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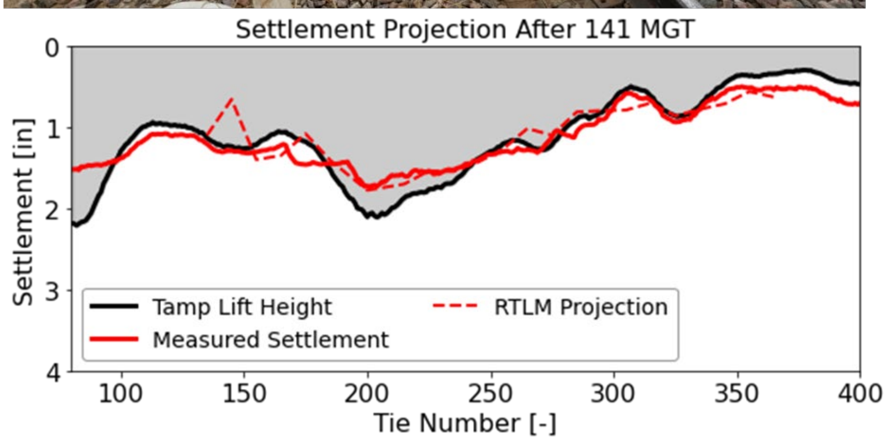
Relationship of Inspection Methods to Ballast Degradation Models: Phase II



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14. ABSTRACT
This report is a follow on of the first phase of a Federal Railroad Administration (FRA)-sponsored project to evaluate lateral ballast behavior and how mechanics-based track geometry deterioration models forecast field behavior. In Phase II of the project, Transportation Technology Center, Inc. modified the Railway Track Lifecycle Model (RTLM) by adding tamp lift height and a site-specific factor and split the model between a logarithmic settlement and a linear surface profile model. The research team also compared forecasting model projections against multiple field measurement locations at the Transportation Technology Center (TTC). The ballast settlement mechanism at most locations was ballast re-compaction and the RTLM captured the settlement behavior if only the tamp lift height parameter was used. If the settlement mechanism was degraded ballast, the logarithmic settlement curve did not capture abrupt changes in settlement rate from wetting and drying so more linear models, such as the surface profile model, should be used.

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Ballast, settlement, mud pumping, fouling index, forecasting, track inspection, track modulus, track, Railway Track Lifecycle Model, RTLM

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

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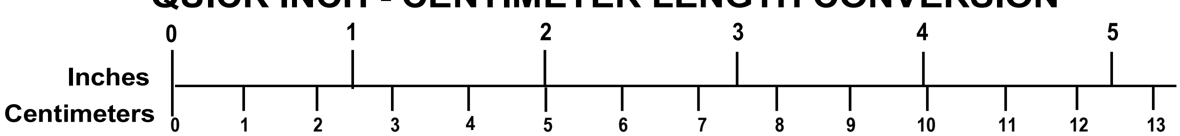
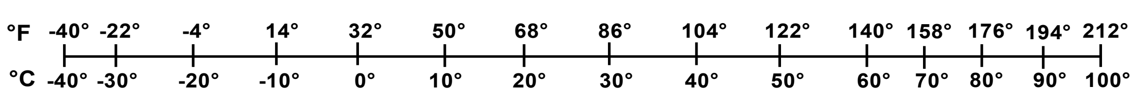
QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Contents

Illustrations

Tables

Executive Summary

In 2022, the Federal Railroad Administration (FRA) funded the completion of a Phase II track geometry degradation study conducted by Transportation Technology Center, Inc. (TTCI). The research team conducted this work at the Transportation Technology Center (TTC) in Pueblo, CO. This study included forecasting ballast-induced track geometry degradation, or loss of stability in a ballast section. This was a difficult task due to the complex ballast degradation mechanisms and challenges characterizing the ballast in a manner that can accurately forecast settlement. Multiple models exist for mechanics-based track geometry degradation, including models previously developed by the research team. However, these models have not been updated recently and they do not incorporate current principles in the understanding of fundamental ballast behavior, ballast inspection technologies, or data analytics. In response to this lack of current information, FRA requested that the research team build on and extend earlier work on mechanics-based ballast condition forecasting models to support the improved safety and reliability of ballast tracks.

Phase II provides an update of the previous mechanics-based models that represent different settlement mechanisms, with inputs that align with outputs from the inspection technologies either currently in use or in development. The updated model(s) will be used to develop indicators of track reliability and can potentially be used to identify locations that are at high risk of degradation or failure. The research team presented modifications of the Railway Track Lifecycle Model (RTLM) equations. A modified surface profile degradation model assumes a linear degradation and is primarily based on the ballast fouling index (BFI).

The potential outcome of this research is a general improvement in the ability to forecast track geometry behavior. This ability could include short-term risk assessments and projections on how track behavior may change depending on ballast maintenance, as well as long-term forecasts that incorporate changes in track structure, tonnage, or climate.

The first portion of the Phase II report presents modifications of the RTLM equations. The first modified model, similar to the original settlement RTLM, retains the logarithmic settlement curve trend. The settlement model was also modified to include tamp lift height and a site-specific correction factor. The tamp lift height was added because lift height has a strong relationship with settlement from ballast re-compaction. Adding the site-specific correction factor addressed any settlement differences that could not be accounted for by the existing measurable parameters (e.g., BFI, vertical track modulus [VTM]) and it serves as a proxy for accuracy.

Identifying the primary settlement mechanism was important because it predicts the success of the settlement RTLM. The most common settlement mechanism identified during testing at TTC was ballast re-compaction, a process in which the upper ballast re-compacts to its pre-tamping elevation. This re-compaction could be identified by comparing the lift height with settlement because they should eventually be equal to each other. The settlement RTLM was well suited for these situations as the settlement has the logarithmic trend that is assumed by the settlement RTLM.

For the ballast re-compaction situations, the primary correlating factor with settlement was tamp lift height. Other factors, such as BFI, track modulus, and tie type, did not have any noticeable relationship and should be assumed as 1.0 in ballast re-compaction scenarios. If only tamp lift height was used, the accuracy of the modified settlement RTLM for all ties was quite high. The relationship between settlement and surface profile was low, with very low settlement/surface profile ratio (SM/u) values (0 to 0.2). This low ratio is due to the ballast settling almost uniformly, which will not produce large surface profile deviations.

The second ballast settlement mechanism is settlement from a degraded ballast location. In this case, the exact mechanism of settlement is more complicated, but the settlement trend tends to be linear, and it can vary depending on moisture levels. In addition, it often exceeds the tamp lift height. Other existing settlement mechanisms, such as subballast, subgrade, and lateral movement, were not measured in this study. Additional factors may include high force regions such as joints or turnouts.

Moisture (climate) was the primary correlating factor with the post-compaction settlement rate for the degraded ballast situation. The projected settlement magnitudes and settlement trends did not agree well with the measured values, but the existing framework did allow for the parameters to be explored. The accuracy of the modified settlement RTLM was not good for this situation and thus the surface profile model may be better suited. The relationship between settlement and surface profile was high, with an SM/u Ratio of 0.8. This indicates that the settlement occurred in a localized dip rather than over an entire area.

An exploratory analysis to investigate how the RTLM and surface profile model could be used to project possible changes in degradation rate due to changes in axle load, BFI degradation, and climate should be explored more fully in the future and verified with actual measured scenarios.

1. Introduction

In 2022, Transportation Technology Center, Inc. (TTCI) completed the follow-on Phase II of a track geometry degradation study that evaluated forecasting models using funding from the Federal Railroad Administration (FRA). This study included forecasting ballast-induced track geometry degradation, or loss of stability in a ballast section, which is a difficult task due to the complex ballast degradation mechanisms and challenges characterizing the ballast in a manner that can accurately forecast settlement. Multiple models exist for mechanics-based track geometry degradation, including models that were previously developed by the research team. However, these models have not been recently updated, and do not incorporate current principles in the understanding of fundamental ballast behavior, ballast inspection technologies, or data analytics. Due to this lack of information, FRA requested that TTCI build on and extend the earlier work on mechanics-based ballast condition forecasting models to support the improved safety and reliability of ballast tracks.

Phase II of this project is to continue updating the previous mechanics-based models so that the models will represent different settlement mechanisms, with inputs that align with outputs from the inspection technologies that are either currently in use or in development. The updated model(s) will be used to help develop indicators of track reliability and can potentially be used to identify locations that are at high risk of degradation or failure.

The potential outcome of this research is a general improvement in the ability to forecast track geometry behavior. This ability could include short-term risk assessments and projections on how track behavior may change depending on ballast maintenance, as well as long-term forecasts that incorporate changes in track structure, tonnage, or climate.

1.1 Background

Forecasting ballast-induced track geometry degradation is a difficult task 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, but 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 the results from a Phase I 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. This research will potentially improve the ability to forecast track geometry behavior and 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.

1.2 Objectives

Phase II continued the modification of the Railway Track Lifecycle Model (RTLM) and demonstrated the model with field data. Phase II primarily focused on data collected from the High Tonnage Loop (HTL) at TTC.

The objectives of Phase II included:

- Modifying the RTLM algorithms based on recommendations from Phase I. Also, represent different types of track geometry degradation.
- Exploring uncertainty in measurement inputs and stochastic analyses
- Collecting track geometry, ballast fouling index (BFI), and track modulus measurements. Analyze data at multiple zones on the HTL
- Demonstrating modified settlement RTLM against HTL results, including fitting field data, determining RTLM projection accuracy, and verifying input parameter relationships with measured settlement
- Exploring uses of mechanics-based models with regard to changes over time in loading, ballast conditions, and climate
- Providing recommendations for future work

1.3 Overall Approach

The multiple approaches used in this project included field testing, computer modeling, and data analytics. Field testing expanded the dataset for analysis and tested the capabilities of inspection technologies. Mechanics-based computer models compared the model projections against field behavior to better understand model performance. Using data analytics aided in processing large datasets gathered from inspection technologies and the development of forecasting models based on this information. This work was done in conjunction with an existing Association of American Railroads (AAR) Strategic Research Initiatives (SRI) project.

1.4 Scope

The scope of Phase II included modifying the RTLM based on recommendations from Phase I to best represent the different types of track geometry degradation. The scope of the field analysis was to collect track geometry, BFI, and track modulus for two sections of track and to present that data in a manner that would be compatible with RTLM projections. The scope of the model demonstration was to test the general attributes of the mechanics-based models and recommend improvements.

1.5 Organization of the Report

The Phase II report contains six sections that are briefly described below.

- Section 1 introduces the work conducted.
- Section 2 provides the modified RTLM and exploration of stochastic analysis.
- Section 3 contains all data collection and model demonstration for four HTL test zones.
- Section 4 consists of an analysis exploring the relationships between the input parameters and settlement measurements.
- Section 5 explores the uses of mechanics-based track geometry deterioration models regarding changes over time in loading, ballast condition, and climate.
- Section 6 summarizes the results and conclusions.

2. Ballast RTLM Updates

The larger goal of the project is to better align the mechanistic-based RTLM and track geometry degradation model with track inspection inputs and outputs. Phase I identified the RTLM as the most comprehensive mechanistic-based track geometry projection model. However, there were multiple recommendations suggested for modifications when comparing the model projections to the track-based geometry field measurements [1]. The two primary recommendations were: 1) to switch the manual BFI-track geometry degradation curve from a manual fit to a power equation fit, and 2) change the track geometry degradation trend from the current logarithmic fit to linear.

This section presents a brief background into various recently developed track geometry forecasting models (Section 2.1), along with the modified RTLM track geometry degradation equations (and the reasoning behind the modifications). Because of the inherent differences between the two measurements, researchers decided to develop two different models depending on whether the measurement was settlement (Section 2.2) or track-based geometry data (Section 2.3). Lastly, Section 2.4 explores a stochastic approach.

2.1 Track Geometry Degradation Forecasting

2.1.1 Recent Track Geometry Degradation Models

Track geometry degradation forecasting is difficult because of the wide range of conditions that may produce track geometry degradation. Track geometry degradation models developed in the 1990s and 2000s (e.g., RTLM), relied on mechanistic approaches, and the input parameters were selected from limited field testing, primarily from the HTL located at TTC [2].

Innovations in track inspection vehicle collection, together with large dataset analysis over the past 5 years, now allow more data-based approaches. Since the completion of Phase I [1], several new degradation models that explore various data analysis techniques for track geometry forecasting have been published [3–6].

Many of these techniques are "statistical-fitting" models. Projections involve using regular inspection intervals to 1) measure track geometry degradation, 2) fit linear or non-linear trends using various regression or machine-learning methods, and 3) extrapolate from the degradation rate into the future. These "statistical-fitting" methods will likely be very useful to the industry because the methods can be scaled to large datasets once the algorithms are mature. In addition, the "statistical fitting" projections are based directly on measured track geometry data instead of derived indirectly from underlying conditions.

However, the extrapolation of "statistical-fitting" methods must assume that important mechanistic factors such as axle load, climate, and BFI do not change over time. Otherwise, the "statistical-fitting" projections will probably be inaccurate. Exploring changes in track geometry behavior due to changes in mechanistic factors may be better suited for "mechanistic-based" models such as RTLM. As a result, multiple types of models (e.g., statistical-fitting and mechanistic-based) may be useful for the foreseeable future.

2.1.2 Settlement Mechanisms

It is well known that track settlement occurs from different mechanisms, such as ballast compaction and subgrade settlement, but there has not been a significant effort to categorize different track responses based on the mechanism. This report explores different track settlement behaviors, depending on the settlement mechanisms. Thus, a brief introduction into the various settlement mechanisms is necessary.

