Rail Temperature Prediction Model Based on Heat Transfer Principles

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ABSTRACT

The Federal Railroad Administration has developed a model and system for predicting rail temperatures using real time weather forecast data and predefined track parameters. The objective is to aid railroads in making more informed decisions on slow speed orders when the rail temperatures are expected to exceed certain limits.

The system has been validated using both forecast and locally observed weather data. The predicted rail temperatures are found to be within reasonable ranges, giving confidence in the validity of the model algorithm. When weather forecast data is used as inputs, the deviations in predicated rail temperatures grow larger as the uncertainties are inherited from the weather forecast data.

In this paper, major improvements in the model algorithm are discussed and demonstration results are presented.

1. INTRODUCTION

Track buckling related derailments are very costly to the railroad industry. According to the FRA Office of Safety database, there were over 150 derailments related to track buckles and/or sun kinks between 2005 and 2009, resulting in over $43 million in damages.

There are guidelines in AREMA's Manual for Railway Engineering for rail installation and track maintenance practices for continuous welded rails (CWR) to minimize the risk of track buckling. However, with all the guidelines followed, precautions still need to be taken in circumstances when a combination of factors becomes conducive to track buckling. For example, on hot summer days railroads impose slow orders when ambient temperatures reach a certain limit. Some railroads issue slow orders based on the ambient temperature from weather forecasts while others deploy track inspectors to measure rail temperatures before issuing slow orders.

The rationale of issuing slow orders using ambient temperature is based on the belief that the rail temperature typically rises 16.5 to 19.5 °C above the ambient temperature. If the rail temperature becomes substantially higher than the stress-free rail temperature, or rail neutral temperature (RNT), longitudinal forces can build up and accentuate the risk of track buckling.

The practice of slow orders is effective in reducing track buckling related derailments and associated costs. However, excessive slow orders and subjective inspections cost the railroad industry millions of dollars each year. Excessive slow orders can also be an issue for high density tracks, possibly impacting the nation’s economic well-being.

For more reliable determination of slow orders and assessment of track buckling risk, the FRA has sponsored the development of a model for predicting rail temperatures based on real-time meteorological forecast data. The model was validated using both forecast and locally observed weather data. The predicted rail temperatures were found to be within reasonable ranges. The model has been implemented into a web-based rail-weather application. It was demonstrated and tested on Amtrak's NEC in 2007. Further trials were conducted at selected locations on UP and

BNSF networks in late 2008. Most of these test locations have local weather stations and other wayside measurement systems continuously collecting weather and track data including rail temperature. The model has been implemented and is predicting rail temperatures for the entire US continent.

The model is based on a transient heat transfer process in which the energy balance continuously changes, causing the rail temperatures to rise or fall [1].

This paper presents major improvements in the model algorithm made through recent research efforts. It also discusses some sample results produced by the model using measured weather data. Future challenges with respect to model improvements will also be highlighted. The main features of the rail-weather system are briefly introduced.

2. RAIL STRESSES AND BUCKLING RISK

Track buckling has been a phenomenon associated with CWR since they were introduced in Europe in the 1950s. CWR track can buckle in both the vertical and lateral planes. A track is vulnerable to buckling when the rails are subject to longitudinal compressive stresses, coexisting with a combination of other influence factors, such as lack of track support, deterioration of ties, imperfections in track geometry, and excitation of trains.

The stress state of CWR is related to the instantaneous rail temperature and RNT, a temperature at which the rails are stress free. The initial RNT is set at rail installation to a level higher than the anticipated rail temperature range to compensate the thermal expansion and to lower buckling risk. It varies among railroads but can be as high as 43 °C. When the instantaneous rail temperature is below the RNT, the rails will be subject to tensile stresses. Otherwise the rails will have compressive stresses.

Although the rail stresses can result from several sources, the single largest source of compressive stresses in rails is the thermal expansion, which is attributed to the difference between instantaneous rail temperature and the RNT. Instantaneous rail temperature varies significantly from day to day and at different times of the day. It can exceed 65.5 °C on hot summer days. The RNT is supposed to remain relatively stable. However, once the track is subject to train traffic, the RNT can change over time and even at different times of the day. Measurements on a tangent concrete-tie track on Amtrak's NEC showed that the RNT could vary about 5.5 ^{o}C on any day. The variation in RNT can be even greater on both lateral and vertical curves. The RNT variation on vertical curves is mainly due to train braking or acceleration and that on lateral curves is attributed to track "breathing" caused by train traffic and weather conditions.

