Real Time Prediction of Rail Temperature

Yu-Jiang Zhang
ENSCO, Inc., 5400 Port Royal Road, Springfield, VA 22151
Phone: (703) 321 4506    Fax: (703) 321 7619
E-Mail: yu-jiang.zhang@ensco.com

Jacinda Clemenzi
ENSCO, Inc., 5400 Port Royal Road, Springfield, VA 22151
Phone: (703) 321 4793   Fax: (703) 321 7619
E-Mail: clemenzi.jacinda@ensco.com

Kevin Kesler
ENSCO, Inc., 5400 Port Royal Road, Springfield, VA 22151
Phone: (703) 321 4444   Fax: (703) 321 7619
E-Mail: kesler.kevin@ensco.com

Sung Lee
U.S. DOT, Federal Railroad Administration, Office of Research and Development
RDV-31 Mail Stop 20, 1120 Vermont Ave., NW, Washington, DC 20590
Phone: (202) 493-6384    Fax: (202) 493-6333
E-Mail: sung.lee@fra.dot.gov

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ABSTRACT

Railroad safety is a top priority of the railroad industry. Preventing track buckling is important to infrastructure integrity and operation safety. It's a common practice that railroads impose slow orders during hot weather in which track buckling risk increases. The difficulty lies in quantification of track buckling risk. Track buckling is influenced by numerous factors, but the instant rail temperature and stress free (neutral) rail temperature are the critical factors. Unfortunately, neither of the two temperatures is easily obtainable. Decisions for slow orders are often based on an arbitrarily ambient temperature limit.

This paper presents a model for predicting rail temperatures based on the real-time meteorological forecast data. The model was developed by modeling the heat transfer process of the rail exposed to the sun. In developing such a model an experimental station is established, composed of a portable weather station and a short segment of rail track with temperature sensors installed on both rails. The model has proven to be able to predict the maximum rail temperature within a few degrees and within 30 minutes of the actual time when the maximum rail temperature happens during the day. The model has been validated for three locations where real time weather data and rail temperature are collected. The current effort has been on developing a real-time, Internet-based GIS map application for use by railroad professionals.

Keywords: rail temperature, prediction, weather, model
1. INTRODUCTION

Track buckling related derailments are very costly to the railroad industry. In 2004 alone, there were 19 derailments with $3,297,503 reportable damages according to the FRA Office of Safety database. To prevent track buckling derailments, railroads have adopted precautionary procedures that involve issuing of slow orders when daily ambient temperatures reach a certain level. Some railroads issue slow orders based on a weather forecast of ambient temperature. Some others send out track inspection personnel to measure rail temperatures before issuing slow orders. This practice is to a certain degree effective in reducing track buckling related derailments and associated costs. However, excessive slow orders and subjective inspections (which in many cases are unnecessary) cost the railroad industry many millions of dollars each year. Excessive slow orders may create congestion and bottlenecks possibly impacting nation’s economic well-being.

The most desirable method of issuing slow orders would probably be based on accurate instant rail temperature and rail neutral temperature (RNT), i.e. the stress free rail temperature. Both temperatures have been dealt with extensively by researchers and the railroad industry. Unfortunately, neither of the two temperatures is easily obtainable. Accurately measuring rail temperatures is limited by numerous factors, including resources, time of the day, rail orientation, location of the measuring points, measuring device, etc. Measuring RNT proves to be even more difficult. Complicating the issue further is that original RNT which is set when rails were installed changes continuously due to operational and environmental factors. Therefore, in practice, decisions for slow orders are often based on an arbitrarily ambient temperature limit.

This paper presents a rail temperature prediction model which can improve the slow order decision making process by providing reasonable rail temperature predictions. The objective is to predict rail temperatures based on real-time meteorological forecast data obtainable from commercial weather services.

The paper briefly discusses the system developed based on the model methodology,
which produces alerts for operations managers and train dispatchers. Such a system should lead to significant savings in operations costs while promoting the safety and mobility in the nation’s railroad systems.

In the proceeding sections, the paper discusses track buckling problems and current practices of quantifying buckling risks. The paper mainly deals with track buckling problems from the perspective of rail temperature. This includes theoretical modeling, experimental data collection, observation of rail temperatures, and preliminary model results.

