Use of Track Based Inspection Technologies to Improve BNSF's Ballast Maintenance Planning

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ABSTRACT

Over the past decade, BNSF has made data collection a priority through the use of both hi-rail inspection vehicles and high-speed train-based inspection platforms. These vehicles allowed BNSF to collect data across its entire track system over regularly scheduled intervals. Data sets such as track geometry, ballast fouling index and free draining layer, helped guide ballast maintenance decisions and improve the understanding of ballast conditions over BNSF's network.

The collection of this data also allowed for large-scale multi-dimensional analysis of track and ballast condition metrics which further informed ballast maintenance decisions. This analysis included, but was not limited to, correlations between track geometry degradation and ballast condition or track geometry degradation forecasting based on machine-learning methods. When implemented, these methods were incorporated into a risk-based ballast maintenance system which further improved ballast maintenance overall. This paper describes how advancements in track-based inspection technologies mentioned above have improved BNSF's ballast maintenance planning techniques and how innovative data analytics can provide a roadmap to future ballast maintenance modeling.

INTRODUCTION

The ballast layer is a key railroad track component that functions to support the track, help resist track movements, and drain excess water away from the track. As with all track components, the ballast will eventually degrade, and its ability to properly function as intended is reduced as time and tonnage accumulate. This ballast degradation can lead to increased settlement rates and track geometry deviations, high levels of displacement, and/or development of mud pumping or ponding water. While ballast degradation cannot be fully prevented, properly planned and executed ballast maintenance can extend the life of the ballast. This paper describes how BNSF Railway improved the capabilities of its track-based inspection program over the past decade and has partnered with Transportation Technology Center, Inc. (TTCI) to better understand the effectiveness of ballast maintenance activities while also improving the understanding of how ballast condition impacts track geometry degradation.

BALLAST BEHAVIOR AND CHARACTERIZATION

Ballast resists movements through the interlocking of its individual ballast particles. In clean ballast, the large ballast particles can provide strong resistance to movement while also allowing water to drain from the track. Over time, these ballast particles degrade, and fines from the degraded ballast and possibly outside the ballast may accumulate in the ballast layer. In North America, this condition is generally characterized with Selig's Fouling Index (FI) [1,2], which refers to the percentage of particles by mass that pass through the #4 sieve (P4) plus the additional influence of particles that pass through the #200 sieve (P200). The equation is shown below:

$$FI = P_4 + P_{200}$$

While Selig's FI is considered to be a key indicator of ballast performance, many other ballast metrics such as ballast shape, moisture, fine type, and fine distribution within the ballast layer are also known to influence performance [1–3]. However, many of these metrics are difficult to characterize and relate to ballast performance, so Selig's FI is typically the standard metric used to indicate ballast condition.

Historically, Selig's FI was measured by physically removing samples and performing gradations. This process was not ideal because it disturbed the track, required track time, was time consuming, and was labor intensive. In the 1990s and 2000s, ground penetrating radar (GPR), which had application in other transportation fields, was developed to represent Selig's FI based on radar response. Using GPR instead of physical sampling allowed for track-based measurement that did not disturb the track and could be scaled-up for use over an entire railroad network.

The primary GPR output in North America is Ballast Fouling Index (BFI) which is the representative FI to a depth of approximately 16 inches below the track surface. In this paper, the term "Selig's FI" refers to a value from physical sampling, while "BFI" refers to the GPR estimation of Selig's FI. Free draining layer, or FDL, a second metric, is also discussed and represents the depth of the clean free drainage ballast layer. FDL is helpful because fines are typically not evenly distributed within the 16 inches below the track surface and fines typically begin at the bottom ballast layer and then gradually accumulate upwards towards the bottom of the tie and eventually reaches the track surface. A simplified example is shown in Figure 1. A fully clean ballast section will have an FDL of 16 (16 inches) while a surface mud condition will have an FDL of 0 (0 inches).

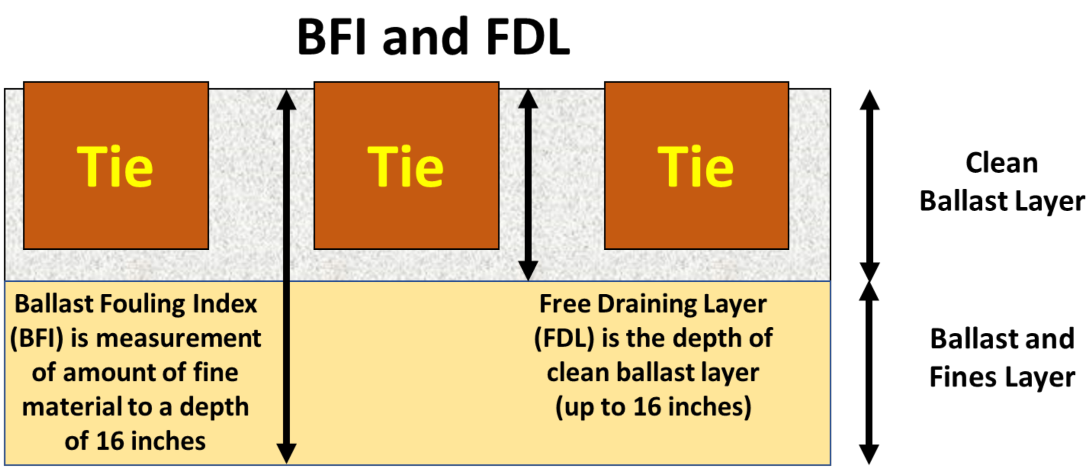

Figure 1. Illustration of Ballast Fouling Index (BFI) and Free Draining Layer (FDL) Measurements.

Ballast Maintenance

Regular ballast maintenance, along with rail and tie maintenance, is important for ensuring the safe and reliable transport of goods and commodities across any railroad track system. When possible, effective ballast maintenance should 1) reduce track geometry deviations and other track issues that interfere with train operations, 2) maximize the time between maintenance cycles, and 3) optimize the productivity of the maintenance.

BNSF maintains ballast using multiple methods [4]. These methods include surfacing, shoulder ballast cleaning (SBC), track lifting (TLU), undercutting (UC), and ditching. Surfacing involves tamping the upper ballast section to level, aligning the overall track geometry, and addressing any deviations. SBC removes the shoulder ballast and replaces it with new and/or reclaimed ballast, a process that improves shoulder drainage and aids in the potential for center fines to either drain from the surface or redistribute to lower levels of the ballast section. TLU lifts the track and adds new ballast to separate the track from the previous roadbed, thereby creating a free draining, clean ballast layer beneath the ties. UC removes the upper ballast and replaces it with clean and or reclaimed ballast. Ditching ensures the right of way and connected ditches are functional and can carry any excess moisture away from the track structure. Diagrams of surfacing, undercutting, track lifting, and shoulder cleaning are shown in Figure 2.

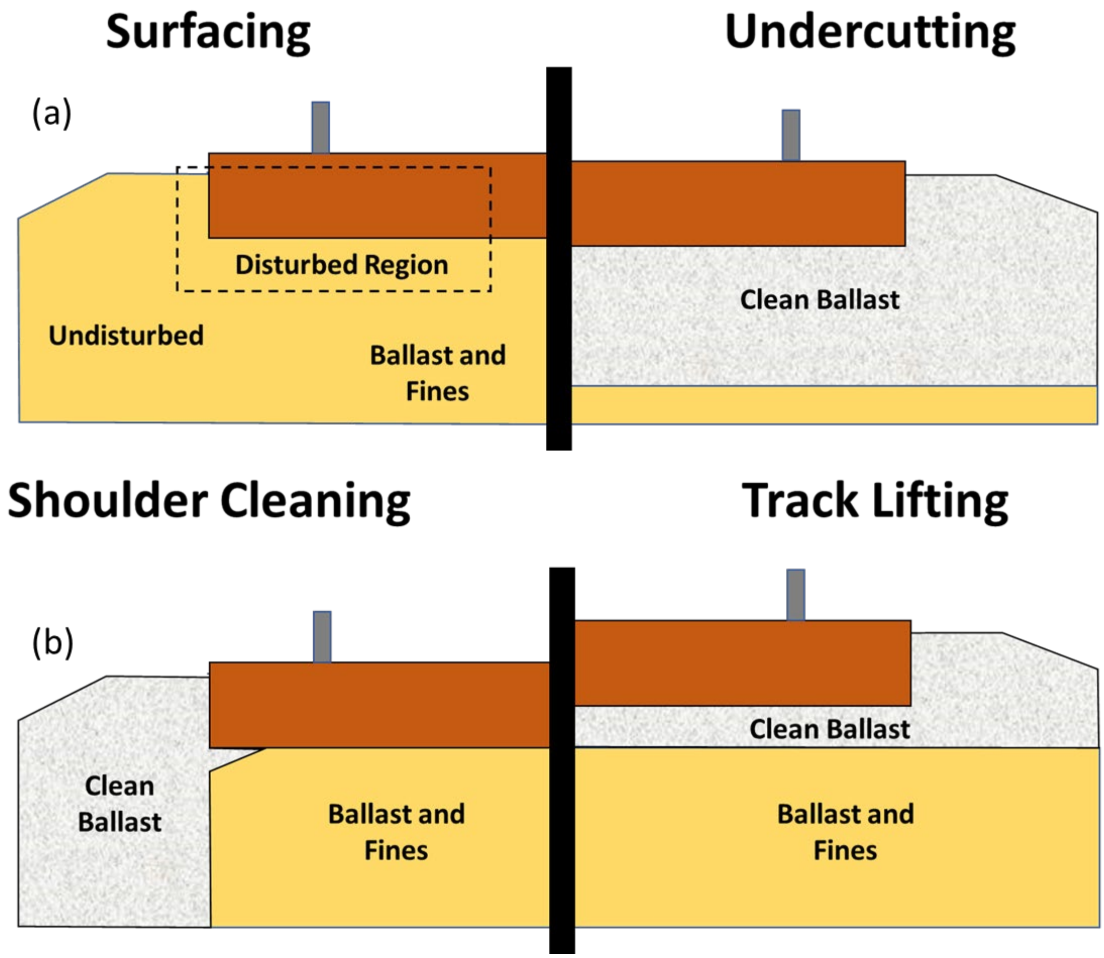

Figure 2. Effect of the Various Maintenance Methods on Ballast Condition: (a) surfacing and undercutting, and (b) shoulder ballast cleaning and track lifting.

Each of these maintenance methods have different effects, impact geometry degradation in different ways, have different production rates (miles per day), and hold their own unique constraints and limitations. For example, SBC is much faster and less intrusive than UC but does not address high center BFI conditions. In contrast, TLU addresses high BFI concerns of both shoulders and centers but may not be suited very well to locations limited by overhead obstructions or immoveable assets. The ballast condition may also influence the effectiveness and productivity of each method. For example, high fines and moisture levels can limit the productivity of undercutting [5] while the depth of the existing free draining layer may influence the optimal lift height during track lifting and surfacing.