Substructure-induced track settlement can occur within multiple substructure regions (e.g., upper ballast, lower ballast, subballast, subgrade, interface layers, and lateral deformation), but only a few common mechanisms are relevant to this report. These mechanisms include:

- Upper ballast re-compaction after tamping
- Upper ballast settlement from mud pumping
- Subgrade settlement

The primary focus of this research is upper ballast re-compaction after tamping, which occurs when vehicle forces re-compact the loose post-tamping ballast particles into a more compact state. This assumes the pre-tamping upper ballast state is fully compact and that it experienced no meaningful settlement.

Tamping raises the track elevation by loosening the upper ballast particles and adding ballast if needed. If the tamp lift height is small (<1.5 inch), there will not be enough room for ballast particles in the crib to be pushed underneath the tie by the vibrating tamping tines. In this situation, the lift comes solely from the loosening of ballast particles underneath the tie. The re-compaction of that tie location from downward vehicle forces should eventually produce settlement magnitudes that are equal to the tamp lift height, which means that the pre-tamp and post-settlement elevations are identical. The settlement trend with tonnage tends to show high initial rates of settlement that reduce with tonnage. This decreasing settlement rate with tonnage is a result of less opportunity for ballast compaction as the ballast approaches the densest possible state from the loading environment. Figure 1 provides a diagram the shows the tamping and upper ballast densification.

If the tamp lift is larger (>1.5 inch), the gap underneath the tie will be large enough to allow the crib ballast particles to be pushed underneath the tie by the tamping tines. Not only is the ballast underneath the tie loosened, but ballast is also added. This means that the post-tamping settlement will be less than the tamp lift height, even at the most compact state possible from the loading environment.

Based on these assumptions, information about the settlement mechanism can be gained by comparing the settlement with the tamp lift height. If the settlement is less than the tamp lift height, this either means that the upper ballast is still in a looser state than the pre-tamping density, or that there was ballast re-arrangement (i.e., additional ballast added underneath the tie) and there are now more ballast particles within the upper ballast region.

If the settlement is greater than the tamp lift height, this either means that the upper ballast is in a denser state than the pre-tamping density, or that there is additional settlement elsewhere in the track system. Increased density could be a result of ballast degradation, as more degraded ballast should produce a more compact state, or it could mean that the pre-tamping ballast was not fully compacted. Settlement elsewhere in the track system could be within the lower ballast layer, subgrade, or even lateral movement of the ballast and/or subgrade.

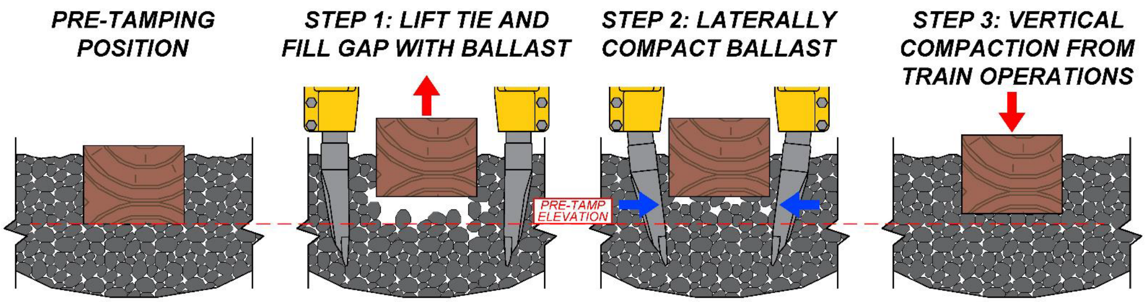


Figure 1. Upper Ballast Re-Densification Settlement Mechanism After Tamping

The second settlement mechanism, upper ballast settlement from mud pumping, is not as well understood. Settlement is generally attributed to "softening" of the degraded ballast. However, this likely means particle movement as there is limited room for ballast and fine compaction. The particle movement may occur from the ballast underneath the tie being "pushed" from under the tie, or from lateral movement of the ballast. This settlement tends to be more linear in nature than ballast re-compaction.

The parameters associated with settlement of degraded ballast is BFI and moisture [1]. BFI is typically measured by ground penetrating radar (GPR) and outputs a value similar to Selig's Fouling Index (FI), which is defined as the percent mass passing the No. 4 sieve in addition to the percent mass passing the No. 200 sieve. Typically, FI (or BFI) values of 1 to 5 is considered clean, 6 to 10 is moderately clean, 11 to 20 is moderately fouled, 21 to 40 is fouled, and 40+ is highly fouled [1].

Subgrade settlement does not involve the ballast and can occur from a wide range of mechanisms. These mechanisms are not the focus of the study, but note that the track settlement behavior will depend on the settlement behavior of the subgrade.

In summary, settlement (and surface profile) trends may give some indication of the settlement mechanisms, which may be useful for maintenance and remediation selection. The opposite is true for track geometry degradation forecasting, as it may be necessary to know the settlement mechanisms to forecast the appropriate degradation trend.

2.2 Settlement Model

The first modified model is a direct modification of the original settlement RTLM . Settlement can be measured directly from survey elevations, track geometry space curves, or wayside instrumentation. Despite the more commonly used mid-chord offsets and track-based geometry than settlement for internal intervention limits, Federal regulation, and maintenance decisions, the research team chose to keep a settlement model. Most historical work still provides a strong fundamental understanding of track geometry degradation.

2.2.1 Original Settlement Model

Equation 1 shows the original settlement RTLM:

$$u = a * N^b \tag{1}$$

Where:

u = Settlement

a = 1st strain constant

N = Number of load cycles

b = Constant

In this format, 'a' is the 1st strain constant and 'b' dictates the shape of the settlement curve. If b=1, the settlement curve is linear, if b<1, the settlement curve is logarithmic and tends to stabilize, and if b>1, the curve is exponential, and the settlement does not stabilize with time. Figure 2 shows examples of how varying the a- and b- constants.

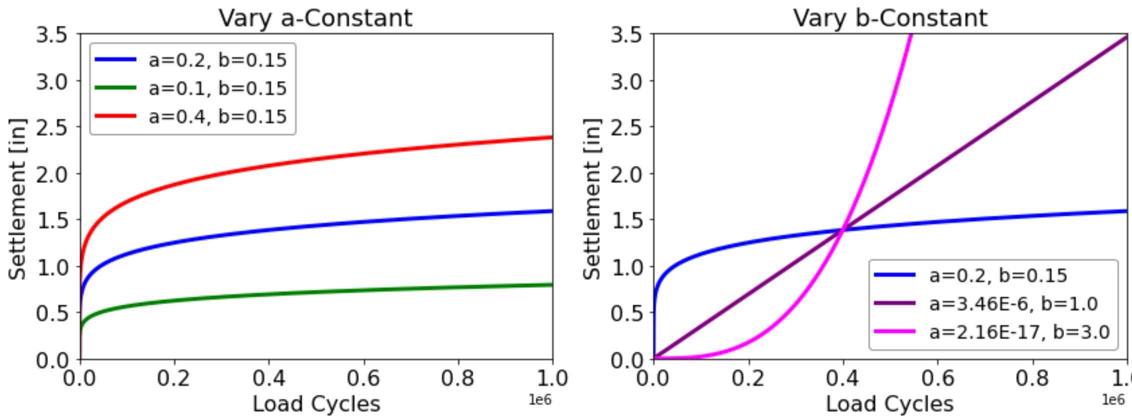


Figure 2. Examples of How Varying the (a) a-constant and (b) b-constant Affects the Settlement Curve

The original settlement RTLM is an expansion of the basic exponential settlement model [2]. The model starts with a recommended 1st cycle strain and then uses correction factors to increase or decrease the 1st cycle strain, depending on track conditions. For example, lower axle loads typically result in lower settlement, so the adjustment factor decreases the 1st cycle strain. For high axle loads, the opposite is true. The 1st cycle strain is calibrated based on the recommendation that the b-constant should be 0.15. If a different b-constant is used (e.g., b=0.35), the 1st cycle strain would need to be adjusted. Equation 2 shows the original RTLM.

$$u_{RTLM} = h_b * \left(\varepsilon_{1(NOM)}\kappa_W\kappa_{An}\kappa_{FI}\kappa_\sigma\kappa_{VTM}\right) * N^b \tag{2}$$

Where:

h_b = Ballast height [inches]

$\varepsilon_{1(NOM)}$ = Base 1st cycle strain (assume 0.0022)

κ_W = Wheel load correction factor

κ_{An} = Abrasion number (AN) correction factor

κ_{FI} = FI correction factor

κ_σ = Track structure correction factor

κ_{VTM} = VTM correction factor

N = Number of load cycles

b = Exponential factor (assume 0.15)

The wheel load correction factor is a ratio with 33 kips assumed for this study to be the base value. Equation 3 represents W as wheel load.

$$\kappa_w = \frac{W}{33} \tag{3}$$

The Abrasion Number (AN) correction factor will not be addressed directly in this report because it is rarely tested and not commonly known. The base value of 1.0 will be assumed. This factor, however, will be covered later as part of the local factor.

The FI correction factor has equations for four different climate regions. The relation until FI = 30 is linear and a non-linear relation exists for FI > 30, and further defined in Equations 5 through 11.

Arid Climate (< 10 inches precipitation/year):

$$\boldsymbol{\kappa_{FI} = 1.0 + 0.01 * FI \quad (FI \leq 30)} \tag{4}$$

$$\boldsymbol{\kappa_{FI} = 1.0 + 0.01 * FI + 0.1 * (FI - 30) \quad (FI \geq 30)} \tag{5}$$

Semi-Arid Climate (10–25 inches precipitation/year):

$$\boldsymbol{\kappa_{FI} = 1.1 + 0.02 * FI \quad (FI \leq 30)} \tag{6}$$

$$\boldsymbol{\kappa_{FI} = 1.1 + 0.02 * FI + 0.1 * (FI - 30)^{1.2} \quad (FI \geq 30)} \tag{7}$$

Wet Climate (25–50 inches precipitation/year):

$$\boldsymbol{\kappa_{FI} = 1.2 + 0.03 * FI \quad (FI \leq 30)} \tag{8}$$

$$\boldsymbol{\kappa_{FI} = 1.2 + 0.03 * FI + 0.1 * (FI - 30)^{1.4} \quad (FI \geq 30)} \tag{9}$$

Very Wet Climate (> 50 inches precipitation/year):

$$\boldsymbol{\kappa_{FI} = 1.3 + 0.04 * FI \quad (FI \leq 30)} \tag{10}$$

$$\boldsymbol{\kappa_{FI} = 1.3 + 0.04 * FI + 0.1 * (FI - 30)^{1.6} \quad (FI \geq 30)} \tag{11}$$

The track structure correction factor depends on the tie type and subgrade. The RTLM also has the track structure correction factors as functions of ballast depth, but a ballast depth of 12 inches is assumed due to its minimal influence. Table 1 lists the correction factors.

Table 1. RTLM Model Track Structure Correction Factors

Tie Type	Clay		Sand	
	Good	Poor	Good	Poor
Wood	0.86	0.88	0.86	0.97
Concrete	1.70	1.73	1.30	1.28

The track modulus also referred to as vertical track modulus (VTM) correction factor, is a linear relation where VTM is track modulus in kip/in/in. Note that track modulus indirectly incorporates almost all the other factors, including track structure and FI/moisture. Equation 12 shows the base value is 5 kip/in/in.

$$\kappa_{VTM} = \kappa_{FI} \tag{12}$$

The RTLM has been in existence since the 1980s and 1990s and uses ballast condition metrics that were available at that time. However, innovations in track-based inspection have changed which track condition parameters are available. BFI and track geometry are now commonly available metrics that can be accessed over an entire track system. BFI can be considered a primary metric (κ_{P1}). VTM is not commonly obtained but can still be measured, or at least estimated, so it is considered a secondary metric (κ_{S1}). Axle load, tie type, and subgrade type are all track characteristics that can be used for particular track regions, so they are considered track metrics (κ_{T1}). κ_{An} is rarely used, so it is omitted. The 1st cycle strain and b-constant are constants. The RTLM equation can be rearranged to represent these primary, secondary, and track metrics, along with the constants and shown in Equations 13 through 17.

$$u_{RTLM} = \kappa_{P1} * \kappa_{S1} * \kappa_{T1} * \kappa_{C1} * N^b \tag{13}$$

$$\kappa_{P1} = \kappa_{FI} \tag{14}$$

$$\kappa_{S1} = \kappa_{VTM} \tag{15}$$

$$\kappa_{T1} = \kappa_W * \kappa_{An} * \kappa_\sigma * h_b \tag{16}$$

$$\kappa_{C1} = \varepsilon_{1(NOM)} \tag{17}$$

2.2.2 Modified Settlement Model

This section proposes modifying the RTLM track settlement model by making three changes: First, the 1st cycle strain will be highly dependent on tamp lift height, and because that is now commonly measured, this metric can be used. However, this requires that the recommended 1st cycle strain be modified as well. Second, the AN is removed because it is rarely measured or known. Third, a new metric called the "Site-Specific Correction Factor" is added and can be used to make adjustments to the 1st cycle strain to account for historical track geometry or non-measurable metrics. This factor can also be used as a proxy for accuracy. A value of 1.0 indicates perfect accuracy, a value less than 1.0 indicates an overestimation (lowers projection value), and a value greater than 1.0 indicates an underestimation (increases projection value). Equation 18 shows the modified RTLM track settlement. The correction factors are similar for all except the base 1st cycle strain and the two added factors.

$$u_{RTLM} = (\xi_{BFI}) * (\xi_{VTM} * \xi_t) * (\xi_{SS}) * (\xi_W * \xi_\sigma) * (\xi_{NOM}) * N^b \tag{18}$$

Where:

$\xi_{1(NOM)}$ = Base 1st cycle strain (assume 0.0022)

ξ_W = Wheel load correction factor

ξ_{BFI} = BFI correction factor

ξ_σ = Track structure correction factor

ξ_{VTM} = VTM correction factor

ξ_t = Tamp lift height correction factor

ξ_{SS} = Site-specific correction factor

N = Number of load cycles

b = Exponential factor (assume 0.15)

2.2.3 Tamp Lift Height Factor

The tamp lift height factor was added because of the strong relationship between tamp lift height and settlement magnitude. The tamp lift factor only requires tamp lift height, and the adjustment factor was developed using the data from Zone 1 that is presented in Section 3.1. This dataset presented the ballast as clean, and both wood and concrete ties are present in the section.