2. FACTORS AFFECTING RAIL TEMPERATURE AND TRACK BUCKLING

It is well understood that track buckling is due to a combination of numerous factors. Figure 1 summarizes the factors/processes that influence track buckling. There is no doubt that the presence of rail longitudinal stress is essential for track buckling to occur. Track panel shift resistance becomes insufficient when rail longitudinal stress is high and results in high lateral buckling force once the track starts to buckle. External excitations are needed in most cases unless the stress level is extremely high and other factors set the perfect conditions for buckling.

Among all factors, perhaps rail temperature can be regarded the most important single influencing factor. The railroad industry has devoted significant resources to monitor rail temperatures with different degrees of success as rail temperature is influenced by many factors. There have also been efforts to correlate ambient temperature with rail temperature (e.g. Esveld, 1989). Linear regression technique is commonly used in quantifying the relationship between ambient and rail temperature. The correlation often focuses on the maximum daily ambient and measured rail temperatures for a specific period of time. The resulting "model" for rail temperature estimation has the following linear form:

\[ T_r = aT_a + b \]  
(1)

Where \( T_r \) = rail temperature;
\( T_a = \) ambient temperature; and

\( a \ & b = \) constants, representing the intercept and slope of the linear relationship

As illustrated in Figure 1, rail temperature is a function of various weather conditions and rail parameters. Ambient temperature is only one of weather parameters that cause rail temperature to change. Obviously a model in the form of equation (1) is inappropriate. Such a model would overestimate rail temperatures in cloudy and windy days and underestimate rail temperatures in clear and less windy days.

Nevertheless the previous studies have established good understanding of rail temperature ranges and track conditions under which track buckling is likely to occur. Computer programs were also developed to quantify buckling risks based on established critical rail temperatures for different track conditions, above which the probability of track buckling increases exponentially. It is widely accepted that in the worst case scenario rail temperature can exceed 40°F above the ambient temperature. On a 90°F day the rail temperature can presumably reach 130°F. The temperature is considered dangerous for track locations RNT may have dropped to 70°F from its original value. Based on this common assumption, railroads issue slow orders and conduct rail temperature measurement when forecast ambient temperature will reach 85 or 90°F and rail temperature will presumably exceed critical rail temperatures (60°F or more above RNT).

The study presented in this paper is not intended to validate if this worst case scenario would account for all cases of potential track buckling rail temperatures. Instead, the study attempts to develop a model that will provide quantitative indication on how high the rail temperature really should be for a specific set of weather conditions for any given hour of the day. For this purpose more weather parameters in addition to ambient temperature will have to be incorporated into the rail temperature prediction model. These parameters are discussed in detail in the following section.
2. MODEL APPROACH

The technical approach chosen in this study is to quantify the rail heating process in the open sun. The model will eventually make use of an existing comprehensive numerical weather model to project rail temperatures for assisting more objective and reliable issuance of slow orders. The benefit to use rail temperature is obvious following the discussion in the previous section. Instead of using the presumed worst case scenario rail temperature, the decision makers can use forecast rail temperatures to determine the needs for actions when the weather is expected to be hot.

The rail temperature model makes use of real-time weather data and track related information as the basis for rail temperature prediction. As an operational decision making assistance tool, the model is intended for up to 9 hours rail temperature forecast. Longer period of forecast is also possible but the level of confidence will diminish along with the weather forecasts. The model can be used with or without a network of rail temperature sensors mounted on rails. Where these sensors are available, the measured rail temperature along with current weather data will be used to predict future rail temperature at 30 minute intervals. In the absence of these sensors, the model will assume the rail temperature is the same as the early morning ambient air temperature in the process of prediction. The system frequently updates predicted rail temperatures based on the current rail temperature, as well as updated weather forecast data from the time of analysis until the end of the day.

The rail temperature forecast model is depicted in Figure 2. The rail temperature is derived by modeling transient heat transfer of a floating body representing a finite rail element. In reality, the rails are not completely afloat in the air since the interspersed ties and plates and continuous crushed rock ballast support the rails. The energy equilibrium for the rail element is of the following form:
\[
\dot{E}_{\text{absorbed}} + \dot{E}_g - \dot{E}_{\text{out}} = \dot{E}_{\text{st}} = \frac{dE_{\text{st}}}{dt} (2)
\]

Where

\( \dot{E}_{\text{absorbed}} \) – Rate of energy absorbed by the rail from the Sun and atmospheric irradiation

\( \dot{E}_{\text{out}} \) – Rate of energy emitted from the rail through conduction, convection and radiation

\( \dot{E}_g \) – Rate of energy generation due to conversion of energy forms

\( \dot{E}_{\text{st}} \) – Rate of energy stored

Equation (2) is a first order, nonlinear, non-homogeneous, ordinary differential equation. The energy balance is affected by weather conditions, rail metallurgical properties, rail size and shape factors, and environmental parameters. In this case, there is no energy generation due to energy conversion. Therefore, this component can be eliminated from the equation. The remaining energy components are influenced by the factors listed below.