Factors influencing track buckling risk has been graphically depicted in the past research [1] as shown in Figure 1. Buckling risk rises for any or a combination of these factors:

- At curves where the RNT may have dropped
- High rail temperatures
- Track misalignments
- Train hunting or unfavorable vehicle/track interactions
- Train braking and acceleration
- Track tamping and insufficient stabilizing
- Spot track repairs and maintenance which can cause either the RNT or the track strength to change
- Lack of track support: localized weak track foundation, lack of shoulder ballast
- Abrupt changes in track stiffness after a prolong rainy period in poorly drained areas
- Transitions between regular track and bridges, tunnel and crossings.

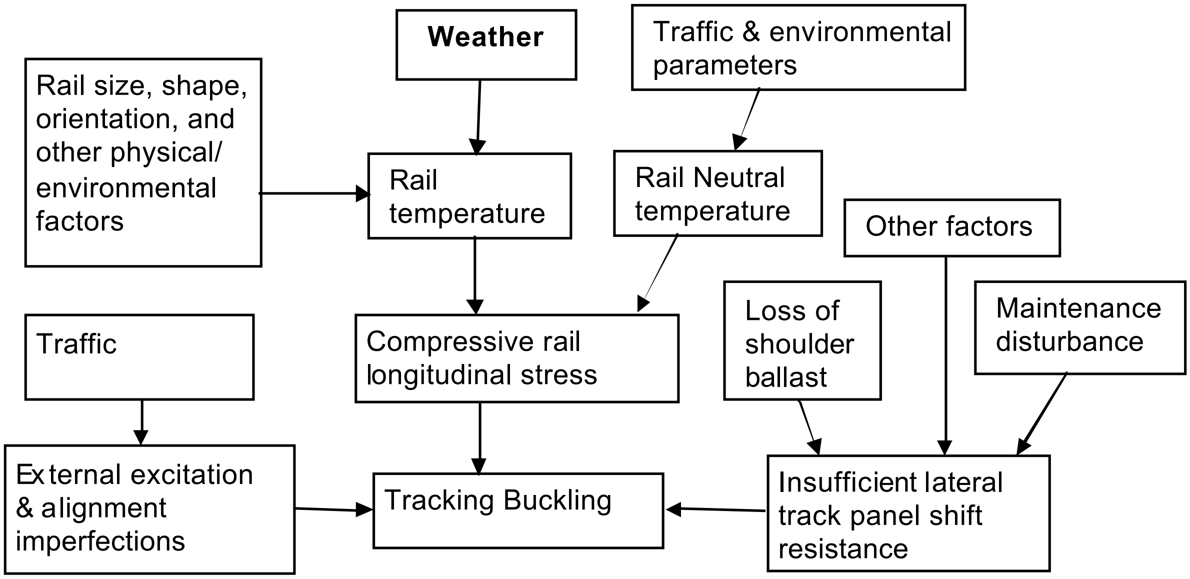

Figure 1 Factors Influencing Track Buckling

It is worth emphasizing that a combination of several of the factors shown above is important in promoting track buckling. Train presence is a key contributor to track buckling because the energy input will accentuate the track buckling forces. Theoretical analyses and tests indicate that without train energy, the rail temperature has to rise significantly above the RNT to buckle an average track [2].

Track buckling can happen in a few of seconds under train load. Unfortunately, it is difficult to pinpoint the track defects after a derailment because much of the evidence is often destroyed during the rescue and clean up process before the investigation begins. After an incident occurs, there is oftentimes debate as to whether track buckling caused the train to derail or the train derailment buckled/damaged the track. Regardless, track owners have devoted significant efforts into managing track buckling risks. Railroads have instituted heat management programs involving measuring and monitoring rail temperatures [3]. Maintenance practices for buckling prevention have been adopted and continuously improved by the railroad industry [3-7]. Extensive research into buckling theory [2,8-10] has helped the development of computerized tools for buckling risk analysis [11]. Despite all these efforts, track buckling related derailments still occur. According to the FRA rail incident database, there were 153 derailments caused by track buckling or sun kinks between 2005 and 2009.

