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RESEARCH RESULTS

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DEMONSTRATION OF MECHANICS-BASED TRACK GEOMETRY DETERIORATION MODELS

SUMMARY

From July 2020 to August 2021, the Federal Railroad Administration (FRA) contracted Transportation Technology Center, Inc. (TTCI) to expand on existing mechanics-based ballast condition forecasting models. This report demonstrates how one of the mechanics-based models performs against field data and makes recommendations for improving that model.

Overall, the model demonstration showed the mechanics-based model, and its variations matched the general revenue service (field) behavior of ballasted track and also identified potential improvements. The field data results reinforced that ballast fouling index (BFI) is a key factor in track geometry degradation. However, the demonstration identified that there are additional unmeasured factors besides BFI that can cause variations in the BFI-track geometry degradation relationship. Linear track geometry degradation with million gross tons (MGT) fit the field data better than the historical logarithmic curve.

Once the model has these updates, future work can focus on making the model more flexible. This work will identify and add other key variables that affect track geometry. Benefits will include higher accuracy, the ability to make projections in track situations with little historical data (assumed values) or become site specific to a particular track section (statistical fits), and incorporate uncertainty and risk.

BACKGROUND

Forecasting ballast-induced track geometry degradation is difficult because of the complex ballast degradation mechanism and difficulty characterizing the ballast. Multiple mechanics-based track geometry degradation models exist, including previous TTCI-developed models. However, these models have not been updated, and they do not incorporate significant recent improvements in understanding fundamental ballast behavior, ballast inspection technologies, and data analytics.

This report summarizes results from a recent FRA project to update previous mechanics-based track geometry deterioration models so that the model inputs align with outputs from the inspection technologies that are either currently used or currently in development [2]. This research will potentially improve the ability to forecast track geometry behavior. This could include short-term risk assessments, projections on how track behavior may change depending on ballast maintenance, and long-term forecasts to incorporate changes in track structure, tonnage, or climate.

MODEL SELECTION

This review compares the Railway Track Life-Cycle Model (RTLM) [1], a TTCI-developed mechanics-based model, against a statistical fit with field data. The RTLM is the most comprehensive mechanics-based model, and it incorporates tonnage, axle load, ballast abrasion number, BFI, climate, tie type, subgrade type, and track modulus.

The details of the RTLM model are beyond the scope of this project, however, there are some key model features. First, the RTLM model projects ballast settlement with a logarithmic fit, meaning there is high initial settlement, and that the settlement rate decreases with MGT. Second, the RTLM model is highly sensitive to axle load, BFI, climate, and track modulus. To convert the settlement to the more commonly used 62-foot mid-chord offset surface profile, a conversion factor of 0.3 is used, but this conversion is expected to vary depending on the situation. The surface profile is referenced as surface magnitude (SM) and represents the maximum absolute value of the 62-foot surface profile.

Figure 1a shows an example of a response with MGT to emphasize the logarithmic curve. Figure 1b shows the settlement at 100 MGT over a range of BFI and climate values. The BFI relation has an inflection point at BFI=30 where the trend becomes non-linear. This inflection is attributed to when most ballast voids become filled with fines and start to inhibit drainage.

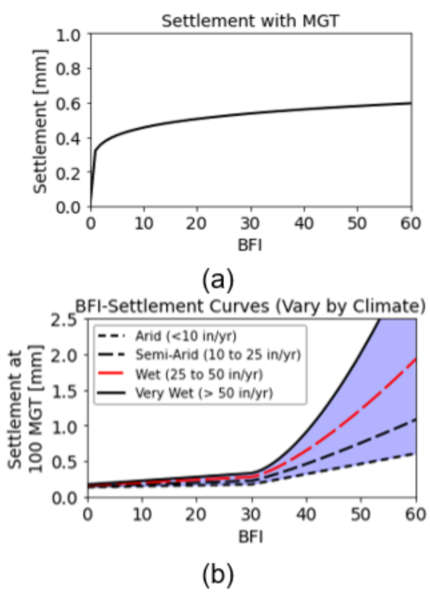


Figure 1. RTLM Model with (a) MGT and (b) Influence of BFI and Climate

DATA COLLECTION

A North American Class 1 provided the data used for the model demonstration. The location was in a wet climate region of the Midwest United States (~30 inches annual rainfall). The data was assessed using a "window analysis" method to evaluate the maximum SM and BFI over a 0.05-mile window.