BNSF's ballast maintenance program is driven by a multifaceted data model which leverages the available data streams to help direct and allocate the aforementioned maintenance methods to needed locations within the network. Developed in house by BNSF, this data model recommends and prioritizes locations for various maintenance activities (i.e., surfacing SBC, UC, and TLU) and is based on a number of factors. Some of the factors influencing the model include, but are not limited to, aggregated track geometry condition, tonnage, historic maintenance, and ballast condition. The roadway planning team can then make adjustments based on more subjective factors that are not easily addressed in the model.

Part of BNSF's long-term initiative is to continuously improve the ballast maintenance model and optimize the three goals of ballast maintenance. These goals include reducing track geometry exceptions, improving maintenance effectiveness, and maximizing maintenance productivity. Achieving these goals requires an understanding of the following:

- the current track conditions over the entire network.
- the measurable factors that lead to track geometry deterioration.
- the effectiveness of the various maintenance activities under a range of ballast conditions.

This data-driven approach requires large amounts of data for analysis. To move towards this goal, BNSF has spent the last 10 years improving its inspection capabilities in areas from minimal- ballast condition assessments to regularly scheduled ballast inspections across the entire network. With data collected systemwide and at regularly scheduled intervals, large-scale data analysis is now possible. The following sections discuss both data collection and data analysis.

BALLAST CONDITION INSPECTION SYSTEMS

In moving to a data-driven approach, BNSF identified the first step as enhancing the ballast inspection system to one that could regularly collect data at scheduled intervals over the entire network. To accomplish this, many enhancements had to be made, including 1) identifying useful ballast condition outputs, 2) increasing GPR collection capabilities, 3) calibrating and improving accuracy, and 4) combining GPR and other inspection methods into a single platform. These enhancements are discussed in this section.

The first enhancement was identifying ballast inspection methods that characterized ballast in a manner that 1) was non-disruptive to the track, 2) reduced track occupancy, 3) provided useful information, and 4) scaled up to characterize the entire network. Used at BNSF since 2009, GPR not only has the capacity to effectively meet each of the above-mentioned criteria, but it also characterized the ballast condition by emitting radar waves into the track and interpreted the radar response. GPR collection systems captured conditions of both the area between the rails (center) and the area from the outside of the rails (shoulders) to a distance where a typical ballast shoulder was defined. The first ballast condition output from GPR was BFI which estimated the number of fines in the top 16 inches of ballast from the track surface. In 2018, an FDL was added as a secondary output metric. Referencing Figure 2, a full setup that included center and shoulder antennas with outputs for both BFI and FDL could be useful in determining what the current track conditions were and how each maintenance implementation could improve the ballast condition for that track.

The second enhancement continuously increased the track miles GPR collects each year. In the early 2010s, GPR was collected using a hi-rail truck platform, a practice that meant collection was often limited to more at-risk subdivisions. However, collection did eventually expand to incorporate almost all subdivisions within BNSF’s network. In 2018, BNSF added GPR to its train-based geometry inspection platform, this shift significantly enhanced BNSF’s collection capabilities and reduced the track occupancy footprint of this data collection. This increase in GPR-collected track miles is shown in Figure 3.

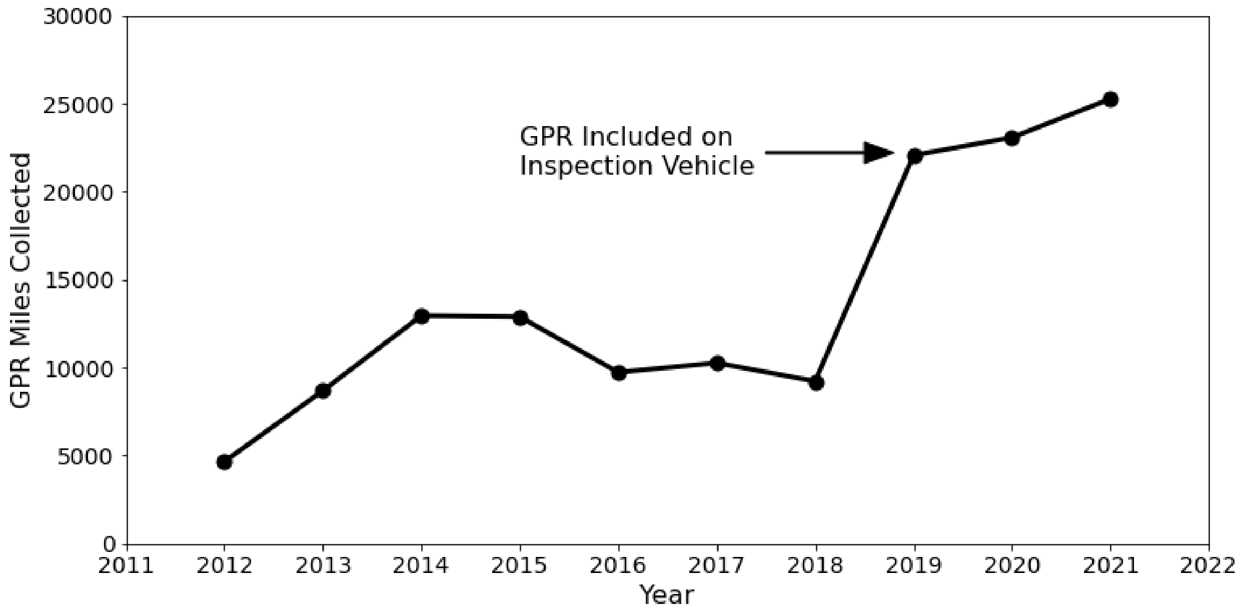

Figure 3. Track miles collected by GPR.

The third enhancement was the calibration of the GPR system to ensure accurate ballast condition information was provided. These calibration events were very useful after adjustments were made to antennae positions on both the hi-rail and geometry-based inspection platforms. Perhaps of greater importance, however, were the continuous improvements made to the accuracy of the GPR outputs. BNSF has performed multiple calibration projects since 2009, most of which involved physically sampling, performing gradations, and then comparing Selig's FI results to the GPR outputs. Physical sampling was tedious, time consuming, inefficient, and prone to a higher level of error. To offset those drawbacks, BNSF developed the Vibro Sampler™, an automatic sampling device, in 2018 [4,6]. The switch from manual sampling to automated greatly increased BNSF's capability to collect samples for comparison with the GPR outputs. This significant increase of the numbers of samples and subdivisions collected, both in post-implementation of the Vibro Sampler™ in 2018, are represented in Figure 4. The increased quantity and diversity of the samples was important to the calibration process and to assist with the reduction of the bias from low sample sizes.

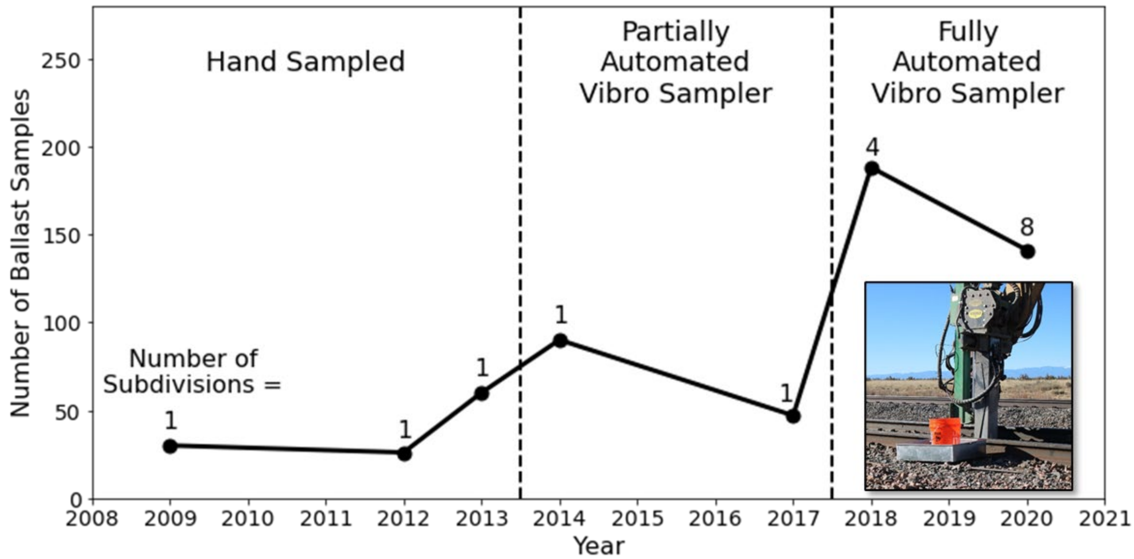

Figure 4. Details on the how many samples, subdivisions, etc.

Figure 5 shows how these sampling calibration events help calibrate the GPR configuration and are extremely important when adjustments are made to that configuration. The graphs in Figure 5 show the BFI on the x-axis and the sampled BFI on the y-axis. The solid black line illustrates a 1:1 line, or perfect accuracy, and the shaded region shows the area between a 1:2 and a 2:1 line. As can be seen, the pre-calibration response tends to underestimate the values, especially in the shoulders. Once calibrated, the configuration ends up with a much higher degree of accuracy with the majority of the values falling within the shaded region.

Note, perfect accuracy is not anticipated because Selig's FI and BFI are calculated from similar, but still different, factors. In addition, the goal of BFI is not necessarily to match perfectly with Selig's FI, but to match with the track performance. For maintenance planning, the key is whether BFI generally can be used to group the ballast conditions into "clean," "moderate," and "fouled", which it does.