Equation 19 shows this as a simple linear factor. It may be possible to expand or modify this factor in the future. Figure 3 presents a diagram of the relationship to the Zone 1 dataset.

$$\xi_t = 2 * u_t + 1 \tag{19}$$

Where:

u_t = Tamp lift height [inch]

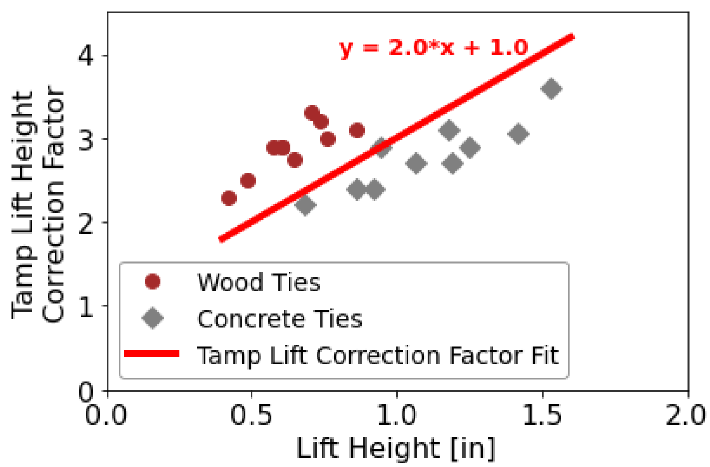


Figure 3. Relationship Between Tamp Lift Height and Tamp Lift Height Correction Factor

2.2.4 Settlement Model Demonstration

This section shows a simple demonstration of the settlement model using common inputs from the HTL. Table 2 shows the various inputs and the calculated adjustment factors. Figure 4 shows the resulting settlement curve. More detailed model demonstrations and interpretations are presented in Section 2.2.4 through Section 2.3.

Table 2. Settlement Model Demonstration Inputs

Parameter	Input	Correction Factor	Correction Factor Input
BFI, Climate	5, Arid	ξ_{BFI}	1.05
Track Modulus	6 kips/in/in	ξ_{VTM}	0.85
Tamp Lift Height [ft]	1.5 inches	ξ_t	4
Site Specific	1	ξ_{SS}	1
Wheel Load	39 kips	ξ_W	1.18
Tie Type, Subgrade	Wood, Sandy	ξ_σ	0.86
		ξ_{NOM}	0.264
		b	0.15

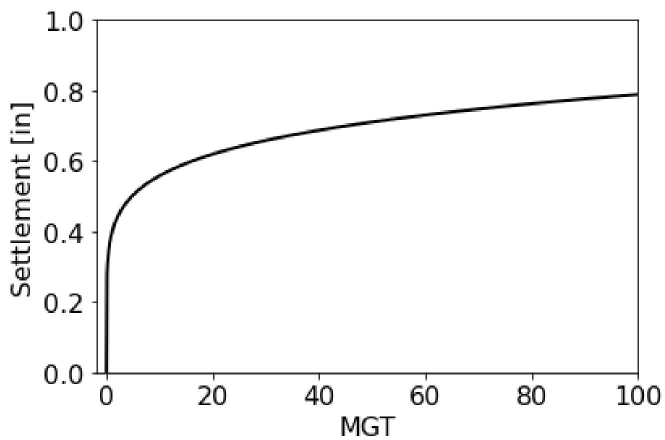


Figure 4. Settlement Model Demonstration Settlement Curve

2.3 Surface Profile Model

The second RTLM version is the surface profile model. Unlike the settlement model, the surface profile model is more suitable for revenue service and assumes data is from a track-based inspection vehicle. The output of the model is referred to as "surface magnitude" (SM), which is the absolute value of the surface profile over a specified track length. The degradation rate (dSM) is measured in inches per 100 MGT.

The research team lists multiple modifications as:

- The BFI-dSM curve is used as the model basis instead of 1st cycle strain because 1st cycle strain cannot be measured with the track inspection intervals used in revenue service. The BFI-dSM curve is a fitted relationship between BFI and the change in absolute value of the surface profile over 100 MGT (dSM).
- The degradation trend with MGT is assumed to be linear instead of logarithmic. This was shown to better fit the data from Phase I and is primarily attributed to the inability of track inspection vehicles to measure the initial ballast consolidation phase. A second attribute is that the settlement at most locations were due to degraded ballast, which tends to have a more linear settlement trend. Therefore, it is better to represent the surface profile field response linearly.

- The model, instead of starting from zero, assumes the post-tamping surface profile based on the pre-tamping surface profile. Because the post-tamping surface profile is rarely measured, the model must assume multiple MGT have accumulated since tamping.

2.3.1 Surface Profile Model Equation

Equation 20 shows the surface profile RTLM. It has a similar format to the settlement model, but it does not rely on 1st cycle strain, and it has a linear degradation.

$$SM = (\xi_{BFI} * \xi_{VTM} * \xi_{SS} * \xi_{W} * \xi_{\sigma}) * MGT^{b2} + SM_i \tag{20}$$

The correction factors are similar to the settlement model, except for ξ_{BFI}, which should be back calculated from available data when possible. The value SM_i is the surface profile after tamping. The BFI-dSM curve follows a power function and is shown in Equation 21.

$$\xi_{BFI} = b * BFI^{a} \tag{21}$$

Figure 5 displays some back-calculated field relationships from Phase I.

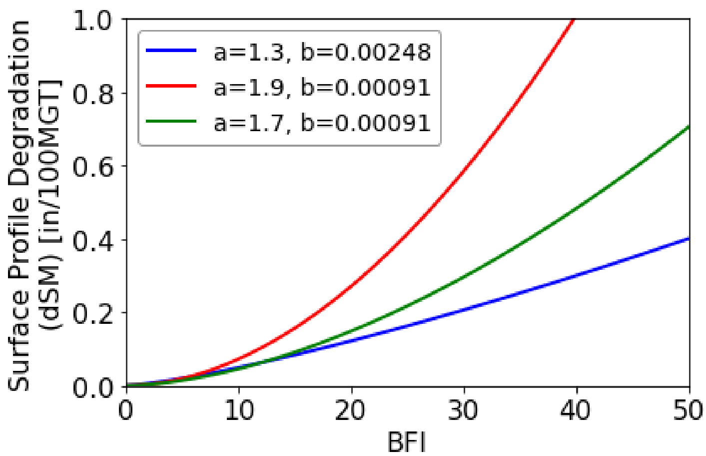


Figure 5. Example Relationships Between BFI and Surface Profile Degradation (dSM)

2.3.2 Surface Profile Model Demonstration

This section presents a simple demonstration of the track geometry model using common inputs. Table 3 shows the various inputs and the calculated adjustment factors. Figure 6 shows the resulting surface profile curve. More detailed model demonstrations are presented in the next sections.

Table 3. Track Geometry Model Demonstration Inputs

Parameter	Input	Correction Factor	Correction Factor Input
BFI	30	ξ_{BFI}	1.3
BFI a-constant	1.7	ξ_{VTM}	1.0
BFI b-constant	0.00091	ξ_{SS}	1.0
Track Modulus	5 kips/in/in	ξ_{W}	1.0
Site Specific	1	ξ_{σ}	1.3
Wheel Load	33 kips	b	1.0
Tie Type, Subgrade	Concrete, Sandy	SMi	0.5

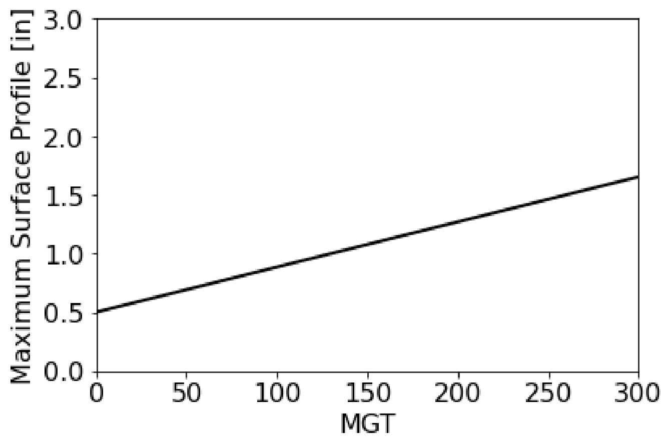


Figure 6. Track Geometry Degradation Model Demonstration Surface Profile Curve

2.4 Stochastic Approach

Stochastic analyses can quantify uncertainty and distributions of outcomes. Many ballast parameters are difficult to measure accurately and are typically only "estimations," which makes stochastic approaches well suited for the RTLM analyses. This section explores the basic use of stochastic approaches on the RTLM analysis. The first case will be exploring the range in settlement outcomes based on the range of typical parameters. The second case will show the range of outcomes based on inherent uncertainty of a few of the measurement parameters, assuming both uniform and normal distributions of those parameters.

2.4.1 Stochastic Analysis #1: Distribution Based on Typical Values

The first stochastic analysis looks at the overall range of possible outcomes from the range of inputs considered typical in track. The goal of this particular analysis is to perform a general assessment of the model to understand outlier behavior.

Table 4 lists the proposed ranges of values under "Typical Values." Table 5 includes the statistical outputs of median, difference in maximum and minimum, and difference between 95 percent and 5 percent values.

Table 4. Stochastic Analysis Inputs

Parameter	Typical Values	Analysis 2 – Uniform	Analysis 2 - Normal
ξ_{BFI}	1 to 26.79 (Arid to Very Wet)	1.13 to 1.29	1.21 – Median 0.08 – St. Dev.
ξ_{VTM}	0 to 1.6	0.7 to 1.0	0.85 – Median 0.08 – St. Dev
ξt	0 to 9	3.1	3.1
ξ_{SS}	1.0	0.65	0.65

Table 5. Stochastic Analysis Output of Settlement (inches) at 100 MGT

Parameter	Typical Values	Analysis 2 – Uniform	Analysis 2 – Normal
Median	3.64	0.68	0.68
Range in Min/Max (Difference in Max/Min)	0 to 85.4 (85.4)	0.53 to 0.86 (0.33)	0.38 to 1.10 (0.72)
Difference in 95%	N/A	0.56 to 0.82 (0.27)	0.53 to 0.84 (0.31)
ξ_{SS}	1.0	0.65	0.65

For the first stochastic analysis, 100,000 samples are used and all the input parameters with ranges are assumed to have a uniform distribution. Figure 7 presents the settlement curve and histogram of 100 MGT settlement values. The results show unrealistically high settlement values (up to 85.4 inches). The user must be aware of the inputs and take care to avoid these unrealistically high combinations (e.g., combinations of wet climates with high BFI, and low track modulus).

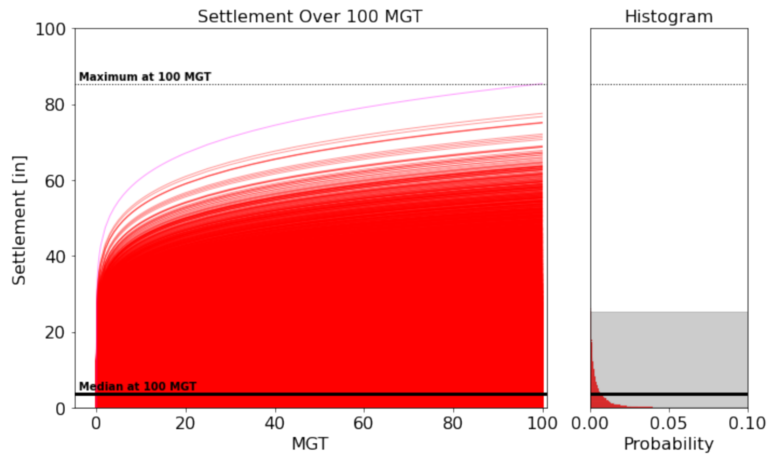


Figure 7. Stochastic Analysis #1 (typical values) Showing Settlement Curve with MGT and Histogram of 100 MGT Values

2.4.2 Stochastic Analysis #2: Distribution Based on Field Data

A more practical use case in stochastic analysis evaluated the range in settlement from inherent uncertainties in ballast or track measurements. Two measurements that have this inherent uncertainty are BFI and VTM. A single location from Zone 3 (Tie #105) is selected. This location is a concrete tie with a tamp lift of 1.05 inches, wheel loads of 39 kips, BFI of 21 (13 to 29) in an arid climate, and a VTM of 4.5 (3.5 to 5.5) kips/in./in. For this example, it is assumed that BFI has an uncertainty of ±8 and VTM has an uncertainty of ±1 kip/in/in. The range in BFI is based on experience from the BFI measurement device used and VTM variation is based on the research team's experience.

A stochastic analysis with two uncertain variables requires the distribution of both variables. For this example, the assumption was that the BFI and VTM parameters were both uniform and exhibited normal distributions, while 100,000 samples were run. Figure 8 shows the results of the uniform distribution, whereas Figure 9 shows the results of the normal distributions.