The window analysis matches the single location projections of the RTLM model, easily accounts for unscheduled maintenance, and keeps a reasonable distance between selected locations.

The analysis avoided transition locations such as nearby bridges, road crossings, and turnouts because these areas typically behave differently than open track. Researchers plan to include transition locations in future analyses.

At each selected window, the SM degradation rate (dSM) was calculated for each surfacing cycle. If a ground penetrating radar inspection occurred within that surfacing cycle, the dSM and BFI values were chosen for comparison. Figure 2 shows both a heatmap of the track geometry and the surface profile degradation for a 1,500-foot section.

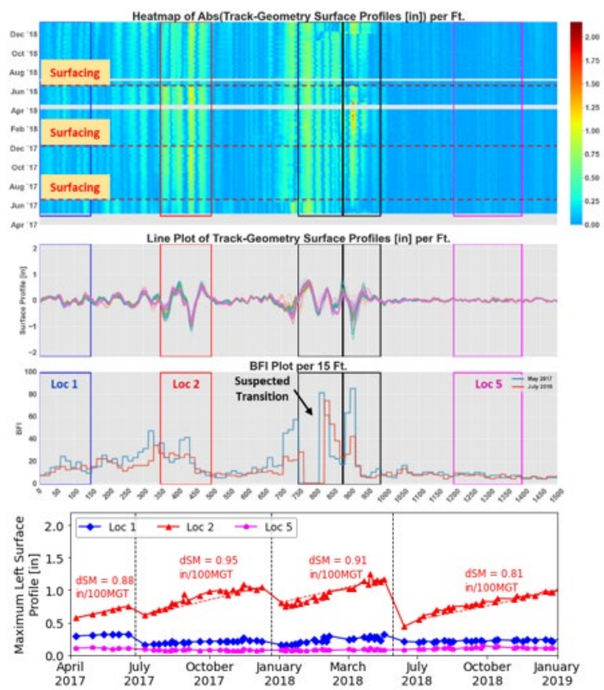


Figure 2. Example Results from Data Collection

Statistical power law fits were used to fit the data that allow for projections of dSM using the BFI value at a particular location. The data was split into three track segments, separated by mainline turnouts, because the ballast maintenance history was anticipated to be different for each track section.

MODEL DEMONSTRATION

The next step compared the RTLM model outputs to the field data. The goal of this comparison was not to determine which method is more accurate. The statistical model will inevitably be more accurate because it was fit to this dataset. The goal was 1) to demonstrate the capability of the RTLM model when it comes to track geometry degradation projections and 2) to determine improvement strategies for the RTLM model.

The first comparison looked at the BFI-dSM curves. Figure 3 shows four RTLM BFI-dSM curves, representing four possible climate conditions. The RTLM curves match the general shape of the field data. At BFI<20, the dSM values are typically less than 0.5 inch/100 MGT; however, at BFI>20, there are more variations and higher values. Note that the RTLM curve is a median fit, so it is not expected to incorporate scatter.

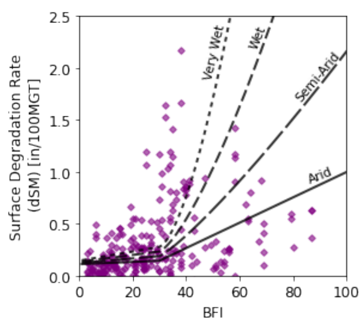
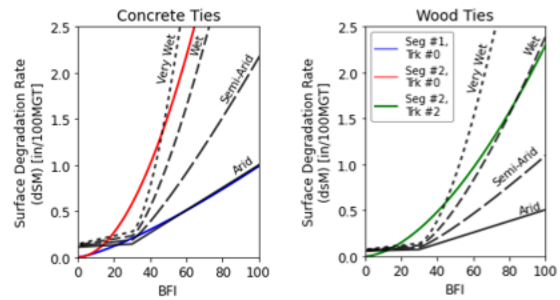