Of the 153 derailment accidents, approximately two-thirds occurred between 1 pm and 4 pm. It is worth mentioning that the ambient temperature at the time of derailments ranged from 4.5 to 41 ^{o}C. In issuing slow orders, a common practice is to assume the rail temperature would rises 16.5 °C above the ambient temperature. This assumption is proven to be valid for many cases but not in extreme scenarios. The measured rail temperature and weather data showed that rail temperature could rise 22.5 ^{o}C above the ambient temperature on clear and calm days, and only go several degrees above the ambient temperature on clear but windy days. Of course, the change of RNT could have contributed to a large portion of these buckling incidents. Unfortunately, the RNT at time of derailment cannot be determined once the track has buckled, resetting the RNT to a new value.

The model discussed in this paper provides physical, quantitative indication on how high the rail temperature will likely be for a specific set of weather conditions for any given hour of the day. For this, more weather parameters in addition to ambient temperature have to be incorporated into the rail temperature prediction model.

3. RAIL TEMPERATURE PREDICTION MODEL

3.1 Development and Validation of the Model Algorithm

The technical approach chosen for the model is to quantify the rail heating process due to the sun. The model makes use of weather forecast data from a numerical weather model to project rail temperatures for the next 12 hours at 30 minute intervals. The technical details of the model have been reported elsewhere [1,12].

The model algorithm was found to be valid as evidenced in the predicted results reported in [1]. Figure 2 shows some sample predictions using measured weather parameters from the weather station established for model development.

The model was implemented and tested in several continuous periods between 2007 and 2008 for 10 US northeast states covered by Amtrak's NEC. Amtrak installed rail-weather stations at two locations which provided measured rail temperature data as well as measured weather parameter data for model validation.

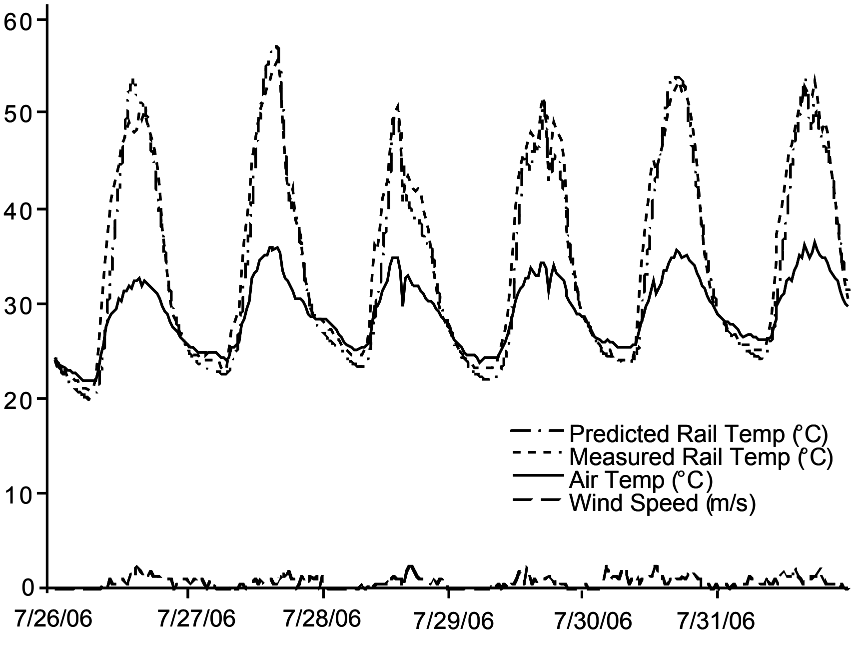

Figure 2 Predicted Rail Temperatures Compared with Measured Data [1]

The model generated rail temperature predictions using weather forecast data from a high-resolution mesoscale metrological model. Predictions for 10 days in September 2007 are given in Figure 3. As expected, the spread in the predictions was wider than that generated using locally measured weather data. The predicted rail temperature peak for September 2, 2007, was about 5.5 °C higher than the recorded value. Detailed examination of the data revealed that for this particular day the weather forecast over predicted the solar radiation but under predicted wind speed. These are two of the three core weather parameters in the rail temperature model. The combination of over predicting the former and under predicting the latter contributed to the seemingly large error for this particular day. A review of the rail temperature predictions for the summer of 2007 further revealed that the model performed reasonably well in predicting the timing of peak rail temperatures. For most days, the predicted time of peak rail temperature was within 45 minutes of the time at which it was observed in measured data. The deviation can be attributed to several sources including weather forecast, locality parameters and limitations of the model itself.