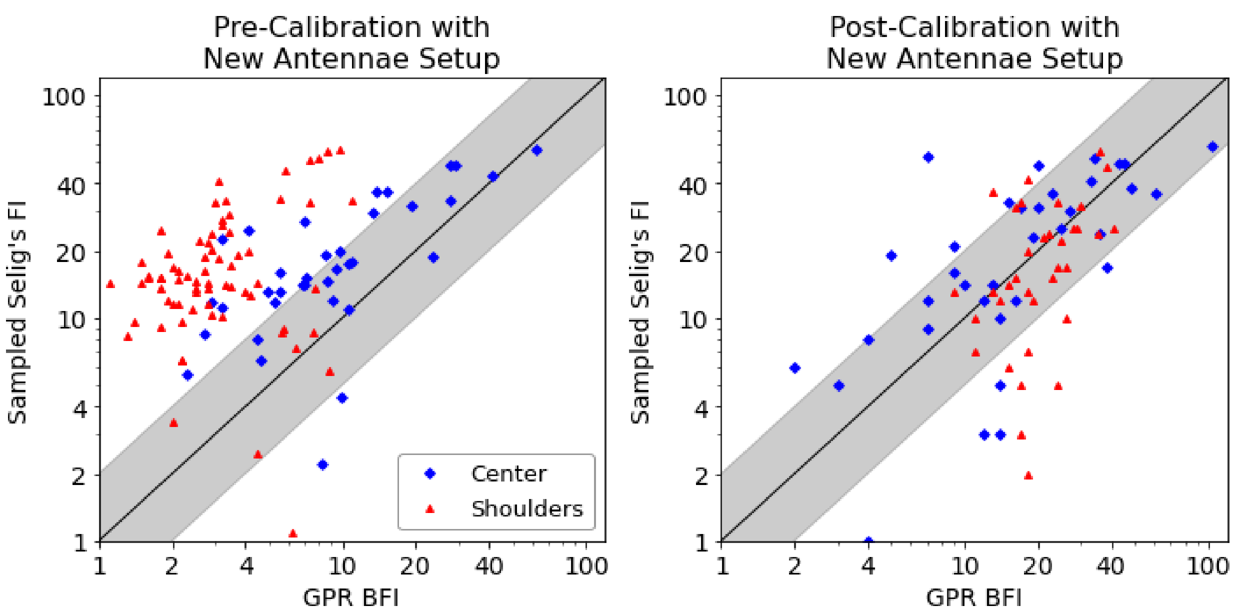

Figure 5. Improvement in accuracy post calibration from new antennae setup.

The fourth enhancement was an increase in the number of track miles collected with GPR.

Adding GPR antennas to a train-based geometry inspection platform allowed for more miles to be collected and reduced the overall track occupancy footprint to collect those miles of data. The GPR system on the geometry inspection platform is shown in Figure 6. A secondary benefit from this enhancement was seen when comparing GPR outputs with other datasets (e.g., track geometry) as the data was already aligned since it was all collected on the same vehicle platform. This pre-alignment greatly increased the ease of comparing multiple inspection types at the same time versus trying to align two to four separate records using multiple alignments and different outputs.

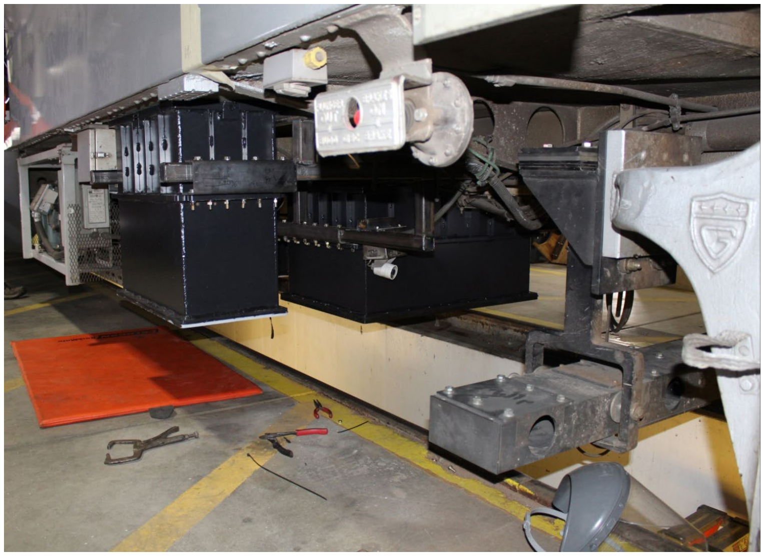

Figure 6. Photograph of GPR system on BNSF's train-based geometry inspection platform.

Through these enhancements, BNSF has significantly improved the quantity and quality in which ballast condition data is captured. Currently, an aggregated BFI and FDL is compiled over the BNSF network, which allows maintenance to be planned based on current ballast condition. With more GPR data being collected each year, this data has become more useful when prioritizing maintenance within the ballast model.

CURRENT BALLAST CONDITION

GPR data is used to identify regions with high BFI and low FDL. The understanding of these two metrics assists decision makers with determining which locations should be prioritized first and which maintenance methods may best suit the conditions. While the ballast model considers many factors, BFI and FDL give general insight into the overall ballast condition and ensure projects are planned based on both condition and risk.

For example, a segment of track that has high BFI and low FDL may indicate a need for track lifting or undercutting. However, when logic is applied to also weigh the risk of the segment in conjunction with this condition, surfacing may be deemed an alternative, yet appropriate, remediation. In contrast, if track lifting or undercutting is deemed appropriate, BFI and FDL data can help define lift heights and or undercut depths to ensure that a clean ballast section is achieved or maintained.

FUTURE TRACK PERFORMANCE

Another use of the GPR data is the assistance with a better understanding of how maintenance affects ballast condition over time and how the ballast condition relates to track geometry degradation. These studies improve ballast maintenance planning by providing a better understanding of the situations that each maintenance method is appropriate and planners to right size maintenance equipment fleet needs. TTCI has partnered with BNSF and the Strategic Research Initiative (SRI) program to perform this analysis. Though still in the early stages, the following are two examples that explore how this inspection data can potentially be used.

Example 1: Influence of Shoulder Ballast Cleaning (SBC)

GPR inspection data can be used to determine the influence of ballast maintenance on ballast condition over time. In this example, GPR data was collected across two 15-mile segments of track over a three-year period. The data was then used to compare how shoulder ballast cleaning reduced ballast degradation in the track centers. The results are presented in Figure 7.

For this analysis, all track near fixed assets (bridges, road crossings, turnouts, etc.) and any undercut locations were removed. Segment 1, Figure 7(a) shows the average change in center BFI over one year across the 15-mile segment that was shoulder cleaned one year and not shoulder cleaned the second year. Segment 2, Figure 7(b) shows the average change in center BFI over two years across a separate 15-mile segment, where part of the segment was shoulder cleaned and part of the segment was not shoulder cleaned. Analyzing the data in this manner, with two separate segments, reduces the opportunity for bias both as a result of when the GPR data collected (e.g., right after rainstorm) or where track behaved differently across each segment. The results from both segments show similar trends where BFI degradation in the track centers is lower where SBC was executed and also holds true for all BFI categories.

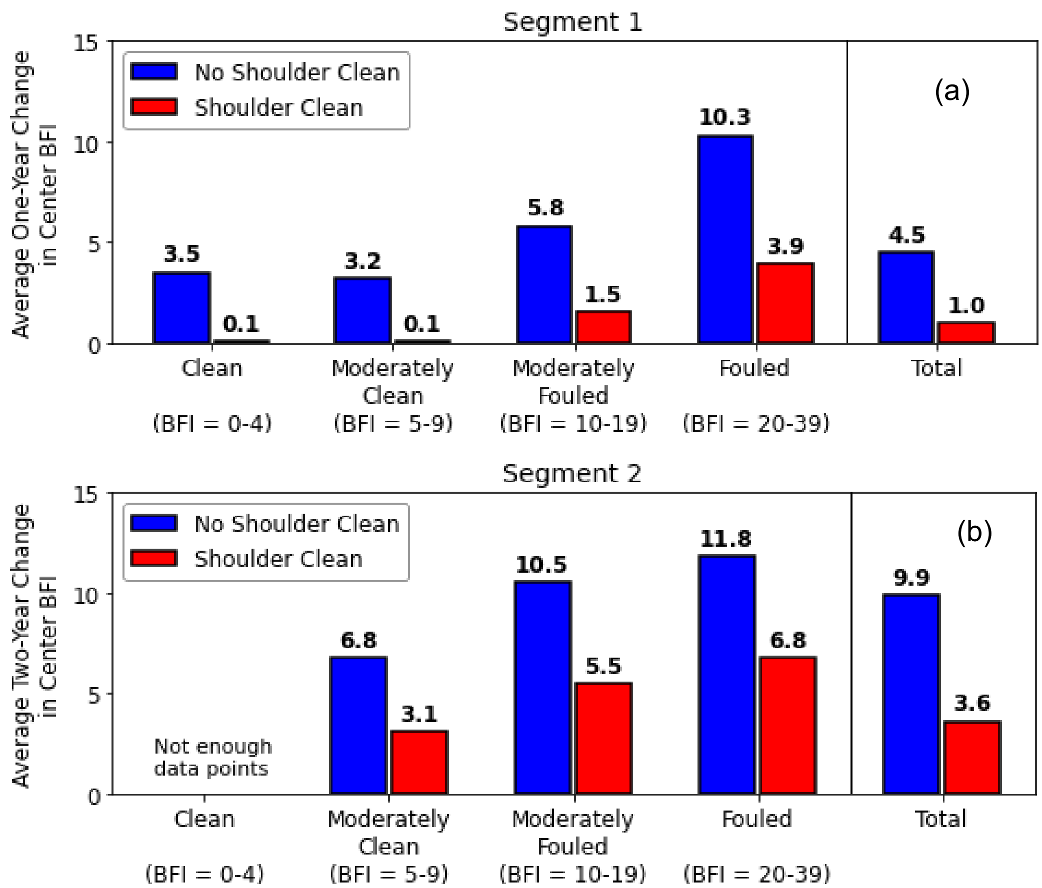

Figure 7. Effect of shoulder cleaning on change in center BFI for two track segments.

This data is useful both for determining how SBC affects the center ballast condition as well as for forecasting future BFI conditions. These results will allow planners to develop consistent shoulder ballast cleaning cycles and improve their ability to maintain the entire ballast section. This analysis will be expanded to determine how these trends compare to track locations across various geographic regions, climate zones, tonnage rates, fine types, maintenance histories, and other relevant factors.

Example 2: Ballast Condition and Track Geometry Degradation

Another example of how the data will be used is to understand and determine how ballast condition affects track geometry degradation. As with ballast degradation, track geometry degradation likely varies significantly by track location due to various factors such as climate, drainage, subgrade, ballast maintenance history, load environment, tie type, and other factors. Using the same data set from Example 1, TTCI and BNSF were able to develop relationships between track geometry degradation and BFI [7].

In this paper, track geometry degradation is defined as the change in a 62-ft surface profile over 100 million gross tons (MGT). This is a difficult parameter to calculate over long stretches because track geometry data is often not aligned, and many track geometry records are needed to establish a degradation trend. The methods of addressing these issues are beyond the scope of this paper but involve finding maximum values within a selected 0.05-mile “window.” This “window” method was used for the first-iteration analysis as using the 0.05-mile window was more manageable and easily accounted for unscheduled spot maintenance which is difficult in a continuous analysis. However, this “window” method is expected to be supplemented by or even replaced with a continuous analysis.

Figure 8(a) shows the fitted curves for three different segments of track with different ballast maintenance histories. The blue line represents a segment of track that was recently undercut while the red and green lines represent track segments that have not been undercut within at least the last 5 years. In addition to ballast maintenance, subgrade, drainage, tie type, and other factors may also play a role. This graph emphasizes how the BFI-surface profile degradation fit can differ significantly at different points across the track. This means that a location represented by the red line where the BFI = 30 may result in higher rates of track geometry degradation than a location represented with the blue line yet having the same BFI =30.