The results show significant variation for both the uniform and normal distributions. The median for both situations was 0.68 inches. The uniform distribution has a max-to-min variation of about 50 percent the median value and 33 percent variation of the 95-percentile range (two standard deviations commonly used for 95 percent confidence intervals). The normal distribution shows even greater range, with a max-to-min variation of about 100 percent the variation, especially on the high range with 1.10 inches.

This emphasizes the large range in settlement magnitudes from assuming uncertainty of just two of the variables using RTLM projections. If additional uncertainties are present (e.g., tamp lift, wheel load, and tonnage), the expectation is that should be even greater.

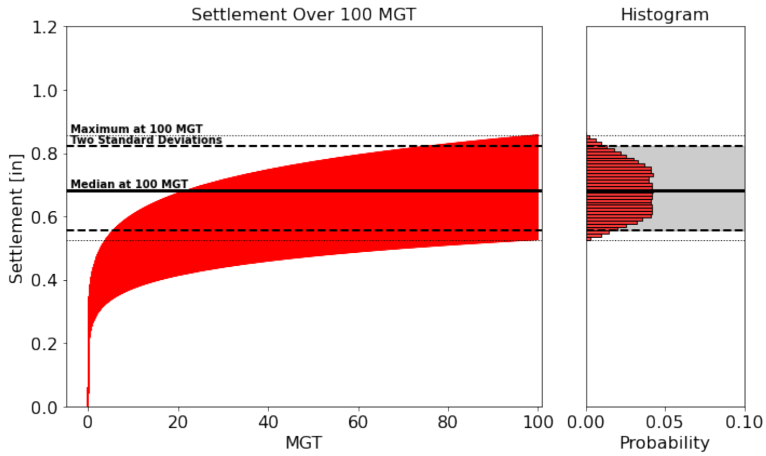


Figure 8. Stochastic Analysis #2 with Uniform Distribution Showing Settlement Curves with MGT and Histogram of 100 MGT Values

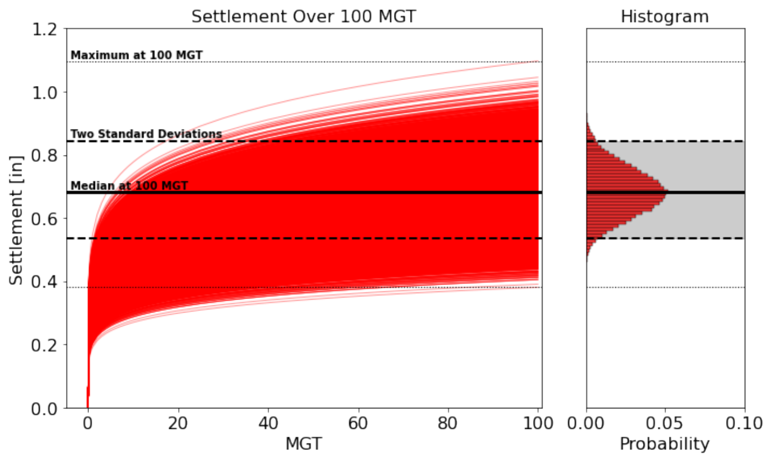


Figure 9. Stochastic Analysis #2 with Normal Distribution Showing Settlement Curves with MGT and Histogram of 100 MGT Values

2.5 Model Demonstration Goals

The modified RTLM requires continual model demonstration (validations) and improved interpretation. The subsequent sections compare the model projections against the field data. Beyond a basic comparison, the model demonstration addressed the following:

- Compare settlement curve shape (b-value) against field data
- Assess accuracy of various correction parameters (ξ_{BFI}, ξ_{Tamp}, ξ_{VTM}, ξ_{σ})
- Determine range in ξ_{SS} (proxy for accuracy)
- Determine u versus SM relationship

3. Testing at TTC: Settlement Model Demonstration

One area well suited for demonstrating the settlement model is at HTL located at TTC. This section presents four different track zones for the demonstration.

Table 6 lists the four zones, along with their location and details. Figure 10 shows the sections within the HTL. Zones 1 and 2 are in Section 36 and were tested prior to spring 2022. Zones 3 and 4 are in Sections 2 and 25 and were tested in spring 2022.

Table 6. Location and Test Details of the Four Zones

Zone	Section	Start Tie	End Tie	# Ties	Length [ft.]	Duration
1	36	Tie 365	Tie 525	160	290	Fall 2020
2	36	Tie 275	Tie 335	60	100	2018 to 2022
3	2	Sec 1: Tie 84*	Sec 3: Tie 16*	221	393	Spring 2022
4	25	Tie 80	Tie 400	333	519	Spring 2022

*Sections 1 and 3 indicates test zone went into surrounding sections.

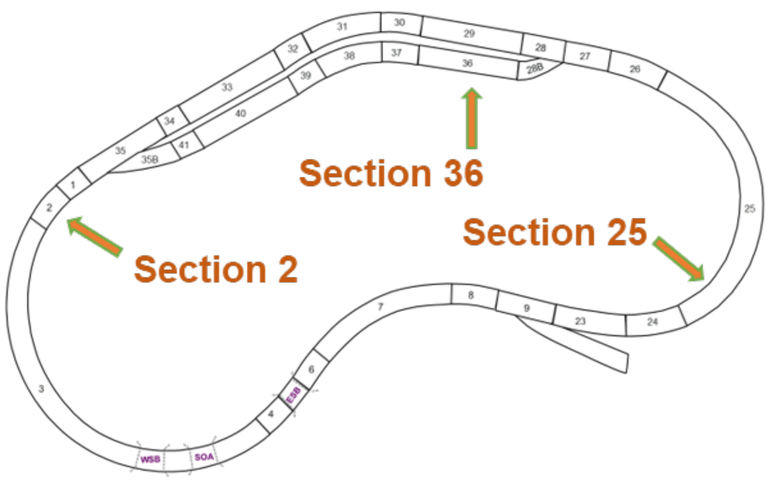


Figure 10. HTL Track Sections Used for Model Demonstration

The settlement of each zone was monitored using top-of-rail (TOR) survey elevations or a Trimble cart, both of which output unloaded rail elevation. Settlements can be calculated directly from the rail elevations. Since the elevations were also monitored along the track, the surface profile and even roughness can be calculated in Zones 3 and 4. For the settlement RTLM, all the necessary inputs were measured or estimated, including BFI, track modulus, tamp lift height, tie type, subgrade type, and axle loads.

TTC's climate is typically considered "arid," as Pueblo receives about 12 inches of rainfall every year. For the testing between January and May 2022, TTC received about 2.75 inches of rainfall, much lower than the 4.51-inch average. This low rainfall amount meant that Zones 3 and 4 remained dry during the entire test period.

3.1 Zone 1: Section 36

Zone 1, located in Section 36, involved the same location that was monitored for changes in lateral tie strength in Phase I [1]. This location serves as a good baseline measurement because it is a tangent section with both wood and concrete ties, as well as clean ballast. Zone 1 serves as a base case, and the results were used to develop ξ_{Tamp}. The research team also calculated the range in ξ_{SS} and the SM/u relationship.

3.1.1 Zone 1 Track Location Details and Measurements

Zone 1 is in a tangent and is split evenly between wood and concrete ties. Figure 11 shows a rough diagram and photographs of the location.

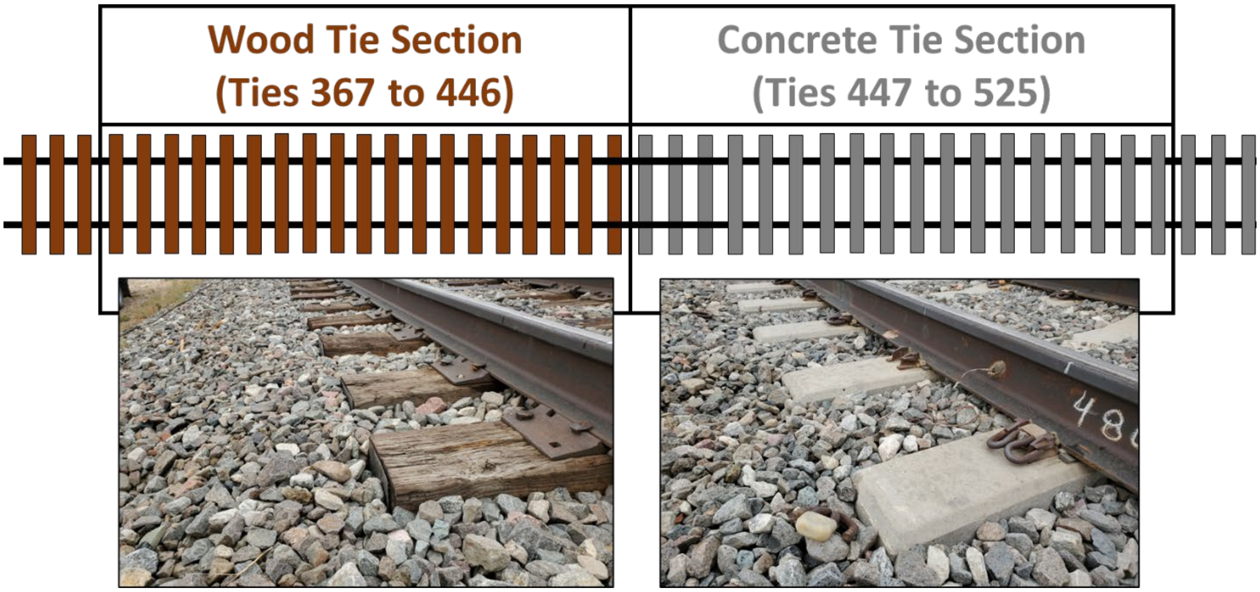


Figure 11. Diagram and Photographs of Ties of Zone 1

For track characterization, the assumption was that the clean ballast has a BFI=5 and the prior track modulus measurements of 6 kips/in/in can be used. The axle loads are 39 kips, and the subgrade is sandy. The two main variables in Zone 1 are: tie type and tamp lift height. TOR survey elevations were measured at 0, 0.1, 3.9, and 22.3 MGT.

3.1.2 Zone 1 Track Settlement and Surface Profile

The following sections analyzed and organized the TOR elevation data prior to the model demonstration. Figure 12 shows the change in rail elevations along the track. The tamp lift height is represented as the thick dashed line in the positive direction. The median lift was 0.69 inch, with a minimum of 0.36 inches and a maximum of 1.32 inches. The maximum lift height occurred at the transition region between the wood and concrete ties, and the larger lift is due to the largest surface profile in that region. The median lift height of the concrete ties was 0.92 inches, slightly greater than that of the wood ties, which was 0.58 inches.

The colored lines in Figure 12 represent the post-tamping settlement (the downwards rail elevation, using the post-tamp elevation as a baseline) at the various MGT intervals. The shaded region represents a mirrored tamp lift height. Any settlement in the shaded region is an indication that all the tamp lift height has been lost, and that the ballast has likely fully re-compacted after tamping. The colored lines show a gradual increase in settlement (downwards rail elevation) with MGT, with the greatest settlement in the regions with the greatest tamp lift height.

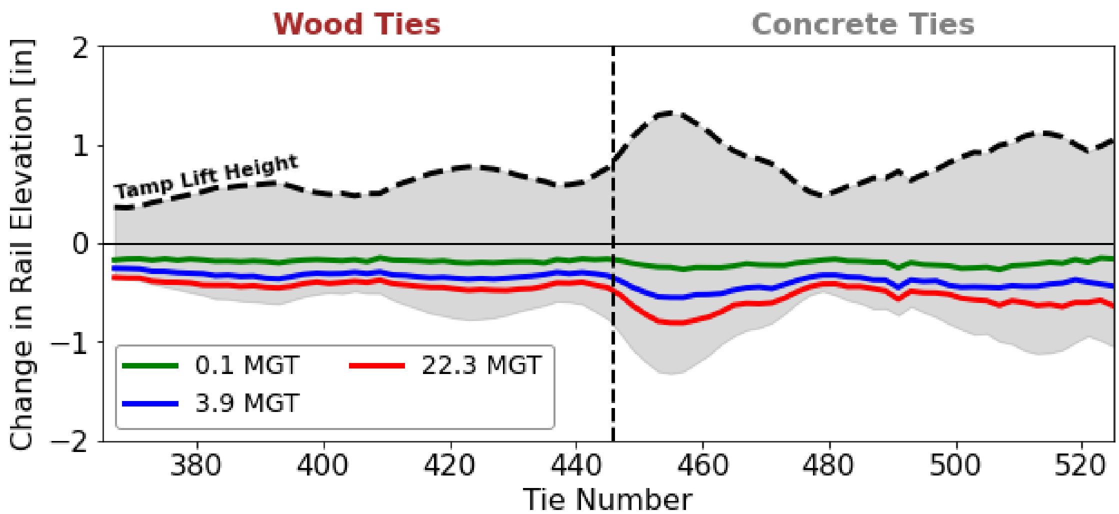


Figure 12. Change in Rail Elevations at Zone 1

Figure 13 shows further evidence of the relationship between tamp lift height and settlement, where the two values are plotted against each other for each tie and measurement interval. In this graph, data displayed at the lower right of the 45-degree black line would indicate that the tamp lift height is greater than settlement, and there is still tamp lift height remaining. Data on the 45-degree black line would show that all the tamp lift height has been lost and the ballast has fully re-compacted. Data at the upper left of the 45-degree black line would indicate that there has been additional settlement beyond ballast re-compaction.