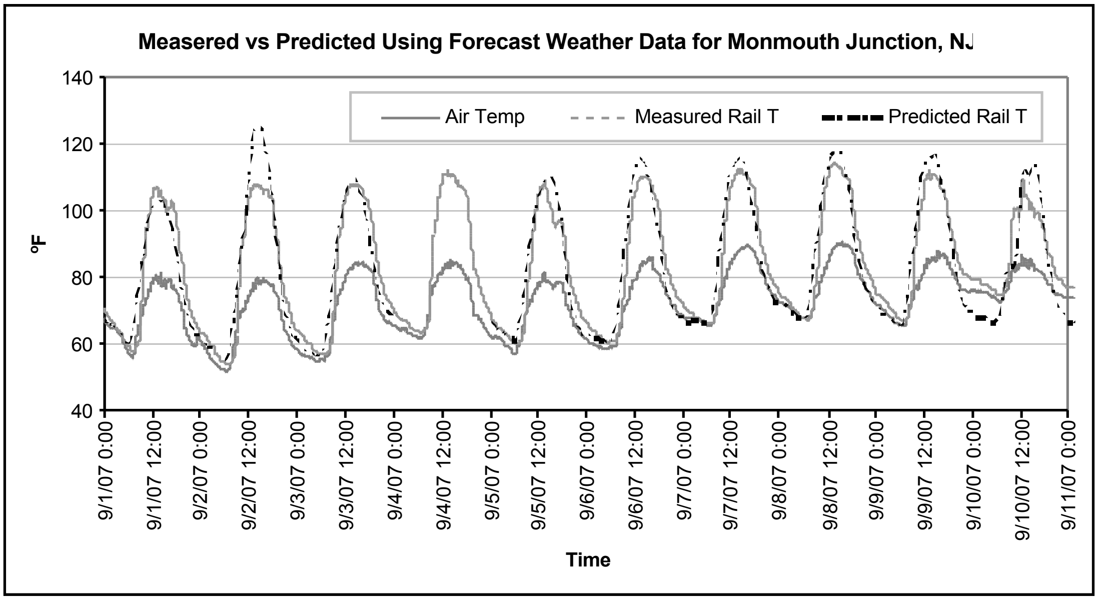

Figure 3 Predicted Rail Temperatures using Forecast Data, Sep. 2007

Further efforts were devoted to improving the model algorithm. Areas of improvement for the model include:

- More precise definition of rail surface area exposed to radiation, convection and conduction heat transfer;
- Refinements of surface emissivity and convection coefficient;
- Inclusion of heat exchange between rail and ballast; and
- Inclusion of solar angles based on time of the day and day of the year for computation of solar energy radiated into the rails

These changes were implemented in a stand alone program which was used for model development. The improved model output is shown in Figure 4 for the same 10 days of September 2007. The predictions for September 2, 2007, matched the recorded values reasonably well. However, the model appeared to over predict rail temperature for September 1, 2007. The recorded weather data showed that solar radiation fluctuated significantly during the hottest period of that day. The sudden and steep drops in solar radiation may not always be felt by the model due to the 15 minute sampling interval for the recorded weather parameters being input into the model. On the other hand, the solar radiation forecast for this particular day were lower than the measured values, but without the sudden dips. Therefore, the model prediction using forecast data seemed to match the recorded data better, although it was a result of error cancellation.