Energy inputs due to solar and atmospheric irradiation:

1. Cloud coverage of the sky
2. Seasons – earth’s position relative to the Sun
3. Solar angle – function of time of the day and the seasons
4. Relative humidity and dew point temperature
5. Rail size and shape factors
6. Rail orientation
7. Rail surface Albedo (the measure of reflectivity of rail surface)

Energy emitted by the rail due to convection:

1. Ambient temperature
2. Wind speed and direction
3. Rail size and shape factors  
4. Rail surface area subject to convection heat transfer  
5. Rail orientation  

Energy emitted by the rail due to radiation  
1. Sky condition (cloud coverage)  
2. Relative humidity  
3. Dew point temperature  
4. Rail size and shape factors  
5. Rail orientation  
6. Rail surface emissivity  
7. Instant rail temperature  
8. Ambient temperature  

Energy exchange at the bottom of the rail:  
1. Heat conductivity and heat capacity of rail, tie, and ballast  
2. Shape factors of each component  
3. Voids and contact surface area  

Net energy gain/loss in the rail to cause rail temperature to change  
1. Specific heat of the rail material  
2. Density of the rail material

During model development, all parameters influencing each energy component were investigated. The energy exchange at bottom of the rail is ignored since the heat conductivity of wooden ties and rock ballast particles are far lower than that of steel. It is assumed that during the time period when the rail temperature is higher than the ambient temperature and that of ballast and ties, the energy emitted from the rail to these components is trapped at the contact surface. The net energy loss/gain at the interface of the bottom of the rail is considered minimal. Hence the model effectively treats the materials beneath the rails as an isolation layer.
For model development and calibration, a local experimental station was established (Figure 3). The station consists of a mobile weather station with an integrated sensor suite, rail temperature sensors, two short segments of 119 lb/yd rails that are installed on three wooden ties, and crushed rock ballast filling between ties and under the rails. The temperature sensors are installed in the web of the rails, collecting rail temperature at regular intervals. The portable weather station next to rail track collects comprehensive weather data at the same intervals.

The collected data are transmitted wirelessly to a data console with embedded data logger. The data console is permanently connected to a development computer. The data is uploaded to the computer hourly for model development and data analysis.

3. PRELIMINARY RESULTS

To demonstrate the model the first step is to examine whether the rail temperature exhibits a relationship that the modeling theory would expect. Figure 4 shows five days of measured weather and rail temperature data. It illustrates various weather conditions and corresponding rail temperature. Weather conditions included the following scenarios:

- Clear day with little wind (Jan. 12, 2006): Rail temperature reached 86°F (30°C), or 26.5°F (14.7°C) above the ambient temperature.
- Clear day with strong wind (Jan. 15, 2006): Rail temperature was 57.9°F (14.4°C), or 17.8°F (9.9°C) above the ambient temperature.
- Cloudy day with little wind (Jan. 13, 2006): Rail temperature was above ambient temperature, but did not raise much.
- Cloudy day with stronger wind (Jan. 14, 2006): Rail temperature was only slight above ambient temperature.
- Generally overcast with little wind (Jan. 11, 2006). Rail temperature was about the same as the ambient temperature.
The rail temperature model algorithm in the form of equation (2) was implemented in a computer routine. The meteorological data collected by the weather station were input into the program for retro-predicting rail temperatures at different prediction intervals. The model was run for the available weather and rail data since November 2006. Figure 5 shows the predicted rail temperatures compared with measured values for the above mentioned 5-day period. The results indicate that the selected model is appropriate for predicting rail temperatures based on weather data. In general the predictions appear to be reasonable. However, there are situations that the model may not have accounted for accurately. These include the effect of wind and heat radiation from the rail to the sky. Currently the model employs a simple method to apply the factor of wind cooling and linearly extrapolates the sky temperature, a parameter used in calculating heat radiation from the rail to the sky. The results indicate that the model may underestimate rail temperatures for some weather conditions, e.g. 1/11/06. The model seems to behave well for sunny days, e.g. 1/12/06 and 1/15/06.