Figure 8(b) shows the individual data points for the red line in Figure 8(a). While the fit generally represents track behavior, there is scatter. This is not surprising and is likely due to other factors that have been known to influence track geometry (i.e., drainage or subgrade). Certain factors will be incorporated into more complicated track geometry degradation forecasting equations. However, some factors are likely uncharacterizable and some degree of uncertainty will always exist.

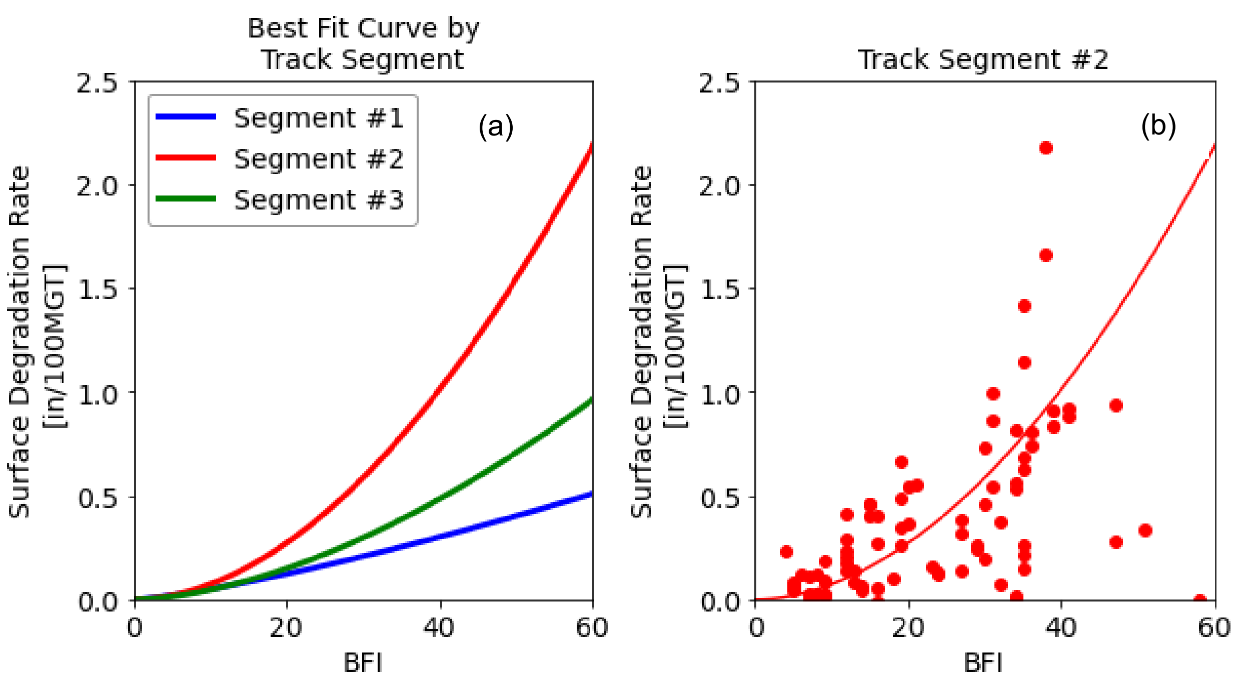

Figure 8. Relationship between BFI and track geometry degradation for entire data set (a) and individual segment (b).

This window method is currently one of the more time-, resource-, and data-intensive methods.

Nonetheless, as a first iteration, the results gathered using this method provide more confidence that BFI is a significant contributor to track geometry and can vary from track segment to track segment. A continuous analysis (1-ft, 0.1-mile, or 1-mile segments) is preferred, but it is difficult to isolate the fundamental ballast-track geometry relationship because maintenance, especially spot maintenance, is rarely constant across the entire track segment. This means that assumptions of when maintenance (e.g., surfacing) occurs cannot be made along the entire continuous segment. Advanced analysis methods such as machine learning will make this process more manageable.

The long-term goal of this detailed analysis is two-fold. The first step is to develop relationships between ballast condition and track geometry degradation that include geographical variation (very wet versus arid climate conditions). Initially, this is accomplished at a detailed level and is then simplified, becoming both more manageable and actionable over large segments of track. Second, as data collection and data analysis capabilities improve, these methods eventually become automated. Machine learning techniques can provide a precise relationship between general ballast condition and track geometry degradation (fitted line) and segments requiring spot maintenance (upward scatter from lines). For example, an output would be a forecasted number of track geometry deviations years out depending on maintenance activity and known ballast condition.

CONCLUSIONS

This paper demonstrates BNSF's shift to a more data-driven ballast maintenance program where multiple enhancements allow for full inspection of BNSF's network. With this data and additional analysis, future enhancements will be made to further optimize BNSF's ballast maintenance models and program.

The implemented enhancements in the train-based geometry inspection platform, allow BNSF to capture GPR data across its entire network annually and is more accurately aligned with other metrics such as track geometry. Enhancements to the program include but are not limited to, installation of GPR antennas on BNSF's geometry inspection vehicles and calibration events which ensure accuracy of the outputs.

As an added benefit the data can be used to better understand risk across the network, effectiveness of maintenance activities, and track performance based on ballast condition. For example, a comparison of shoulder ballast cleaned versus a non-maintained segment of the same subdivision showed a reduction in center ballast degradation where shoulder ballast cleaning occurred. As a second example, the aligned track geometry and GPR data can be used to develop and understand relationships between ballast condition and track geometry degradation. A comparison of three track segments with different ballast maintenance histories showed variations in the BFI-track geometry degradation curve. This suggests that specific BFI conditions may influence track geometry degradation differently depending on the location.

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List of Figures

Use of Track Based Inspection Technologies to Improve BNSF's Ballast Maintenance Planning

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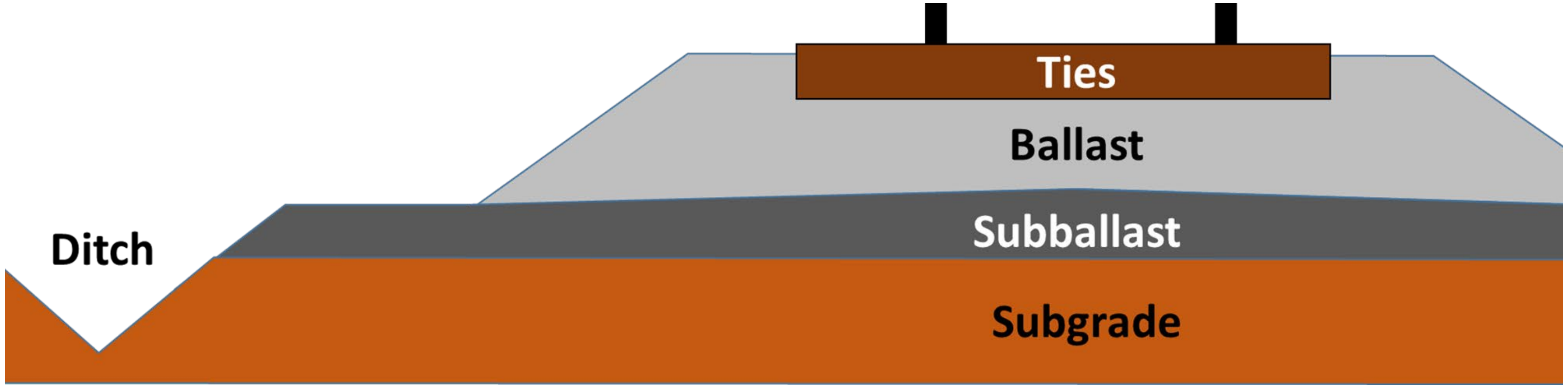
Agenda

- **Introduction**
- Ballast Degradation
- Ballast Maintenance
- Ballast Condition Inspection Systems
- Inspection System Data Analysis
- Conclusions

Introduction – Ballast Layer

- **Key track component:**
  - Supports track
  - Provides resistance to track movement
  - Drains moisture away from track
- **Degrades over time and requires maintenance**
  - Remove and replace used ballast particles
  - Create separation between substructure layers
  - Improve drainage for the structure
- **BNSF's Ballast Maintenance Program**



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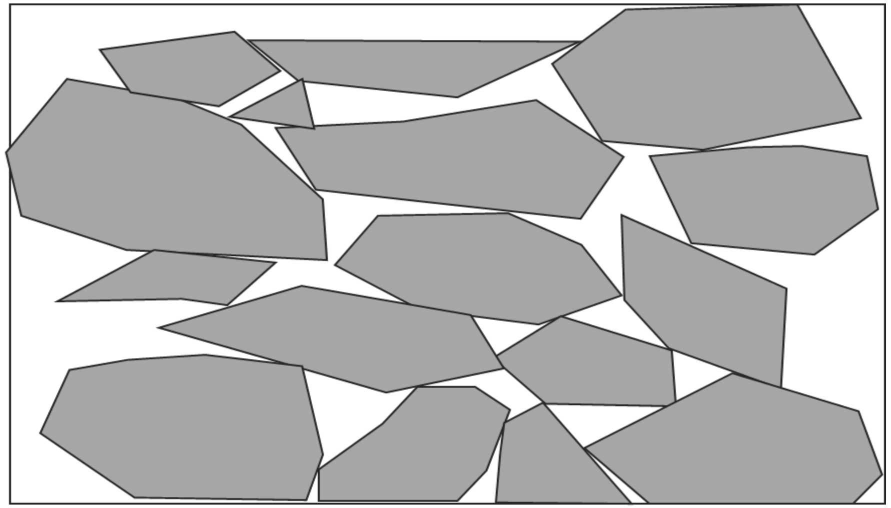
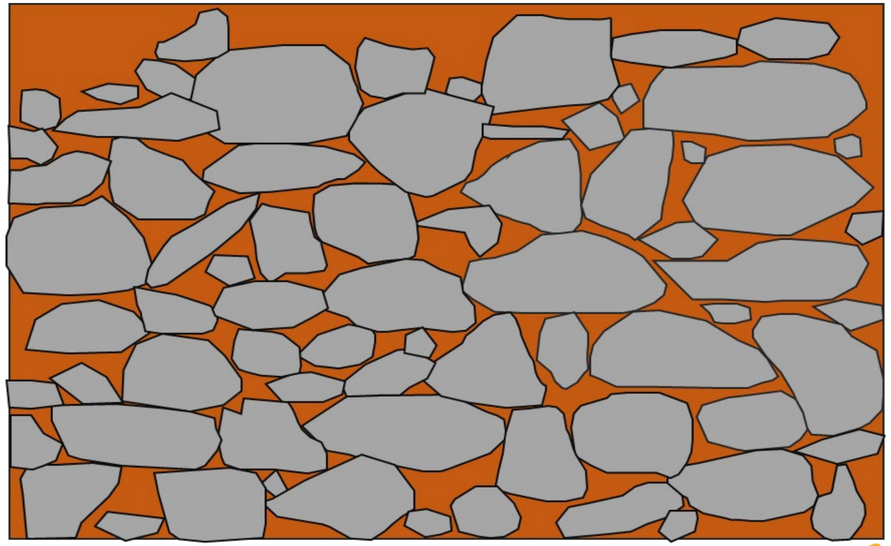
Ballast Degradation - Mechanism