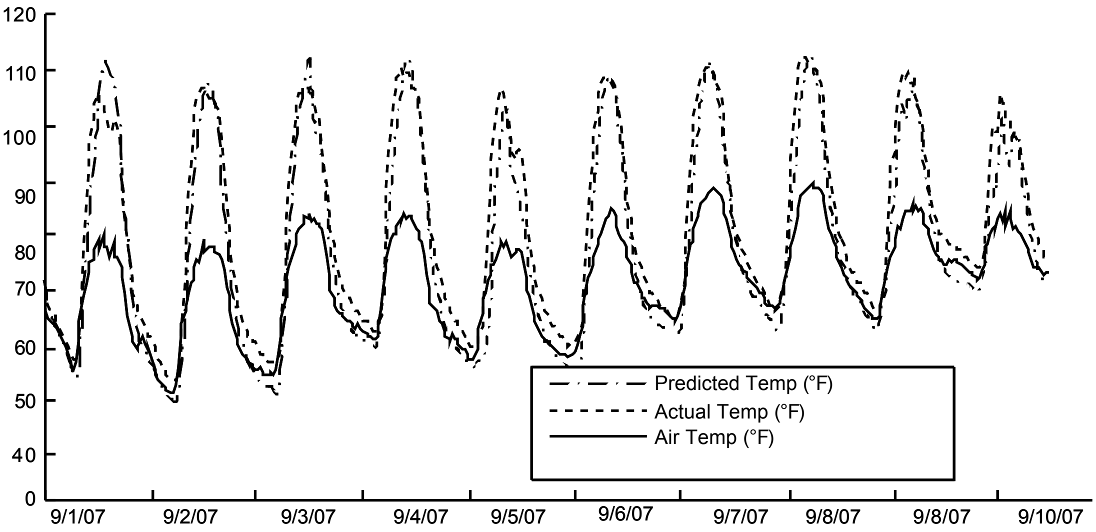

Figure 4 Predicted Rail Temperatures Using Recorded Data, Sep. 2007

The new model algorithm was also applied to seven locations where recorded weather data and rail temperature data was available. These locations are on Amtrak's NEC, from Washington, DC, to Boston, MA. Model predictions for Monmouth Junction, NJ, for 13 days of August 2009 are shown in Figure 5.

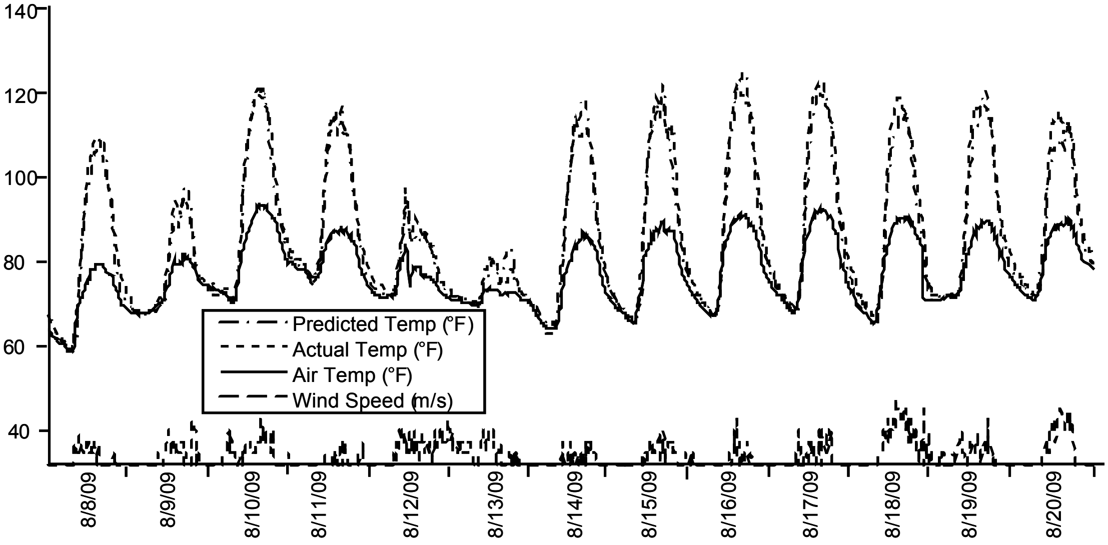

Figure 5 Predicted Rail Temperatures Using Recorded Data, Aug. 2009

The results seem to indicate that the model has captured the major modes of the heating and cooling process of the rails exposed to the energy from the sun and surroundings. However, on some days the model predictions still deviate from the actual rail temperatures, even using recorded weather parameters. Factors influencing the accuracy of the model predictions have been discussed previously [1]. Since the model has been developed with practical application in mind, the parameters that are difficult to obtain from typical weather service providers have not been extensively investigated. Locality parameters, such as surrounding condition, blockage of wind by trees or structures, and elevation of the track, have not been built into the model as those parameters can vary from one location to another.

Rail material properties and surface conditions also influence the predicted results but their effects do not appear to be very significant. Wind is one of the dominant parameters affecting rail heating/cooling process. The wind speeds at the measurement point 9 meters above surface and at the rail surface differ considerably. The direction of the wind for a particular location may change every few minutes. There are models for interpolating wind speeds at different heights above the ground. However, the variation in locality parameters often renders these models invalid for the tens of thousands of the 9x9 km weather grids all over the US.