Some of the parameters involved in the model may vary with seasons and geographical locations of different latitudes. The model was also verified for hot summer days. Figure 6 shows the model results for Springfield, VA for the week July 26 - 31, 2006. The model predicted the maximum rail temperatures within 2 °C (3.6 °F), except for July 26, 2006, for which the model overestimated the maximum rail temperature by approximately 4 °C (6.8 °F). It happened that during the hottest moments of the day a few quick passing clouds prevented the rail temperature to go up as predicted.

The measured daily maximum ambient temperatures and rail temperatures corresponding to the plots in Figure 6 are given in Table 1. The ambient temperature on July 31, 2006 was the highest. However, the highest rail temperature was observed on July 27, 2006, which reached 34.7 °F above the maximum ambient temperature. This underlines the fact that maximum ambient temperature does not dominate the rail heating process. On some hot days
the ambient temperature can linger at the proximity of maximum temperature for a couple of hours, while on some other days, the ambient temperature may drop quickly after reaching the maximum. These two scenarios will result in different rail temperatures. Of course, other factors such as wind and solar radiation also play important roles in affecting rail temperatures.

It is worth pointing out that on January 28, 2006, a relatively mild winter day, the rail temperature reached 93°F, nearly 30°F above the ambient temperature. This could sound alarm if the rail had been re-stressed for the winter season to reduce tensile stress and hence lowered the RNT with a rail plug.

The predicted daily maximum rail temperatures from February 1 to May 31, 2007 are plotted against the measured values as shown in Figure 7. The scattered plot illustrates that predicted rail temperatures agree reasonably well with measured values. These rail temperature predictions are based on observed weather data. The predictions are in 30 minute intervals.

The model accurately predicted the peak rail temperatures for most days. However, the model has overestimated or underestimate the peak rail temperature for some days. One of the reasons is that the model currently assumes a constant difference between ambient temperature and sky temperature in calculating energy radiated from the rail to the sky. In reality, the sky temperature can be 60°C below ambient temperature for clear sky or close to ambient temperature for overcast and rainy weather. The difference between the two temperatures also varies with latitude and seasons of the year when the earth's axis tilted at different angles toward the sun. Extensive literature search failed to identify models or procedures to quantify the sky temperature under different sky and weather conditions.

Other major factors affecting model accuracy include weather data updating intervals, wind speed and direction, and rail surface emissivity. Better dealing with these parameters should improve the model accuracy.
4. REAL WORLD APPLICATION

For practical application, the model will use weather forecast data for prediction of future rail temperature. Currently, the model receives real time weather forecast data decimated in 30 minutes intervals. The weather data are for 1700 forecast grids of the size 12x12 kilometer, covering 10 US states in the northeast. The real time weather data is transmitted into a file server. A data processor loads the processed weather data into a database. A web-based application will provide interfaces for users to view the rail-weather map and query the application to produce reports.

In addition to the station established for model development, two additional validation stations were established by Amtrak. Each station consists of a local weather observation station and rail temperature sensors. The rail-weather application predicts rail temperatures for the next 9 hours for the abovementioned forecast grids. The measured weather data and rail temperature data from these stations were used to verify the accuracy of the model predictions.

Figure 8 shows the rail temperatures predictions for December 15 – 31, 2006, using both forecast weather data and locally observed weather data at Springfield, VA. The solid line labeled "Predicted Rail T_m" is the rail temperature prediction using observed weather parameters. The dotted line labeled "Predicted Rail T_f" shows the rail temperature prediction using forecast weather data.

There are several degrees difference between the two sets of predictions on most days. On some days the predictions from forecast weather data are higher than those from observed weather data. On some other days the predictions from forecast weather data are lower. The fact that the trend is not consistent reflects the effects on rail temperatures of multiple weather parameters.

Figure 9 shows the comparison of two weather parameters involved in the model. The upper portion of the figure shows the observed and forecast solar radiation energy. The lower portion of the figure shows measured and forecast ambient temperatures in Celsius. It is seen that the
forecast data are very close to observed data for 12/23/2006. The predicted rail temperatures using the two sets of data are also very close as shown in Figure 8. On 12/17/2006 and 12/30/2006 the forecast weather data were also close to that observed at the local station. However, the predicted rail temperatures differed by several degrees. These differences are due to other weather parameters, one of which is wind speed not shown in the Figure 9. Modeling the effect of wind is particularly challenging. The forecast wind speed differs significantly from the locally observed values. The observation point where the anemometer is installed is several feet above the track level at which the wind speed and direction can vary significantly. Also, none of the three validation stations is clear of surrounding obstacles, such as trees, bushes and buildings. This means that the wind in some cases may not cool down the rail as the model has assumed.