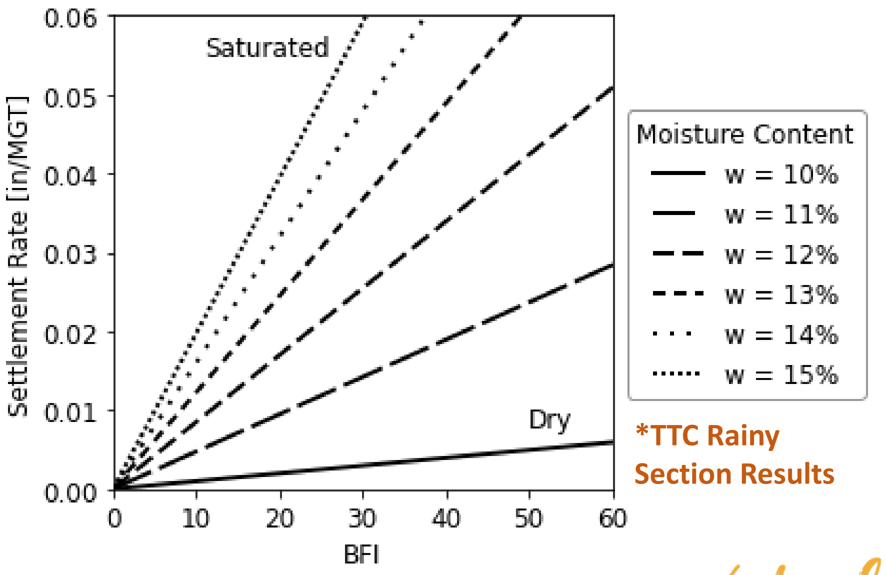
- **Ballast performance is highly influenced by particle shape and gradation**
  - Strong angular particles create interlock
  - Large like-sized particles allow drainage
- **Ballast condition changes over time**
  - Ballast breakdown (primary mechanism)
  - Introduction of fines from outside sources
- **Degradation and fine introduction**
  - Influence how ballast particles interlock
  - Impede the track structures ability to drain





Ballast Degradation – Effects on Track Performance

- **Degradation often results in reduced performance**
  - Higher track geometry deformation
  - Ponding of water and blocked drainage
  - Ballast and tie degradation
- **Multiple factors influence ballast performance**
  - Degraded particle shape
  - Amount and type of fines
  - Moisture levels

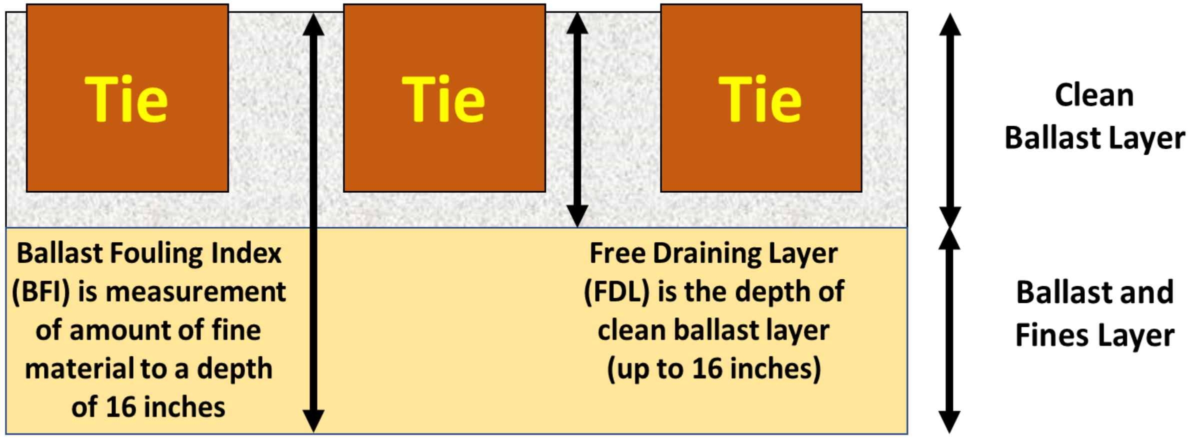


*TTC Rainy Section Results

Ballast Degradation – Characterization

- **Characterizing the individual particle level is not feasible**
  - Must use simple indices that characterize general behavior
- **Fine Levels**
  - Selig's Fouling Index (FI) → Mass gradation ($FI = P_4 + P_{200}$)
  - Ballast Fouling Index (BFI) → GPR interpretation
- **Free Draining Layer (FDL)**
  - GPR interpretation of 'depth to fouling'

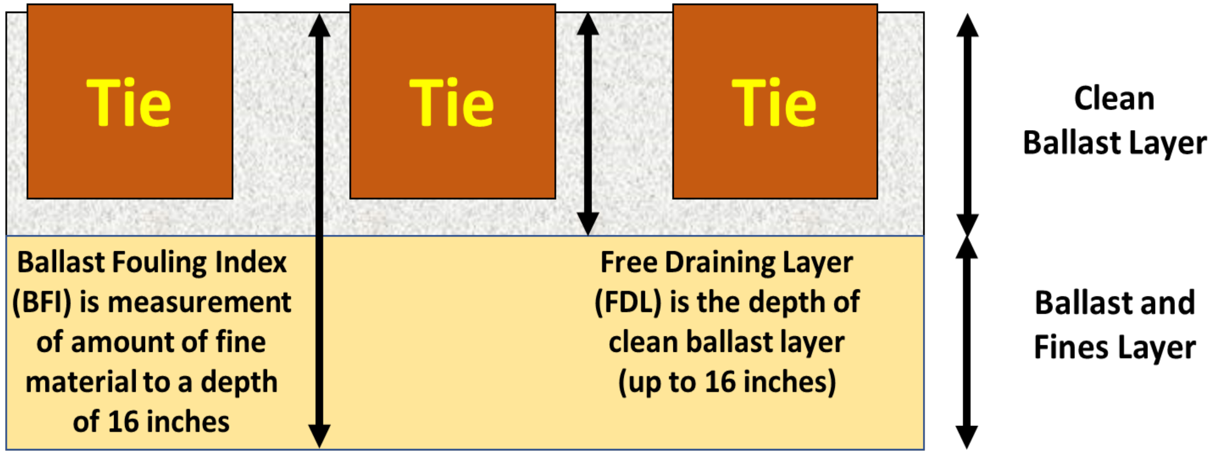
BFI and FDL



Ballast Degradation – Characterization

- **BFI and FDL are not comprehensive ballast characterizations**
  - Similar but measure different aspects
    - Supplement one another
  - Other influential parameters exist but are not typically characterized
    - Not all influential parameters are measured

BFI and FDL



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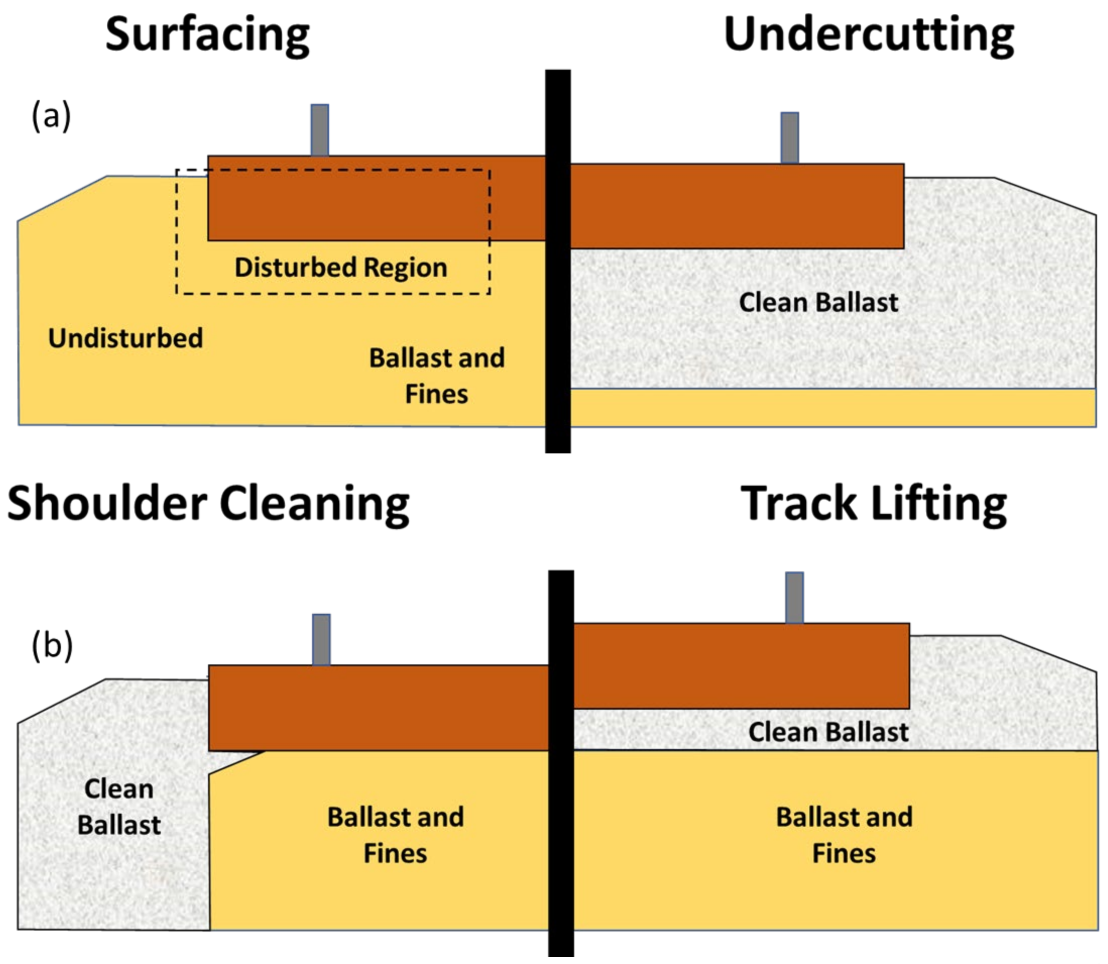
Ballast Maintenance