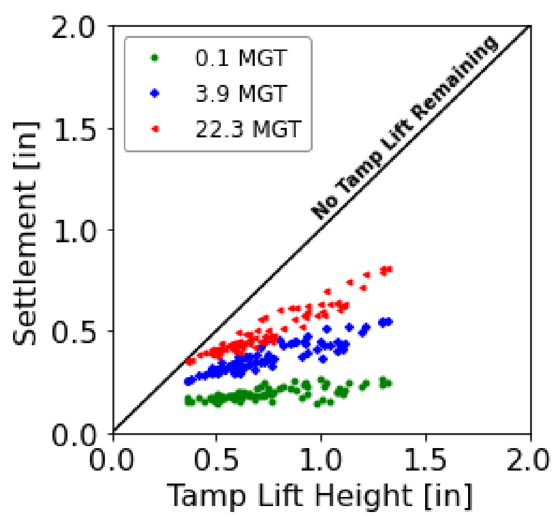


Figure 13. Relationship Between Tamp Lift Height and Settlement at Zone 1

The results in Figure 13 show a strong relationship between the tamp lift height and settlement. This was expected because greater tamp heights typically mean the ballast is in a less dense state after tamping and is therefore more suspectable to re-compaction. The graph shows that the data gets closer to the 45-degree black line with each measurement interval (indicating more re-compaction), and that the relationship slope also increases. It can be anticipated that the ballast will eventually fully re-compact to the pre-tamp levels and stay on the 45-degree line unless there are additional mechanisms besides ballast re-compaction that produce settlement (e.g., subgrade). It can also be observed that the lower lift heights will fully re-compact at a lower MGT than higher lift heights, which has been the basis of previous work that includes design lift tamping [7].

The 62-foot surface profile was calculated manually using the loaded TOR elevation data and is presented, along with the settlement, in Figure 14. The results show very little surface profile issues at this region, with the only significant degradation occurring at the wood/concrete transition (Tie 457).

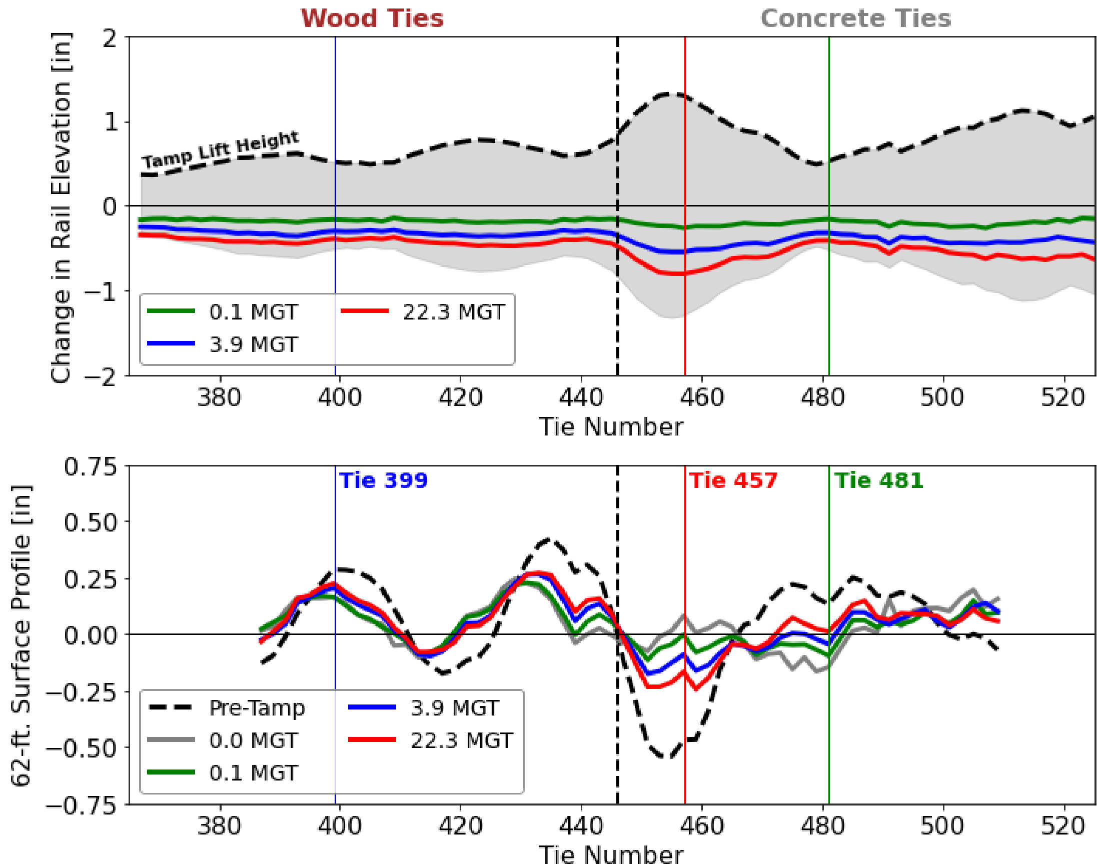


Figure 14. Zone 1 Settlement (upper) and Surface Profile (lower)

The relationship between settlement and surface profile degradation (SM/u) is not well known, but it can be calculated by taking the slope of the line when the two values are plotted against each other. Figure 15 plotted the SM/u values along the track. Figure 16 shows three ties are an example.

Figure 15 shows an oscillating SM/u value with peaks reaching 0.42. In Phase I, a back-calculated estimate of SM/u was 0.3. This value is represented by the dotted line. While settlement is fairly uniform across the track section, the oscillating SM/u values occur because there are still slight differences in the surface profile degradation.

Figure 16 uses three example locations to show the SM/u calculation. As can be observed, the trend for each tie is fairly linear, and the linear slope can be calculated using a regression analysis.

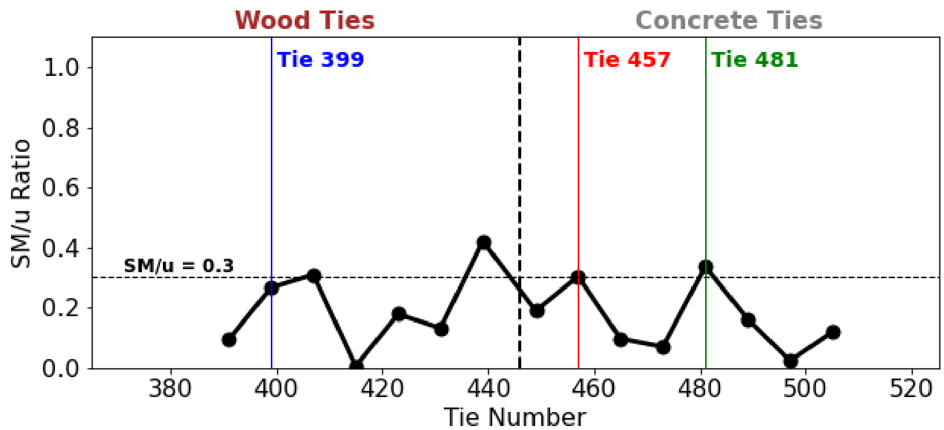


Figure 15. SM/u Values Along Zone 1

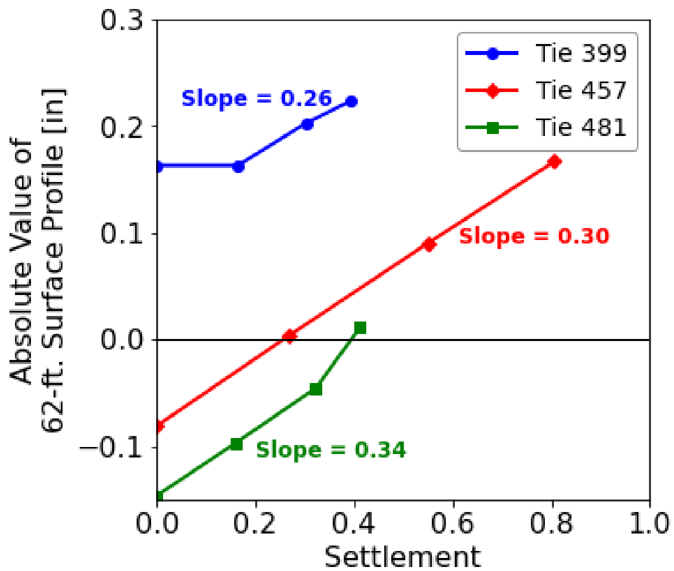


Figure 16. Calculation of SM/u Relationship Using Three Examples in Zone 1

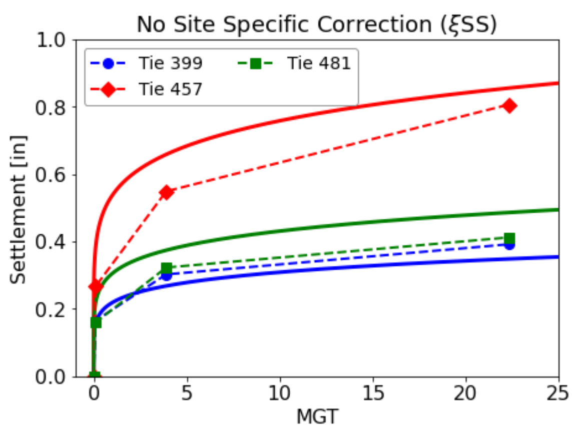
3.1.3 Zone 1 Model Demonstration

This section compares the settlement RTLM projections with field data. Ties 399, 457, and 485 are shown for demonstration purposes. Table 7 shows the model inputs.

Table 7. Zone 1 Model Demonstration Inputs

Input	Tie 399	Tie 457	Tie 485
ξ_{BFI}	1.05	1.05	1.05
ξ_t	2.21	3.59	2.04
ξ_{SS}	1.23	0.89	0.85
ξ_{VTM}	0.85	0.85	0.85
ξ_W	1.18	1.18	1.18
ξ_σ	0.86	1.3	1.3
ξ_{NOM}	0.0264	0.0264	0.0264
b	0.15	0.15	0.15

Figure 17 shows the settlement curve projection and data. Figure 17(a) assumes no site-specific correction factor, while Figure 17(b) fits the data with the site-specific correction factor. The results show a decent match with the b=0.15 assumption, and that fits the data fairly well. The one exception is Tie 457, which may need a higher b-value (probably because it is in the wood/concrete tie transition region).



(a) **(b)**

Figure 17. Zone 1 Model Demonstration Using (a) No Site-Specific Correction Factor and (b) Including Site-Specific Correction Factor

The site-specific correction factor can be used as proxy for accuracy. Figure 18 plots the site-specific correction factor for 10 wood and concrete ties along the track, as well as the cumulative distribution for both wood and concrete ties. The graph also includes basic statistics for reference purposes. A logarithmic scale is used for the y-axis because 2.0 and 0.5 should be equidistance from the 1.0 line, but of opposite direction. The green shaded region indicates accuracy within a 2:1 ratio.

The results show a distinct difference between the wood and concrete ties, with the wood ties having a ξ_{SS} above 1.0 and the concrete ties having a ξ_{SS} below 1.0. The standard deviation of each tie type is very small (only 0.05). This is not surprising since the tamp lift height was the main parameter that varied along the track, and the tamp lift height factor was calculated from this dataset.

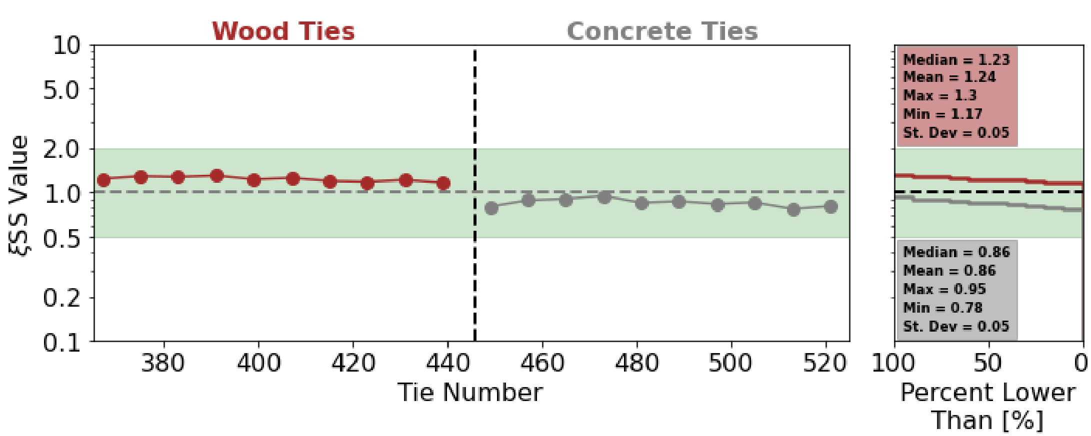


Figure 18. ξ_{SS} Along Track for Zone 1

3.1.4 Zone 1 Summary and Commentary

Zone 1 is a basic situation with a stable ballast and subgrade section. Most settlement appears to consist only of ballast re-compaction after tamping since the settlement profile closely matched the tamping profile. There were slight differences between the wood and concrete ties.

3.2 Zone 2: Rainy Section

Zone 2, a different location in Section 36 called the "Rainy Section," has a degraded ballast test location from 2017 up to the present time in 2022. This location is representative of a severe degraded ballast location that can be artificially wetted to simulate wetting events and wetter climates to show how rain events and changes in rainfall affect settlement.

3.2.1 Zone 2 Track Location Details and Measurements

Zone 2, which is in a tangent, has wood ties and consists of ballast with an FI of 40. The fouled ballast is in two adjacent 20-foot test zones. For this purpose, however, a single 40-foot test zone can be assumed. Figure 19 shows a photograph of Zone 2 during artificial wetting.