The differences between locally observed weather parameters and forecast weather parameter highlight the needs to have more frequent weather forecast updates in order to reduce the uncertainties in rail temperature predictions. This requirement for short forecast intervals and high-resolution weather forecasts has posed challenges for longer term forecasts. The current 9 hourly forecasts are the best available due to limitations of the scope of the research project. Longer period of weather forecasts would translate into lower accuracy and resolution in rail temperature predictions.

5. CONCLUSIONS
The current industry practice of relying on forecast ambient temperatures for slow orders is inadequate because ambient temperatures are not linearly related to rail temperatures. Previous effort in modeling rail temperature using linear regression approach would lead to predicted rail temperatures far off the actual values.

A prediction model has been developed as the core component of a system for predicting rail temperatures, offering more accurate prediction of rail temperatures. The model is based on
a transient heater transfer phenomenon of a rail in the open sun. The algorithm was verified and calibrated using locally measured weather and rail temperature data. The preliminary results indicated that the model was able to predict rail temperature within a few degrees of accuracy in most cases, providing the weather data is accurate.

The rail temperature prediction model will inevitably inherit the uncertainties from the weather forecasts. Short weather forecast intervals are deemed important for accurate rail temperature predictions. Further validation and improvement of the model continue at the time the paper is written. Dealing better with key weather parameters should result in more accurate rail temperature predictions. Other factors, such as rail orientations, rail surface conditions and shape factor, and temperature gradient within rail cross section are also of interest to this project, although the current research points to minor effects on rail temperatures of these parameters.

The rail temperature predictions from such a system are expected to provide quantitative information for operation managers, train dispatchers and maintenance managers in slow order decision making process.

6. ACKNOWLEDGEMENTS

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7. REFERENCE

1. Esveld, C. 1989 Advanced Railway Engineering
### TABLE 1. Differences between Maximum Rail and Ambient Temperatures for July 26-31, 2006

<table>
<thead>
<tr>
<th>Date</th>
<th>Max. Ambient $T_{\text{amax}}$, °C (°F)</th>
<th>Max. Rail $T_{\text{ramax}}$, °C (°F)</th>
<th>Difference °C (°F)</th>
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<td>33.2 (91.76)</td>
<td>50.6 (123.1)</td>
<td>17.4 (31.3)</td>
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<td>7/29/2006</td>
<td>34.9 (94.8)</td>
<td>51.7 (125.1)</td>
<td>16.8 (30.2)</td>
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<td>7/30/2006</td>
<td>35.6 (96.1)</td>
<td>53.3 (127.9)</td>
<td>17.7 (31.9)</td>
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<tr>
<td>7/31/2006</td>
<td>36.8 (98.2)</td>
<td>53.3 (127.9)</td>
<td>16.5 (29.7)</td>
</tr>
</tbody>
</table>
FIGURE 1. Factors Influencing Track Buckling

- Rail size, shape, orientation, and other physical/environmental factors
- Train passes, other
- External excitation & alignment imperfections
- Compressive rail longitudinal stress
- Rail temperature
- Rail Neutral temperature
- Loss of shoulder ballast
- Insufficient lateral track panel shift resistance
- Maintenance disturbance
- Traffic & environmental parameters
- Other factors
Emitted convection, $\dot{E}_{\text{conv}}$
Emitted radiation, $\dot{E}_{\text{rad}}$
Reflected
Radiation energy from the Sun & atmosphere
$\dot{E}_{\text{absorbed}}$
Energy stored, $\dot{E}_{\text{st}}$
$\dot{E}_{\text{other}}$

FIGURE 2. Transient Heat Transfer of a Rail Element
FIGURE 3. Experimental Station
FIGURE 4. Measured Rail Temperatures and Meteorological Data
FIGURE 5. Predicted Rail Temperatures Overlaying with Measured Data
FIGURE 6. Predicted Rail Temperatures versus Measured Data, July 2006
Predicted versus Measured Daily Rail Temperature
2/1/07 to 5/31/07

Predicted Daily Max Rail Temperature, °C

Measured Daily Max Rail Temperature, °C

R² = 0.9703

FIGURE 7. Predicted and Measured Daily Maximum Rail Temperatures
FIGURE 8. Predicted Rail Temperatures using Forecast and Observed Weather Data for Springfield, VA
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