site equipments were installed later on, from 11/2009, in the vicinity of Paris
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Measurement layout

Measuring equipment is installed at trackside in a shadow free place, usually fixed on catenary poles to be energy fed by solar panels on a standalone regime.

Figure 1: Station setting on a catenary pole (left-hand) – Rail temperature sensor (right-hand)

The layout of all sites is the same, allowing the following measurements:

- air temperature,
- rail temperature of each rail. Sensor is conductively pasted under the rail and fixed by a plate
- air humidity is obtained by moisture sensors. These sensors have been gradually replaced by relative humidity sensors the output of which is more relevant to Meteo France’s measurements. A consequence is that not all air humidity data could be used.

Measurement validation

Site measurements where compared to Meteo France’s data for the same period at the nearest reference station, to ensure relevance between databases (SNCF’s and Meteo-France’s), in order to use them similarly. Figure 2 shows that results are quite similar.

Figure 2: Comparison between maximal day temperature from Météo France (magenta) and from SNCF (red) – Saint Quentin site July 2006
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There exists however other input parameters which could influence air and rail temperatures. In the following example of data collected at Lille site, it appears that relative humidity may well play an important role. An example of this influence is highlighted below. Inside the red ellipse, relative humidity reaches a constant and high level which in turn seems to be linked with low air and rail temperatures. Investigation into influence of other meteorological input parameters (relative humidity, sunniness, wind, rain, cloud coverage) has been tackled in [3].

![Graphique synthétique Juin 2008](image)

**Figure 3:** Influence of relative air humidity (Lille site). June 2008 recordings (green: rail temperature; red: air temperature; blue: relative air humidity).

### 3. Some physical considerations about air and rail temperature

Solar energy received per unit horizontal earth surface unit is a function of solar ray inclination (figure 4), which varies according to geographical position $\varphi$ (latitude) and year period $\delta$ (solar declination). Solar declination varies between $-23.5^\circ$ (winter solstice on the 21st of December in the northern hemisphere) and $+23.5^\circ$ (summer solstice on the 21st of June in northern hemisphere).

![Figure 4: Solar ray inclination to local upright direction](image)
Air and rail “sidereal week”\(^2\) average temperature histograms exhibit a nearly Gaussian behaviour (Figure 5). This Gaussian behaviour is more clearly seen for air temperature because of a larger number of available samples (18 years instead of approximately 5 years for rails).

Despite the afore mentioned lesser amount of rail temperature samples, the differences between samples of averaged maximum rail and maximum air temperature (over a week), are quite similar across sites 1 to 25, although variations due to site locations are of course still apparent.

This similarity is an indirect proof that ambient and rail temperatures statistical behaviour are equally Gaussian.

\(^2\): let \(q\) be the day rank in a given year; the « sidereal week » (se) is the day range for which \(E(q/7)+1\) exhibits the same value se, \(E(r)\) being the integer part of real number r. For a given se value, solar inclination is the same. Using “sidereal week” reference eliminates every calendar singularity due to leap year or country conventions, for example week numbering may differ from a country to the other.
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Figure 6: Differences between maximum rail and air afternoon temperatures averaged over a week

4. Data processing and results

Differences between rail and air temperature have been fitted to a linear law depending on solar ray inclination to local upright direction:

$$\bar{T}_r - \bar{T}_a = a + b \cos(\phi - \delta)$$

In the above relation $\bar{T}_r$ and $\bar{T}_a$ are the maximum (or minimum) rail and air temperatures averaged over a sidereal week. For a stronger relevance to operational track works operational organisation, day duration is divided into four “work slots”: night from 0 to 6 o’clock and 18 to 24 o’clock – morning from 6 to 12 o’clock – afternoon from 12 to 18 o’clock. Maximum (or minimum) are computed for every such “work slots” as well as for the whole day duration.

The following plot (Figure 7), that was obtained in April 2009, prove the validity of the assumed linear law.

Figure 7: Linear fitting (max rail – max air) on afternoon (week averages)
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**Table 2: Linear relationships between temperature differences and solar angulation (as of 14/04/2009 for average maximum temperatures)**

<table>
<thead>
<tr>
<th>Day-periods</th>
<th>RJ-AJ day-air</th>
<th>RN-AJ night-air day</th>
<th>RMA-AJ (rail morning-air day)</th>
<th>RAM-AJ (rail afternoon-air day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{T}_r - \bar{T}_a = a + b \cos(\varphi - \delta)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.75</td>
<td>0.67</td>
<td>0.63</td>
<td>0.74</td>
</tr>
<tr>
<td>$a$</td>
<td>-3.4</td>
<td>-8.9</td>
<td>-6.4</td>
<td>-3.5</td>
</tr>
<tr>
<td>$b$</td>
<td>20.6</td>
<td>16.8</td>
<td>19</td>
<td>20.5</td>
</tr>
<tr>
<td>RN-AN</td>
<td></td>
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</tr>
<tr>
<td>$R^2$</td>
<td>0.75</td>
<td>0.56</td>
<td>0.66</td>
<td></td>
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<tr>
<td>$a$</td>
<td>-6.6</td>
<td>-4.1</td>
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<td>$b$</td>
<td>17.2</td>
<td>19.5</td>
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<td>RMA-AMA</td>
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<tr>
<td>$R^2$</td>
<td>0.73</td>
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<tr>
<td>$a$</td>
<td>-4.5</td>
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<td>$b$</td>
<td>19.4</td>
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<tr>
<td>RAM-AAM</td>
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<tr>
<td>$R^2$</td>
<td>0.76</td>
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<td>$a$</td>
<td>-3.19</td>
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<tr>
<td>$b$</td>
<td>20.2</td>
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</table>

It was also proceeded to investigations about influence of other explicative factors, like for example longitude $\lambda$, according to the following linear equation

$$\bar{T}_r - \bar{T}_a = a + b \cos(\varphi - \delta) + c\lambda$$

Such additional factors are of less importance than $\cos(\varphi - \delta)$.