For track characterization, the assumption is that the degraded ballast has a BFI=40, the axle loads are 39 kips, and that the subgrade is sandy. The track modulus can vary anywhere from 3.5 kips/in/in when dry to 1.5 kips/in/in when wet. Climate, an additional variable for this test, should be represented as an arid climate when dry and a very wet climate when wet.

Since the Rainy Section has a single dip, the maximum dip location is measured over multiple surfacing cycles. Although four surfacing cycles (2018a, 2018b, 2019, and 2021; shown in Figure 22) are included, only the last two (2019 and 2021; shown in Figure 22) are emphasized because they accumulated more than 10 MGT. The measurement intervals varied for each surfacing cycle.

Figure 19. Photograph of Zone 2 During Artificial Wetting

3.2.2 Zone 2 Track Settlement and Surface Profile

The TOR elevation data is again analyzed and organized prior to the model demonstration in subsequent sections. As in the Section 3.1.2, the tamp lift height in Figure 20 is represented by the thick dashed line in the positive direction, and the colored lines are the post-tamp settlement. Only part of the section is characterized due to an issue from Tie 307 to Tie 335. The results again show that the settlement follows the contour of the tamp lift height. In this case, however, Zone 2 shows settlement that is greater than the lift height.

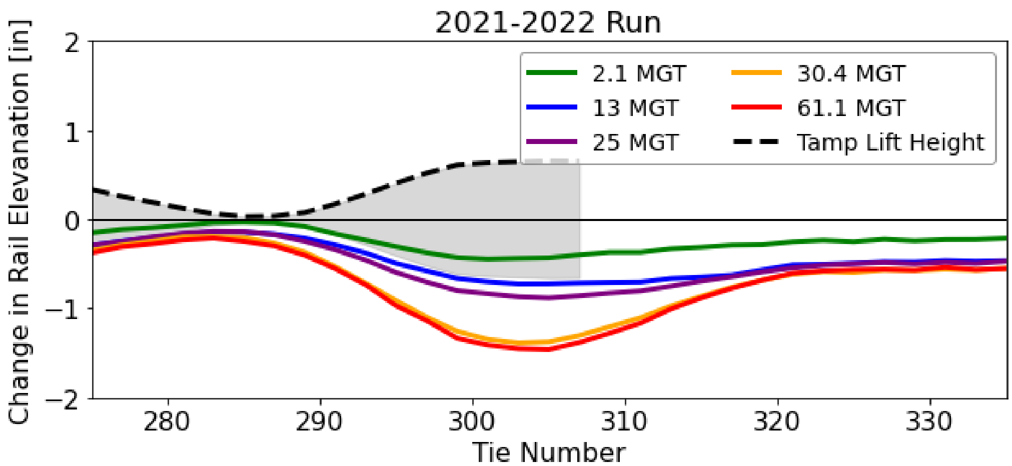


Figure 20. Change in Rail Elevations at Zone 2

When plotting the settlement against tamp lift height, as shown in Figure 21, much of the data past 8 MGT will be to the upper left of the 45-degree line. This suggests that settlement mechanisms beyond ballast re-compaction were occurring. Since this location has a high FI level and it was artificially wetted multiple times, the settlement is likely due to softening and movement of the degraded ballast.

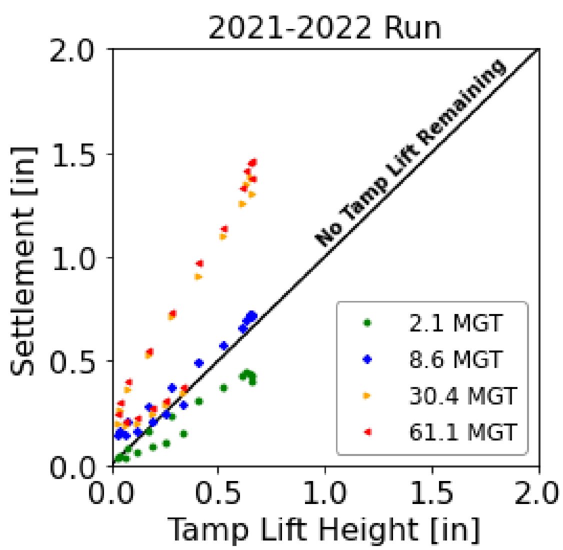


Figure 21. Relationship Between Tamp Lift Height and Settlement at Zone 2

Figure 22(a) shows the settlement of the tie in the middle of the dip of the various runs. The results show that initial settlement is similar for almost all runs, between 0.5 and 0.8 inch. Only 2019 and 2021 have data beyond 10 MGT, and both show continual settlement with MGT. There is, however, a slight difference between these two trends: the 2019 trend shows a gradual linear increase, while the 2022 trend shows leveling followed by a sudden increase that resulted from an artificial wetting test in the spring of 2021. These varying situations will be useful when using the RTLM to look at changes in settlement because of changing moisture conditions.

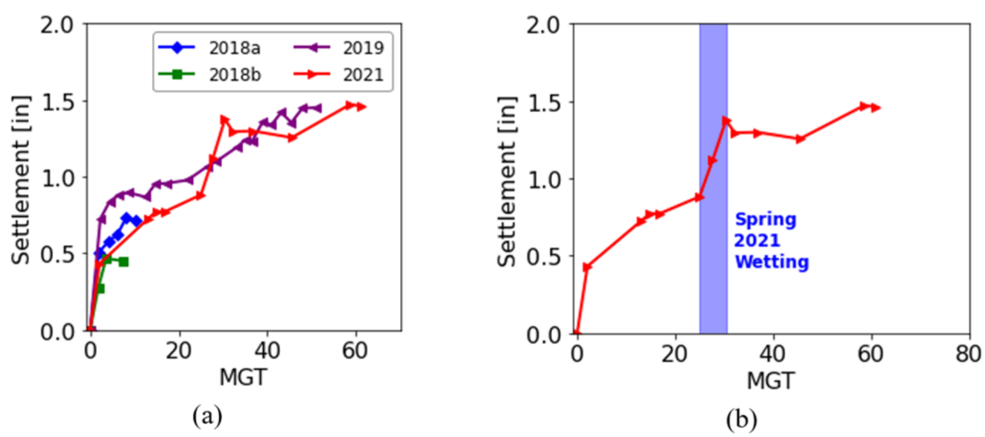


Figure 22. Zone 2 Settlement for (a) All Runs and (b) 2021 Run Specifically

The 62-foot surface profile was again calculated manually with the loaded TOR elevation data. Figure 23 presents this, along with the settlement. While the surface profile range is limited, due to the small measurement length, the surface profile still shows a distinct dip that degrades in a similar fashion to settlement.

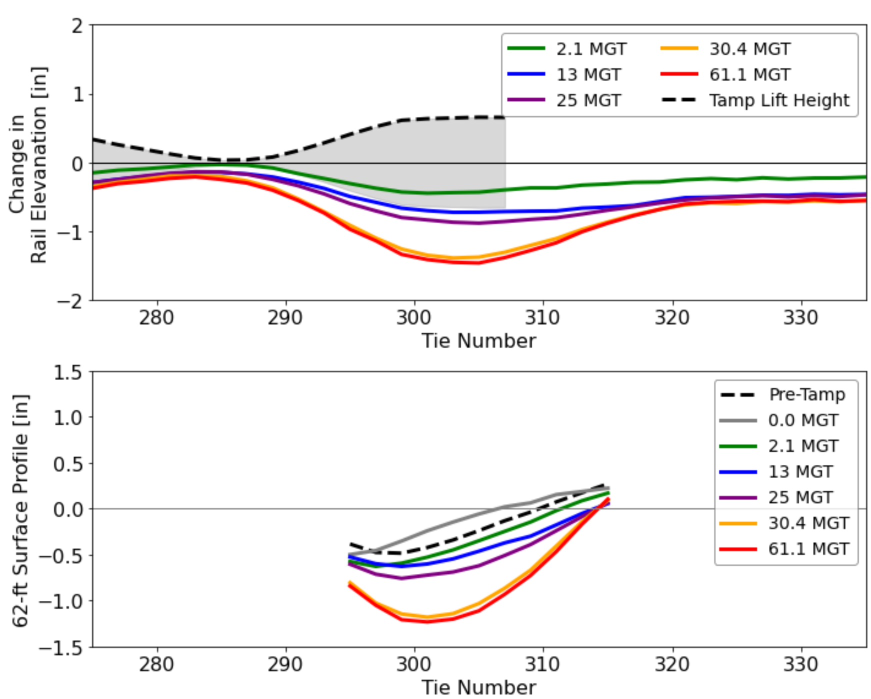


Figure 23. Zone 2 Settlement (upper) and Surface Profile (lower)

Using a process similar to that in Zone 1, Figure 24 calculates the SM/u relationship for the 2019 and 2022 runs. The results, although similar in some respects, show a much higher relationship than Zone 1, with values around 0.8. There is an expectation of higher SM/u because Zone 2 is experiencing significant variation in settlement, with much higher settlements in the center of the dip than in Zone 1. This leads to higher surface profile degradation rates, which suggests that single dips will tend to have a higher SM/u relationship.

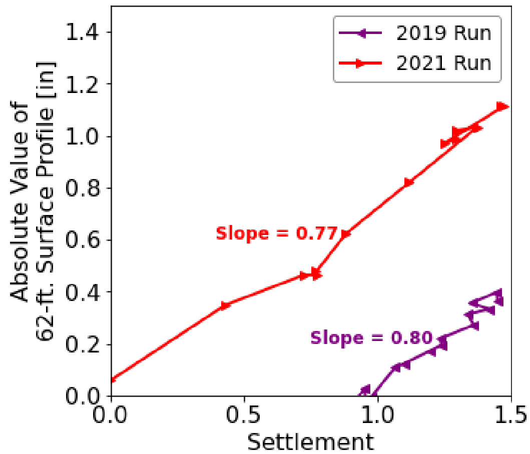


Figure 24. Calculation of SM/u Relationship Using Three Examples in Zone 2

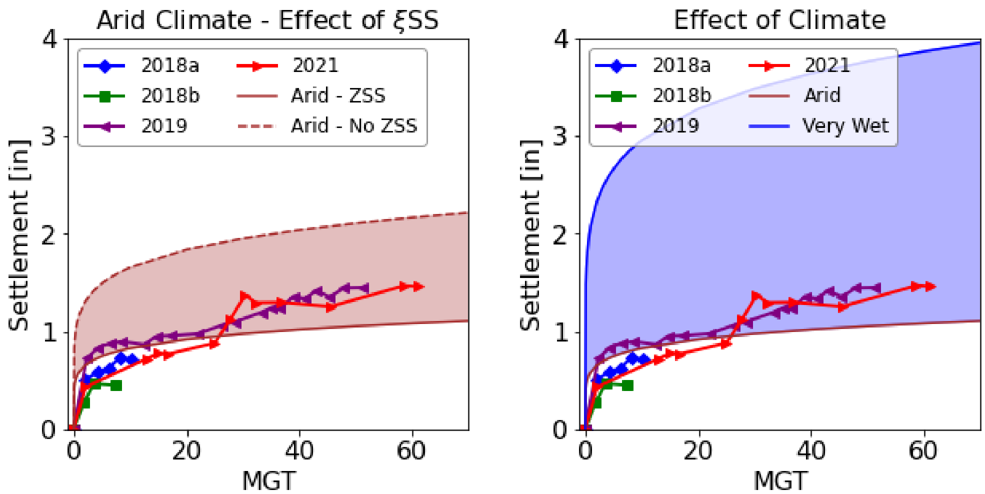
3.2.3 Zone 2 Model Demonstration

The model demonstration in Zone 2 focused more on long-term trends, particularly those trends that are due to changes in moisture. Table 8 shows only the 2021 cycle and the model inputs.

Table 8. Zone 2 Model Demonstration Inputs

Input	2021 – Arid	2021 – Very Wet
ξ_{BFI}	2.4	6.88
ξ_t	3.6	3.6
ξ_{SS}	0.5	0.5
ξ_{VTM}	1.225	1.525
ξ_W	1.18	1.18
ξ_σ	0.86	0.86
ξ_{NOM}	0.0264	0.0264
b	0.15	0.15

Figure 25 looks at some important variables used to project the settlement curves. Figure 25(a) shows the arid climate with a fairly high initial settlement that is reduced in half with the ξ_{SS} factor. This shows a fairly good match for the initial ballast re-compaction up to about 20 MGT, and then it underestimates the response. Figure 25(b) varies the effect of climate, assuming a ξ_{SS} of 0.5 for both curves. The results show unrealistically large initial settlements for the very wet climate.



(a) **(b)**

Figure 25. Zone 2 Model Demonstration Using (a) Arid Climate Assumptions and Vary ξ_{SS} and (b) Different Climate Assumptions with ξ_{SS} = 0.5

To eliminate the influence of the unrealistically high initial re-compaction settlement, Figure 26 compares two climate curves (arid and very wet) starting at 20 MGT. This means the "Very Wet" curve follows the arid curve until 20 MGT and then continues along its original settlement rate.

The results show a change in response, but the "Very Wet" curve does not replicate the very high settlement rates of the 2021 run during artificial wetting. This suggests that the settlement RTLM does not well represent the settlement mechanisms beyond ballast re-compaction.