- **Improves safety and reliability of railway infrastructure**
- **Planned ballast maintenance**
  - Reduces track geometry deviations
  - Improves the tracks ability to drain
  - Maximizes time between maintenance cycles
  - Optimizes the productivity of maintenance

Ballast Maintenance

- **Multiple ballast maintenance strategies**
  - Surfacing (tamping)
  - Undercutting (UC)
  - Shoulder ballast cleaning (SBC)
  - Track lifting (TLU)
- **Each method has pros and cons**
  - Affect different regions of ballast structure
  - Production rates
  - Expense
  - Limitations



BNSF Ballast Maintenance Model

- **In-House statistical model**
- **Multi-faceted**
- **Multiple data streams**
- **Recommends maintenance**
- **Prioritizes locations**
- **Some Factors:**
  - Aggregated track geometry condition
  - Tonnage
  - Historic maintenance
  - Ballast condition

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Ballast Condition Inspection System

- **Identifying Ballast Inspection Method**
- **Increase GPR Miles Collected**
- **GPR Calibration**
- **Track Inspection Vehicle**

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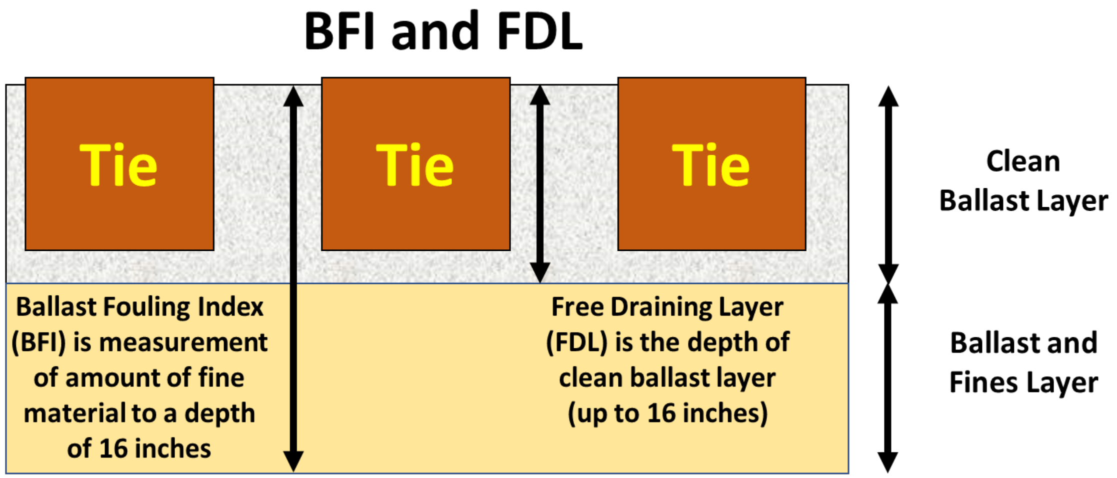
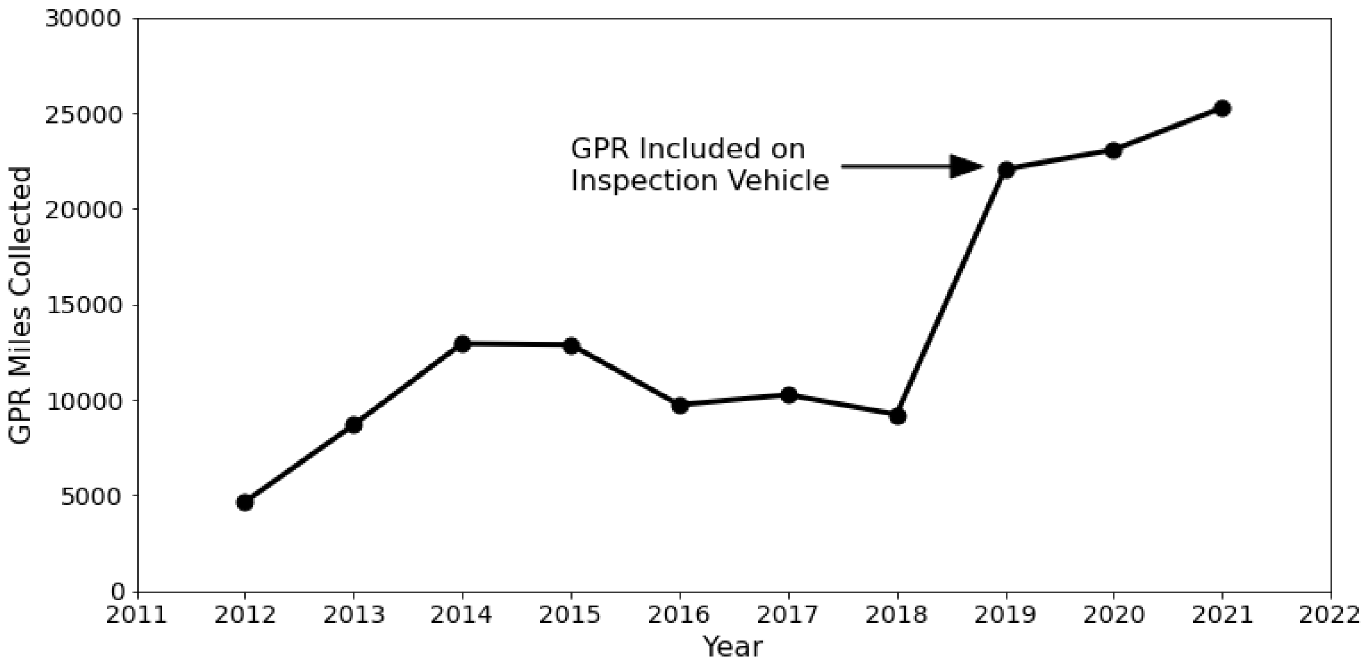
Enhancement 1: Identifying Inspection Method

- **Ground Penetrating Radar (GPR)**
  - Non-disruptive to track
  - Reduces track occupancy
  - Provides useful information
  - Can be scaled
- **Outputs**
  - Ballast Fouling Index (BFI)
  - Free Draining Layer (FDL)



Enhancement 2: Track Miles

- **Scaling up miles collected allows analysis of BNSF's entire network**
- **2018 GPR transition from hi-rail platform to train-based geometry inspection platform**



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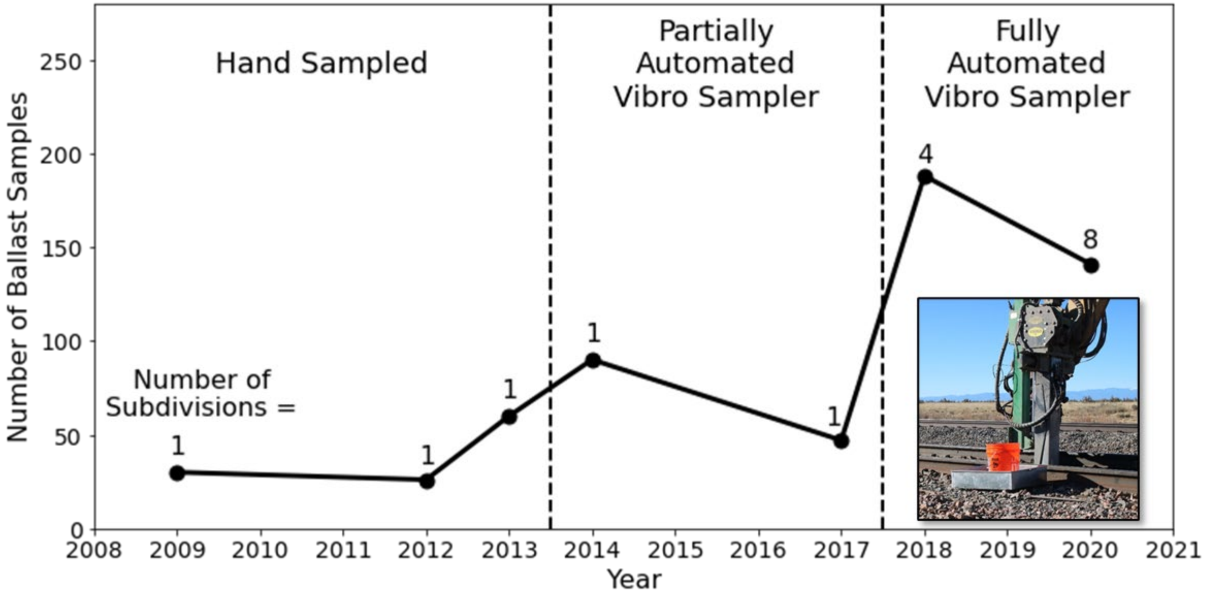
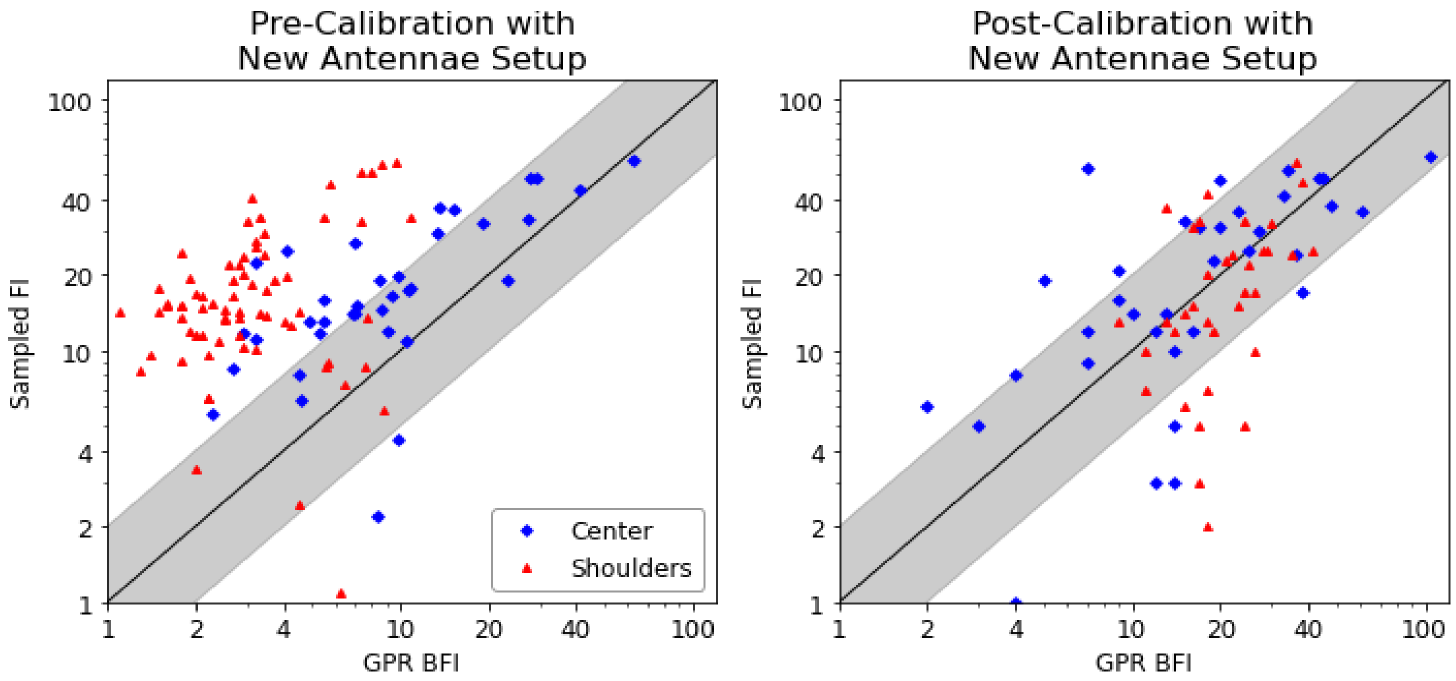
Enhancement 3: Calibration