**Confidence intervals for rail temperature**

Let us now recall two results:

1. Average temperature $\bar{T}_m$ we can deduce from $n$ values of random variable $\bar{T}$ (in our case temperature averaged over a sidereal week) is roughly Gaussian so that the normalised variable

$$U = \frac{\bar{T}_m - m_m}{\sigma_m \sqrt{n}}$$

is a unit Gaussian, $m_m$ being the mathematical likelihood, $\sigma_m$ the standard deviation and $n$ the sample size$^3$.

$^3$ this is a consequence of central-limit theorem which holds for any collection of random variables following the same probability law (whether Gaussian or not)
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2- Difference between rail and air temperature can be fitted to a linear law

\[ \bar{T}_r - \bar{T}_a = a + b \cos(\varphi - \delta) \]

Given the assumed normalised Gaussian law for \( \bar{T}_a \) (Figure 8)

![Figure 8: Normalised Gaussian law](image)

the confidence interval for \( \bar{T}_a \), with an \( \alpha \% \) risk level, is equal to the area under the curve between

\[-u_\alpha \quad \text{and} \quad u_\alpha : P(m_a - u_\alpha \sigma_a < \bar{T}_a < m_a + u_\alpha \sigma_a) = 1 - \alpha\]

(\( n \) equals 1 because we restrict ourselves to confidence interval over a prescribed “sidereal week”)

From results 1 and 2 above, average rail temperature is a Gaussian \((m_r, \sigma_r)\), with \( m_r = m_a + a + b \cos(\varphi - \delta) \)

so that confidence interval is

\[ P(m_r - u_\alpha \sigma_r < \bar{T}_r < m_r + u_\alpha \sigma_r) = 1 - \alpha \]

with the same risk level.

Computation of confidence intervals for various risk levels is a straightforward process, as long as \( u_\alpha \) values are tabulated (in Excel for example).

We can summarize rail temperature prediction in two ways:

**Prediction 1:** For two rail temperatures \( T_1 \) et \( T_2 \), give the probability \( 1 - \alpha \)

of the following occurrence \( P(T_1 < T < T_2) = 1 - \alpha \)

**Prediction 2:** Given a probability level \( 1 - \alpha \), determine the two limiting temperatures \( T_1 \) and \( T_2 \).

The development and ensuing validation of the software required more than three years of track measurement work to be carried out. The relationship between the air and rail temperature, for both
Challenge G: An even more competitive and cost efficient railway left and right rails, together with prediction quality have been carefully monitored during the measurement works.

5. Making results available for operational needs

A software (dubbed “Predictor”, because of its scope) has been written to help use the above results for operational railway works planning.

A geographical interactive input and output interface has been chosen. Immediate conversions from geographical to rail conventions are automatically background-performed so that Infrastructure planners may keep on referring to lines, tracks or kilometric conventions they are accustomed to everywhere around the world, enabling easy data input and output.

Figure 9: Case study (Paris-Marseille line, probability of rail temperature between 40°C and 60°C on 19 August. Colour legend: red if 0<p≤0.25 / yellow if 0.25<p≤0.5 / blue if 0.5<p≤0.75 / green otherwise)

Predictor customisation

The Predictor was developed for the French railway network. It has been populated with:
- climatological data from 81 Météo France recording sites (lowest and highest daily temperatures for 18 years)
- French railway network map (lines, tracks, mileposts, longitudes, latitudes, altitudes).

The software is not restricted to the above initial configuration, so long as appropriate meteorological data and railway network geographical data is fed in.

Expectations

High quality predictions of thermal risk will save time on track works planning and management. The operating speed and the numerous query functions of the software enable works to be planned in an
optimal way. In addition, real time software answers secure better risk management over the duration of the works.

As of today, the «Predictor» software has been installed across SNCF railway network to help select best time slots and organise future track works, according to which temperature range is to be expected.

It is being routinely used over at least 20 regional track maintenance sites to prepare track works planning well ahead of time.

6. Conclusions

Rail temperature is a critical factor of track stability, because of compression or traction thermal stresses which develop inside rails and ensuing track buckling risks. Controlling this factor is thus a key issue for reducing any track works or operational hazards which may result from rail temperature exceeding some thresholds.

The afore paper demonstrates that, for a given site and year period, strong statistical relationships exist between rail temperature and atmospheric air temperatures, which are routinely produced for numerous countries by meteorological institutes and downloadable at a reasonable cost from whichever place around the world.

Practical use of this research work is already being done for maintenance teams by SNCF, with an application software specifically fitted to railway and track issues, through interactions between a geographical GPS based railway map and railway references making sense for infrastructure operators. These features include lines, tracks, stations, mileposts and more generally every single item like bridge, tunnel, switch, track component... This generic approach, along with Unicode coding conventions makes it easy to shift from a railway network configuration to another railway network configuration, for whichever national language or alphabet. It is also enabling seamless access to web resources such as satellite maps and photos as well as to mobile applications.

This decision tool helps making better choice of time window for track works so as to reduce rail thermal stresses and - should no other solution exist - to organise the necessary complementary operations ensuring track stability (like preliminary rail cutting for example).

This research is still giving rise to other ongoing developments: the next step will be dedicated to feasible day to day maximum rail temperature forecast for a one single day or for a range of several days, depending upon available meteorological forecasts. This aims at answering operational needs of modern track maintenance, which requires track works to be performed at any time over the year [3].

References


Acknowledgments
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