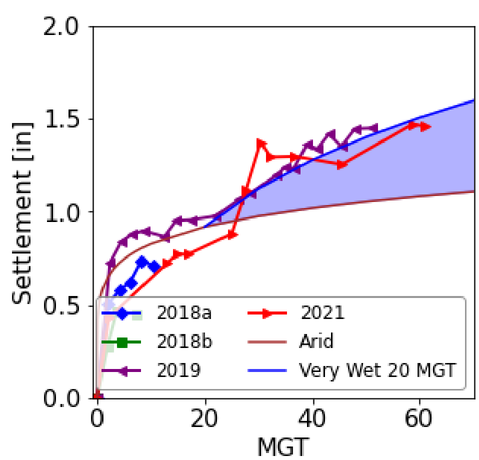


Figure 26. Zone 2 Model Demonstration with a Change in Climate Curve at 20 MGT

3.2.4 Zone 2 Summary and Commentary

Zone 2 differs from the other three zones because it involves a degraded ballast location that was artificially wetted to simulate wetter climates. The settlement exceeds the tamp lift height, indicating that settlement is occurring from mechanisms beyond just upper ballast re-compaction. The settlement projection trends do not fit the data well, which suggests that the logarithmic fit is not well suited for settlement mechanisms beyond ballast re-compaction.

3.3 Zone 3: Section 2

The third zone analyzed is in Section 2. Measurements were taken in this zone from September 2021 to June 2022. As with Zone 4, Zone 3 has a much larger analysis length, so instead of a single BFI and track modulus measurements, the BFI and VTMs were measured in 10 tie intervals in the middle of the section. This allowed for a more detailed analysis of which factors affect localized variation in settlement along a single section of track.

3.3.1 Track Location Details and Measurements

Zone 3 is located within Section 2, a spiral going into a five-degree curve. Zone 3 consists of concrete ties. The ballast is degraded with noticeable fines, and it has surface mud pumping in certain regions. Figure 27 shows a photograph of the section.

Figure 27. Photograph of Zone 3

The ballast and track were characterized using a variety of methods. A Trimble pushcart system—which measures the elevation of each tie in the section—measured the track geometry. This was similar to the TOR in previous sections. Measurement intervals were taken at 0, 0.1, 6, 23, 40, 78, 101, 132, and 141 MGT.

The BFI was measured using a GPR pushcart system called the RABIT, which Earth Science Systems (ESS) developed. This system outputs an aggregated BFI in 10 tie intervals. The VTM was measured using a Light & Heavy (L&H) test. This test measures the rail deflection under a light car (10 kips) and a heavy car (40 kips). Two measurements that can characterize the vertical track stiffness are: track stiffness and track modulus. Although these measurements are similar, track stiffness accounts for the entire track, while track modulus removes the influence of the rails. Both measurements can be calculated from the 10- and 40-kip measurements using the following equations:

$$k = \frac{P_2 - P_1}{y_2 - y_1} \tag{22}$$

Where:

k = Track stiffness

P_2 = Heavy car wheel load (178 kN / 40 kips)

P_1 = Light car wheel load (44 kN / 10 kips)

Y_2 = Rail deflection from heavy car

Y_1 = Rail deflection from light car

Equation 23 calculates the track modulus as the following:

$$\text{VTM} = \frac{k^{4/3}}{64EI^{1/3}} \tag{23}$$

Where:

VTM = Vertical track modulus

E = Rail modulus of elasticity (200 GPa / 2.9E7 psi)

I = 136RE rail section modulus (3,900 cm^4 /93.7 in^4)

Figure 28 presents the BFI and VTM results. The BFI results have an inherent measurement uncertainty of about ± 8, represented by the shaded region. In addition, surface mud pumping was observed between Ties 110 to 140. The track modulus is also shown and was fairly uniform, ranging from 3.2 kips/in/in to 5.2 kips/in/in with a median value of 4.5 kips/in/in.

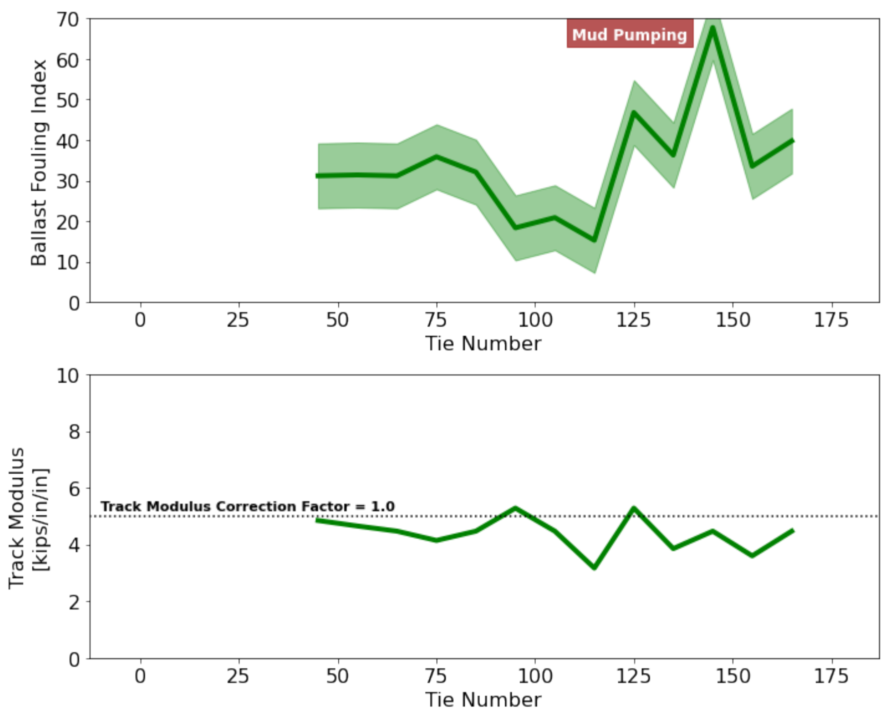


Figure 28. BFI and Track Modulus Values Along Zone 3

3.3.2 Track Settlement, Surface Profile, and Track Roughness

Figure 29 shows the change in rail elevation in Zone 3 over the surfacing cycle, which has a layout similar to that of Zones 1 and 2. The results show lift heights varying from near zero to about 1.5 inches. The settlement increases incrementally with MGT, and it is fairly uniform, with the minor deviations following a contour similar to that of the tamp lift height. This suggests that Zone 3 settlement is primarily from upper ballast re-compaction. This is different from Zone 1 in that the settlement does not appear to exceed 1.0 inches, even in locations where tamp lift height is greater than 1.0 inches.

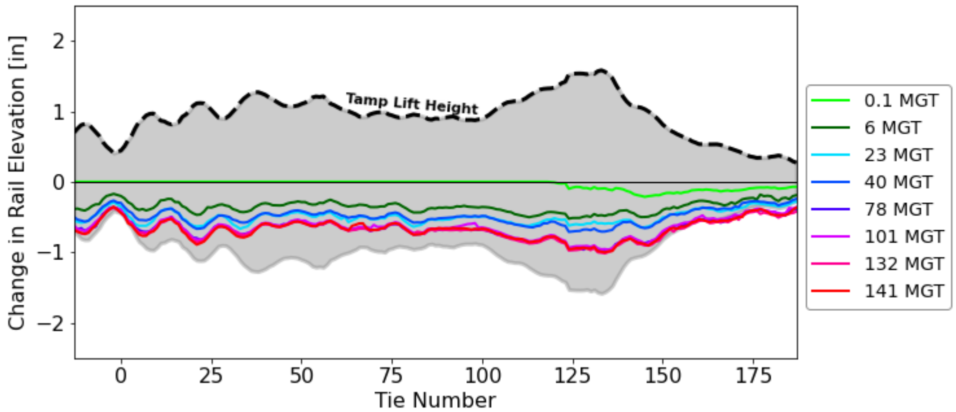


Figure 29. Change in Rail Elevations at Zone 3

The ballast re-compaction mechanism with a maximum settlement of 1.0 inches is clearly shown in the tamp lift height-settlement relationship plot in Figure 30. The data points exhibit the typical behavior, getting closer to the 45-degree line and increasing in slope. However, there is a difference at about 0.75 inches, when the slope starts to get slightly shallower.

This change in behavior can be attributed to when the lift height was high enough (0.75 inches in this case), ballast particles in the crib could be pushed under the tie during the tamping process. This means there was more ballast present post-tamping than there was pre-tamping. Thus, the track could not return to its original elevation even when it had a similar ballast density.

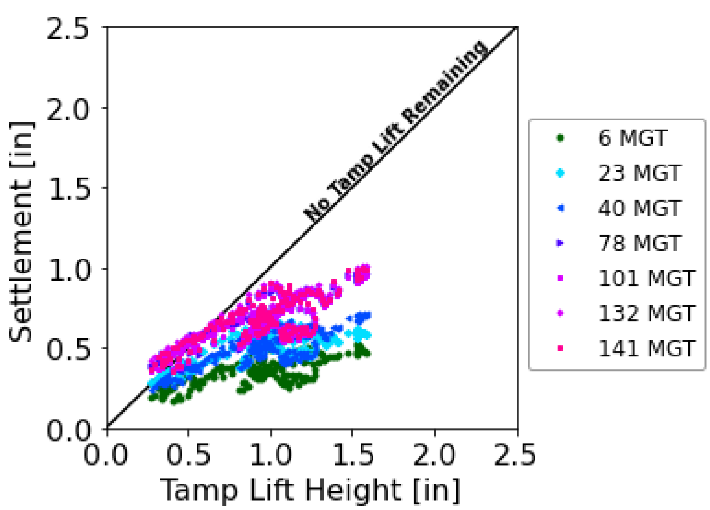


Figure 30**. Relationship Between Tamp Lift Height and Settlement at Zone 3**

The 62-foot surface profile was calculated manually using the Trimble elevation data. Figure 31 presents this profile, along with the settlement. The results show very few surface profile issues at this region. Similarly, the surface roughness, i.e., standard deviation, has relatively low values (as 0.35 is considered optimal for surfacing).

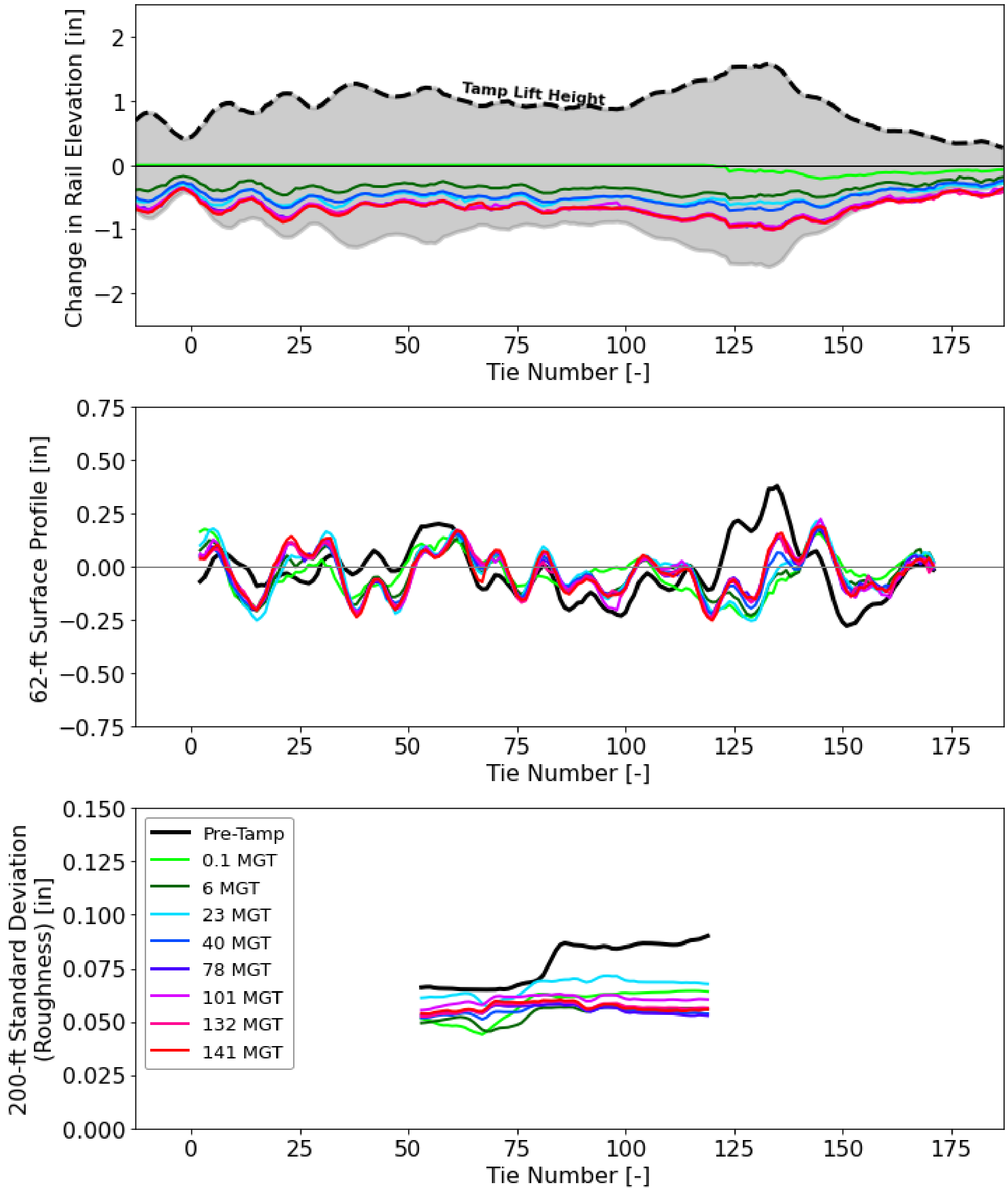


Figure 31. Zone 3 Settlement (top) and Surface Profile (middle), and Track Roughness (bottom)

Figure 32 shows the SM/u relationship every 10 ties. The values are low (0.0 to 0.17), as the maximum value does not exceed 0.17. This is because the settlement is mostly uniform along the track and did not translate in the surface profile.