- **Ensures accurate information is being provided**
- **Useful after adjustments to antenna position**
  - All platforms
- **Improvements in sampling process**
  - Vibro sampler
  - Diversity in calibration samples



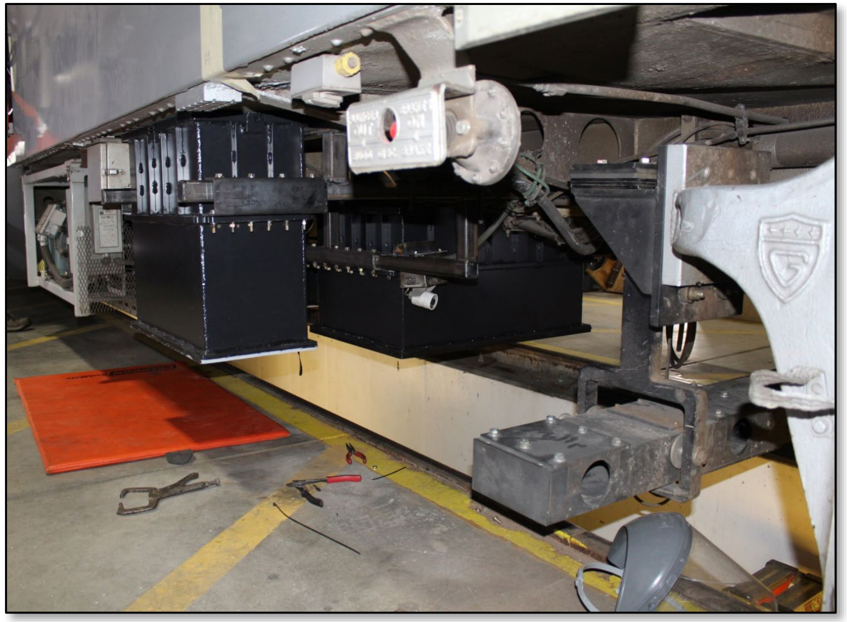
Enhancement 3: Calibration Example

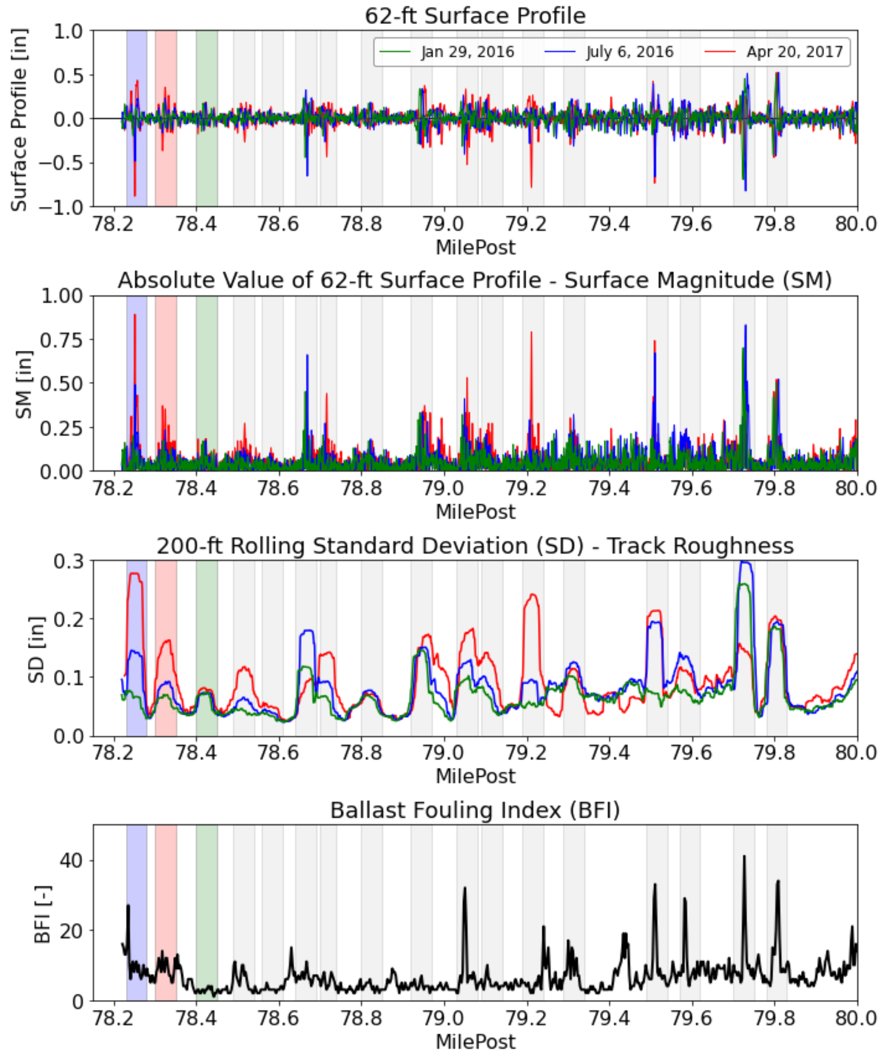
- **Calibration ensures accuracy**
  - Improves confidence from interpreted results
- **Example shows improvements in response post-calibration**



Enhancement 4: Track Inspection Vehicle

- **GPR to geometry inspection platform**
  - Increase in miles collected
  - Aligns with other datasets
  - Reduces track occupancy



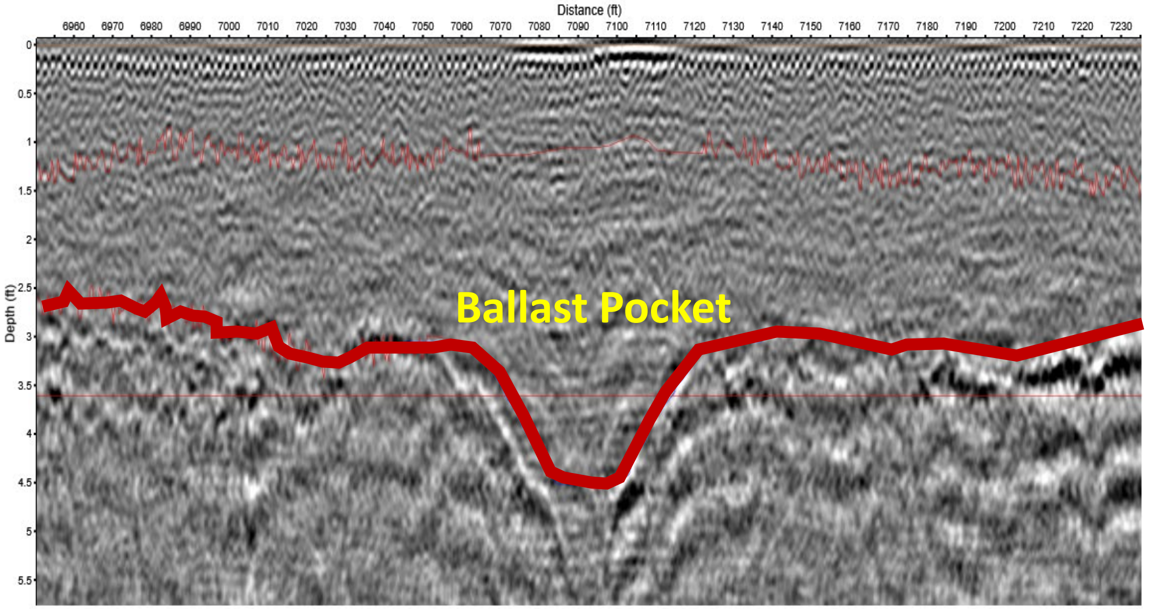


Agenda

- Introduction
- Ballast Degradation
- Ballast Maintenance
- Ballast Condition Inspection Systems
- **Inspection System Data Analysis**
- Conclusions