Attempts were also made to include the heat exchange between the rails and ballast. The ballast itself was found to be more complicated to model than the rails because the uneven surface of the rock particles makes it difficult to select radiation and convection coefficients. In addition to the heat exchange with the rails, the ballast also conducts heat to and from the underlying subballast and subgrade layers. Choosing appropriate depth for heat conduction and computing the body volume for heat transfer is extremely onerous.

3.2 Rail Temperature Prediction System

In parallel with the model algorithm improvement, the rail temperature predication system was extended to cover the entire continental US. Figure 6 shows the configuration of the system. A file server receives weather forecast data for 12 hours at 30 minutes intervals. A data processer residing on the server processes and feeds the weather data to the rail temperature prediction model. The predicted rail temperature and key weather parameters are stored in the database which also resides on the same computer server. An internet server hosts the web-based rail-weather application which retrieves data from the database and displays the results on the map-based user interface. The user interface contains the interactive US rail network as well as the base US geographical map layer. The weather forecasts cover the entire US continent for continuous 9x9 km weather grids. For the rail-weather application, the grids not bordering railroad tracks were filtered out and a discrete base rail-weather map was created.

When accessing the application through internet, a user will be presented with a color coded rail network map of the US continent. When the map is zoomed to a certain level, contiguous 9x9 km grids covering rail tracks become visible. The color of the grids was pre-programmed according to the predicted rail temperatures, with red for alarm level, yellow for warning level, and green for normal or safe level. The application also predicts buckling risks for different types of rail track. This was done by referencing a risk matrix for various combinations of track structure characteristics and rail temperatures. The risk matrix was built using the CWR SAFE software developed by the FRA through Volpe National Transportation Systems Center.

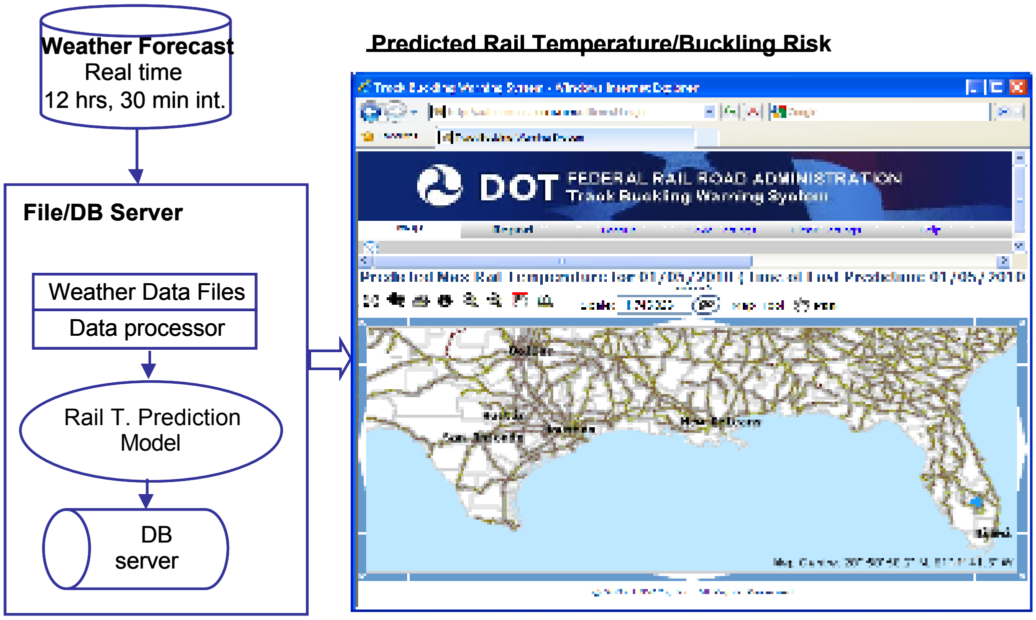

Figure 6 Current Rail Weather System

The differences between locally observed weather parameters and forecast weather parameters highlight the needs to have more frequent weather forecast updates in order to reduce the uncertainties in rail temperature predictions. The requirement for short forecast intervals and high-resolution weather forecast has posed challenges for long-term forecasts. The current 12 hour forecasts are limited by the scope of the research project. Longer term forecasts would translate into lower accuracy and resolution in rail temperature predictions.

4. ACKNOWLEDGEMENTS

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