Figure 3. RTLM BFI-dSM Curves against Field Data

Figure 4 plots the four RTLM climate curves and the three statistically fit curves from the three field data track segments in blue, red, and green, respectively. Overall, the RTLM and statistically fit curves agree well, with some minor shape differences. Figure 4a assumes concrete ties, and Figure 4b assumes wood ties. Figure 4a shows how two track sections in the same subdivision (blue and red lines) can vary as significantly as the RTLM-assumed variation of different climates. The difference between the statistically fit curves (blue and red lines) is likely due to different ballast maintenance histories as Segment 1 (blue line) was undercut 2 years before the study while Track 0 in Segment 2 is B (red line) has not been undercut for at least 5 years.

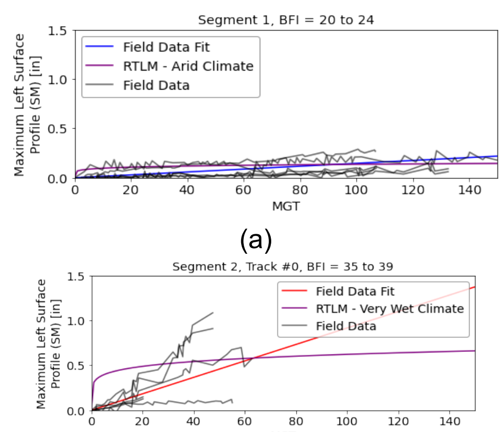
Figure 4b shows that Segment 2, Track 2 (green) has similar behavior to Segment 2, Track 0 (red), if considering tie type. Both Segment 2 curves (red and green) also match well with the initial wet climate assumption.



(a) (b)

Figure 4. RTLM and Best Fit Curves for (a) Concrete and (b) Wood Ties

Figure 5 plots the SM degradation with MGT for two example situations. Figure 5a and Figure 5b include the RTLM model (logarithmic curve, purple), the statistical fit based on field data (linear response, blue, red), and the field data (gray).



(b)

Figure 5. RTLM Model with (a) MGT and (b) Influence of BFI and Climate

Figure 5a shows all the data in Section 1 that had BFIs between 20 and 24. Referencing Figure 4a, Segment 1 was recently undercut, so it had the shallowest BFI-dSM curve. In this instance, the RTLM and field data fit match well.

Figure 5b, however, shows the data in Segment 2, Track 0 that had BFIs between 35 and 39. Figure 4a shows Segment 2, Track 0 has the steepest curve and highest track degradation rates. The results clearly show the linear response better suits this dataset than the logarithmic fit.

SUMMARY AND NEXT STEPS

Overall, the mechanics-based RTLM model matches the field data well with room for improvement. First, the RTLM BFI-dSM curve shape matches the field data, and the assumed climate variation in the BFI-dSM curves is like the variation in the statistical fits. While the variation in the RTLM model and field data are from different factors (climate versus ballast maintenance history), both factors can be accounted for using similar methods. Also, a switch from the RTLM BFI curve to a power law fit is recommended because the power law inputs are easier to back-calculate from field data, and in-depth comparisons show the power law provides a better fit.

Second, a replacement of the logarithmic degradation curve (Figure 5) with a linear degradation is recommended. While the logarithmic fit often matches settlement data well, it is not shown in this track geometry dataset. One potential reason is that the high initial settlement rates are often not captured by the first track geometry run, and the ballast has already consolidated. Another reason is that linear responses may be more common in high degradation locations, which are the focus of this study. Third, the RTLM model was developed for settlement, and likely does not have a clean linear conversion to surface profile degradation.

Future studies will continue to analyze field data and implement the recommendations made in this study to develop a modified track geometry deterioration forecasting model. The end vision is a hybrid model that uses machine learning statistical fits on top of a mechanics-based foundation using data that can be input from track inspection vehicles.

REFERENCES

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CONTACT

Hugh B. Thompson III
Program Manager
Federal Railroad Administration
Office of Research, Development and Technology
1200 New Jersey Avenue, SE
Washington, DC 20590
(202) 493-6383
hugh.thompson@dot.gov

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