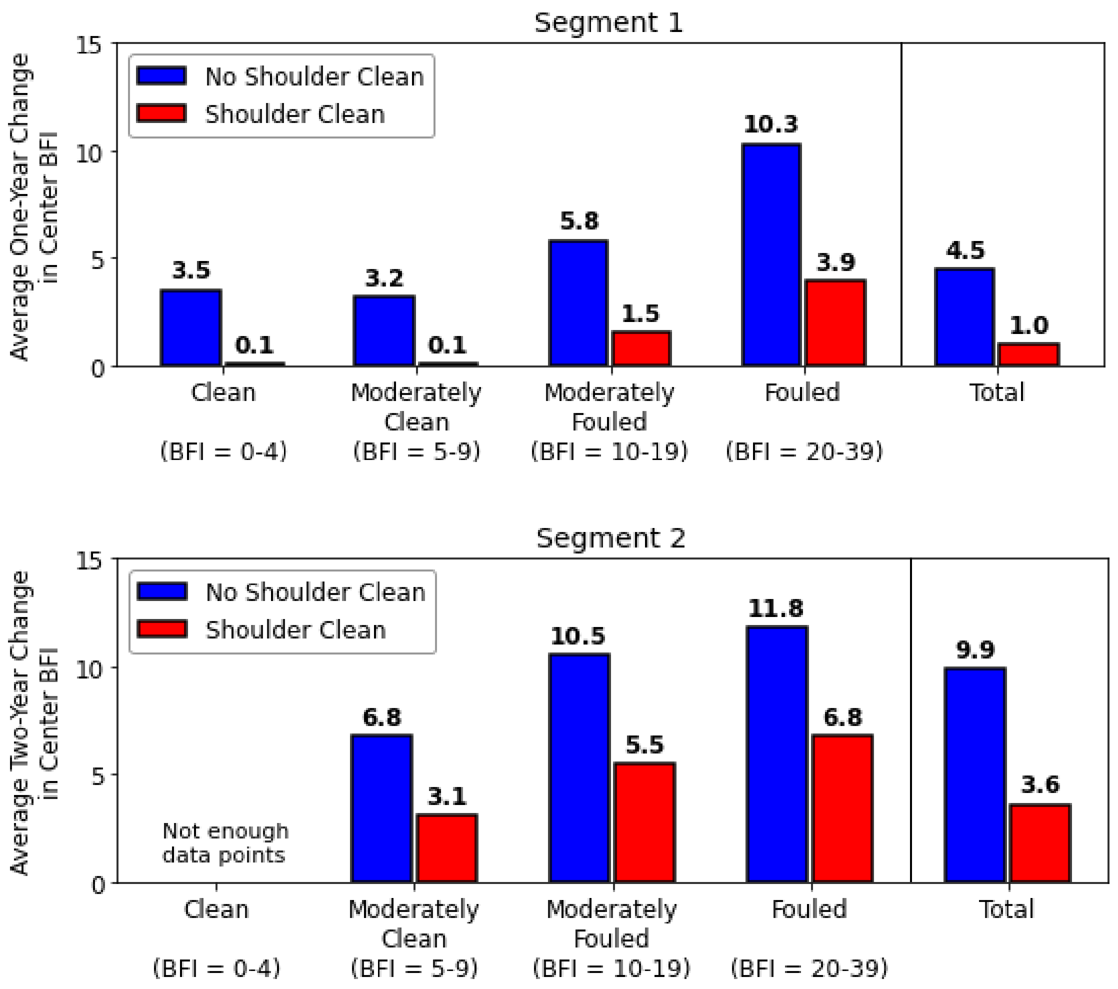
Ballast Condition Data Analysis

- **Current ballast condition**
  - Prioritize maintenance
  - Identify which type of maintenance will be most effective
- **Future ballast condition (Trends)**
  - Degradation rates
    - Ballast and track geometry
  - Influence of maintenance
  - Relationships between variables



Influence of Shoulder Ballast Cleaning (SBC)

- **Two 15-mile track segments**
- **Influence of SBC on center BFI**
- **SBC shows a reduction in center ballast degradation**
- **Info useful for:**
  - Effect of shoulder cleaning
  - BFI projections



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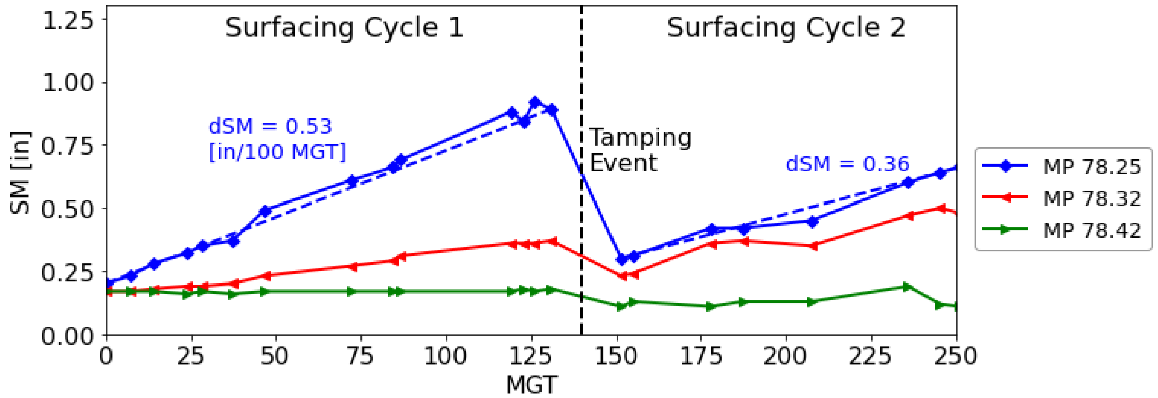
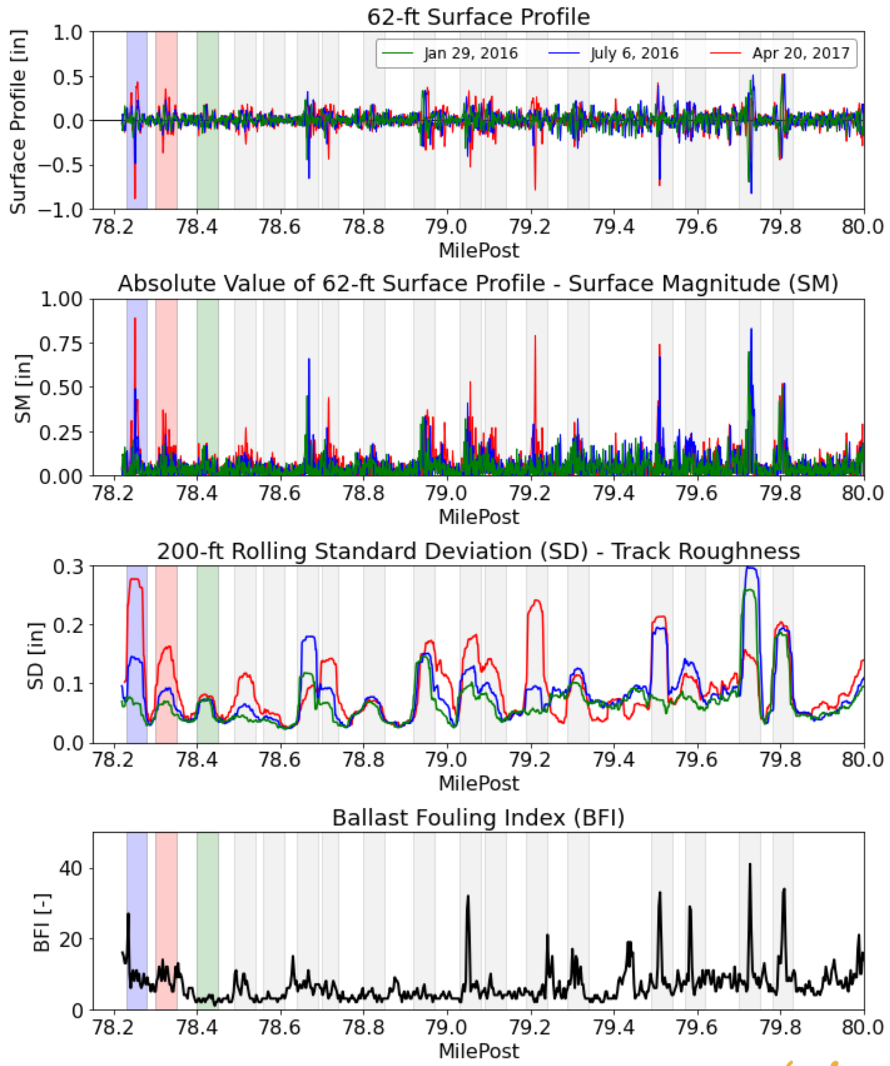
Ballast Condition and Track Geometry Degradation

- **Same two 15-mile segments**
- **Align track geometry with BFI**
- **First-iteration analysis**
  - Select maximum from 0.05-mile "window" and calculate degradation rate
  - Accounts for unplanned spot maintenance





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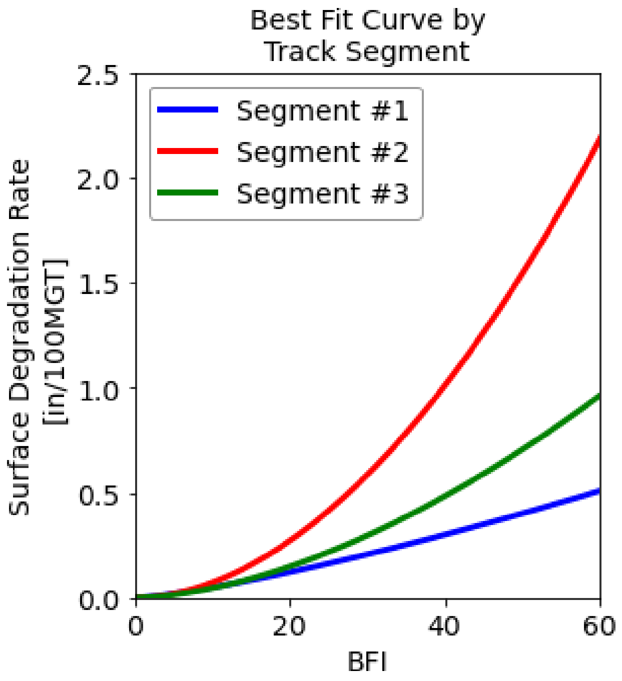
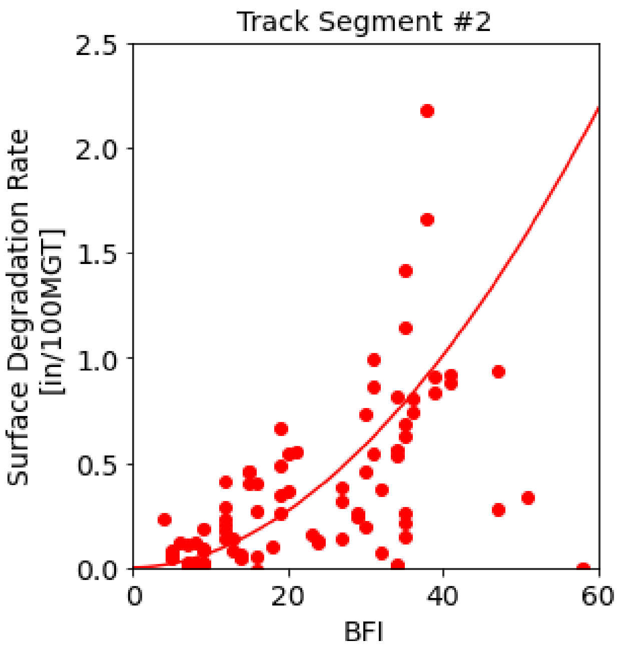
Ballast Condition and Track Geometry Degradation

- **Split up by track segment (mainline turnouts)**
  - Separate ballast maintenance history
- **Each track segment has unique curves**
  - BFI=30 may have different response based on track segment
- **Scatter for each track segment**
  - Moisture
  - Subgrade
  - Drainage Profile





Future of Analyses

- **Diversify samples**
  - Climate
  - Dynamic Loading
  - Tonnage
  - Maintenance
- **Shift to "Big Data"**
  - Increased automation in data organization and analysis
  - Scale up to larger track sections
  - Advanced analysis techniques
    - Machine learning

Agenda

- Introduction
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Conclusions

- **Measuring BFI and FDL helps allocate ballast maintenance resources**
- **Implementation of the train-based GPR collection allow BNSF to capture data across the entire network**
    - Is more accurately aligned with other metrics
- **Multiple calibration efforts have improved both GPR data quality and the interpretation of GPR results**
- **GPR can be used to help determine the effectiveness of maintenance activities**
- **GPR data can be used to develop and understand relationships with track geometry degradation**

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