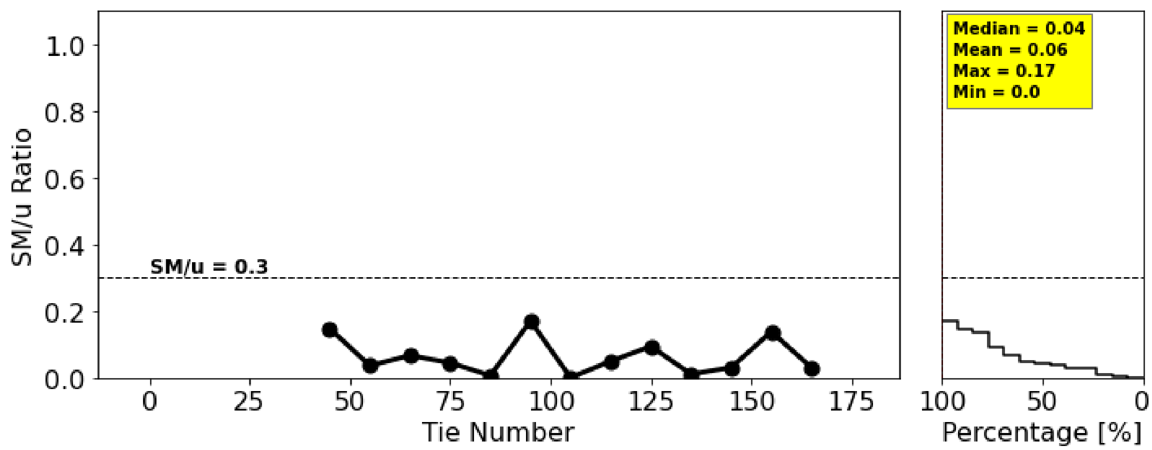


Figure 32. SM/u Values Along Zone 3

3.3.3 Zone 3 Model Demonstration

The model demonstration involves analyzing several 10-tie blocks centered between Ties 45 and 165. The "10-tie blocks" are used (instead of a particular tie) to be consistent with the BFI measurement, which is an average over 10 ties. Table 9 lists the correction factor values for the ties.

Table 9. Zone 3 Model Demonstration Inputs

Tie Number	Distance (feet)]	ξ_{BFI}	ξ_t	ξ_{SS}	ξ_{VTM}	ξ_σ
45	115.20	1.43	3.24	0.36	1.02	1.3
55	134.83	1.45	3.30	0.33	1.05	1.3
65	154.41	1.43	2.96	0.41	1.08	1.3
75	174.05	1.95	2.90	0.26	1.13	1.3
85	193.77	1.53	2.84	0.42	1.08	1.3
95	213.24	1.18	2.79	0.58	0.96	1.3
105	232.82	1.21	3.09	0.51	1.08	1.3
115	252.60	1.15	3.52	0.46	1.27	1.3
125	272.14	3.15	3.96	0.22	0.96	1.3
135	291.73	1.99	3.87	0.28	1.17	1.3
145	311.34	5.45	3.00	0.14	1.08	1.3
155	330.85	1.69	2.32	0.37	1.21	1.3
165	350.39	2.38	2.02	0.30	1.08	1.3

Figure 33 displays the measured data and the RTLM projections at various MGT intervals along the track. Figure 33(a) shows the projections without the site-specific correction factor, while Figure 33(b) shows the projections with the site-specific correction factor. The graphs indicate that, without the site-specific correction factor, the results are consistently over-projected. Ties 125 to 145 show extreme over-projections, with settlement projections of almost 6 inches. The over projection at these locations is due to the high BFI values. This suggests that BFI values over 50 will likely produce unrealistic results.

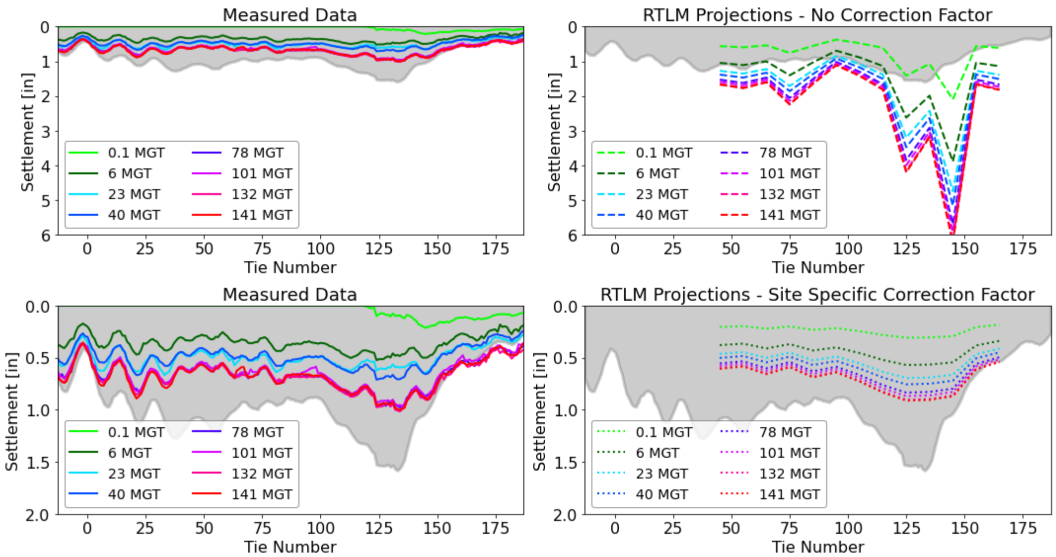


Figure 33. Zone 3 Model Demonstration Using (a) No Site-Specific Correction Factor and (b) Including Site-Specific Correction Factor

Figure 34 shows the same data as Figure 33 but with 1) the measured data, 2) RTLM projections without the site-specific correction factor, and 3) RTLM projection with the site-specific correction factor for each MGT interval. This presentation emphasizes the over-projections in the situation without the site-specific correction factor.

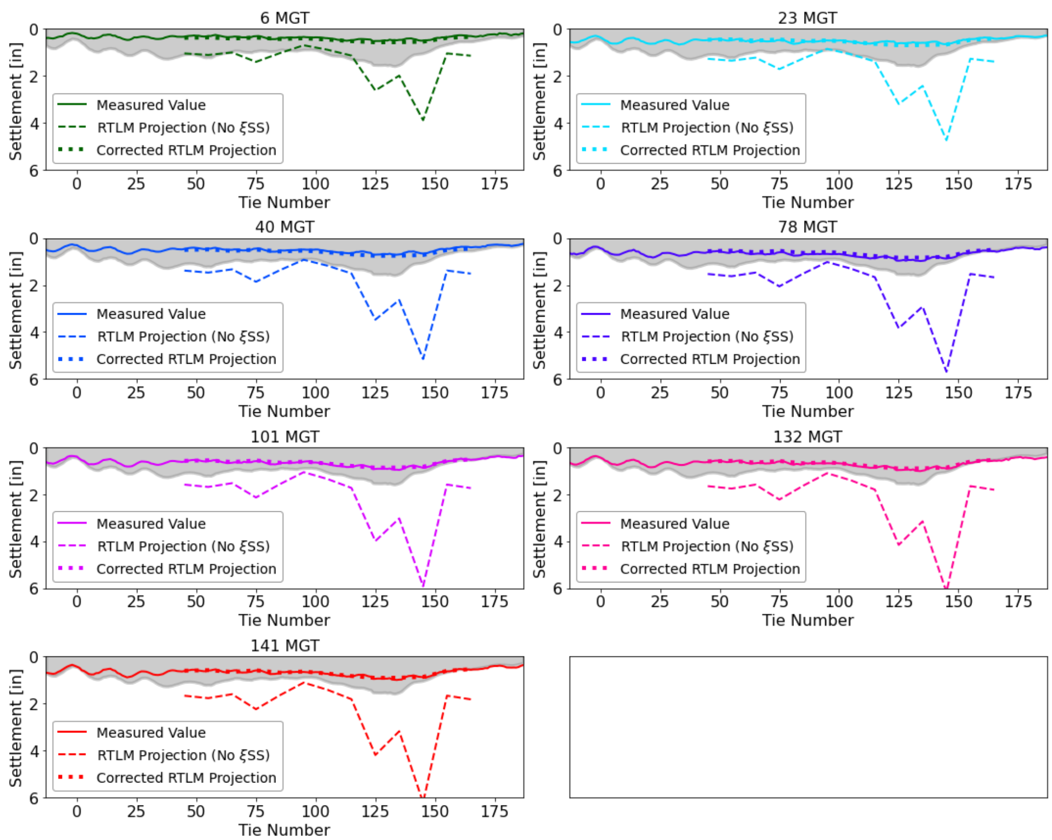


Figure 34. Zone 3 Model Projection by MGT Measurement Interval

Figure 35 plots the measured and projected (with site-specific correction factor) settlement at each tie with MGT. The results show that the logarithmic settlement trend agrees well with the data. The red line indicates the tamp lift height, and the data shows that the settlement tends to stabilize at values lower than the tamp lift height. The exceptions are Ties 155 and 165, which stabilize at the tamp lift height. This can be attributed to the smaller lift heights in those areas.

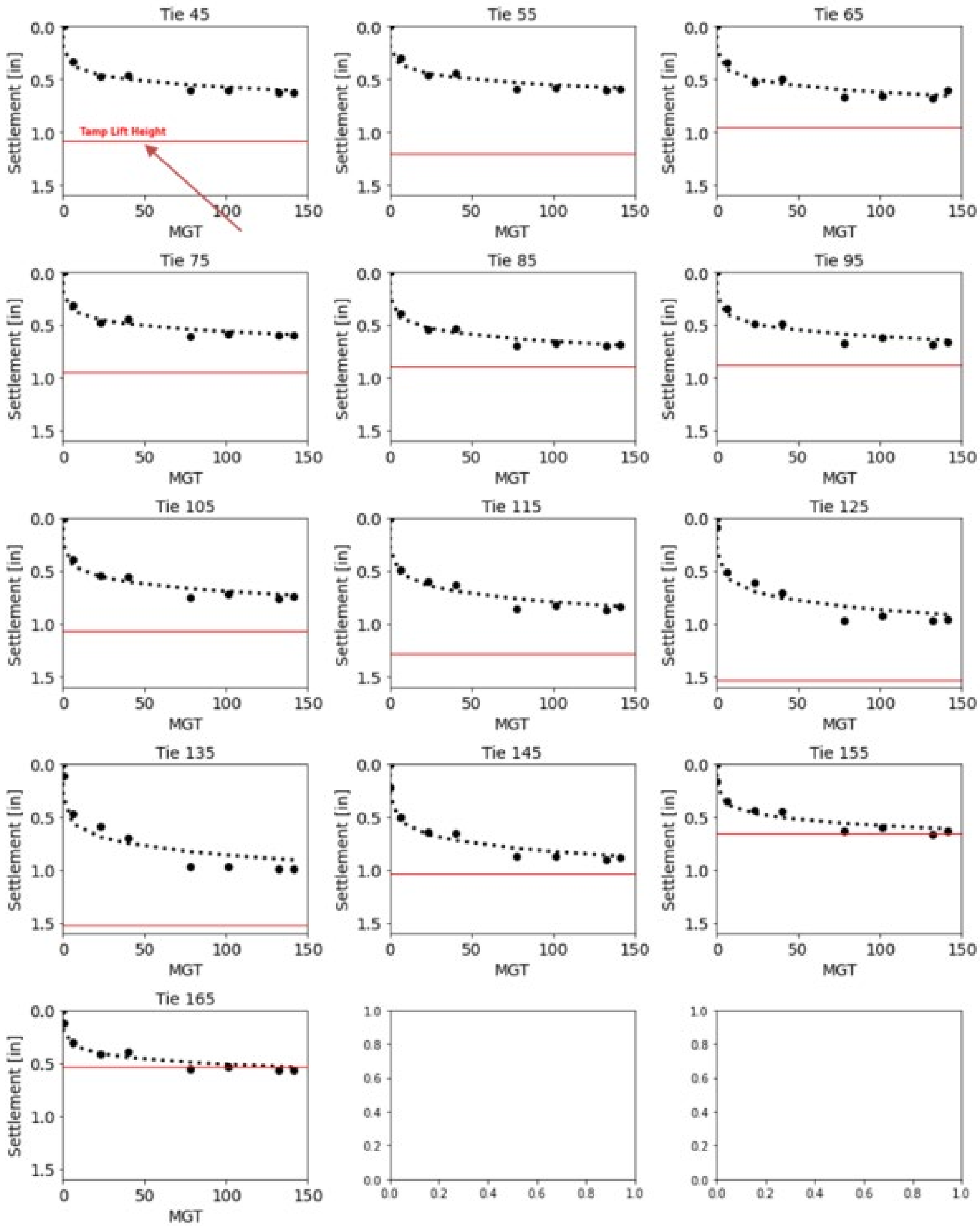


Figure 35. Zone 3 Model Projection by MGT for Each Tie Interval

The site-specific correction factor (ξ_{SS}) can be used as proxy for accuracy. Figure 36 shows the values of the measured ties, along with the statistics. The median and mean values are 0.36 with a range from 0.14 to 0.58. This indicates that the non-corrected RTLM projection over-projects the settlement in this section. The over-projection is greatest (lowest ξ_{SS}) in ties with the highest BFI, which suggests that BFI is not a significant factor in track experiencing settlement from ballast re-compaction.

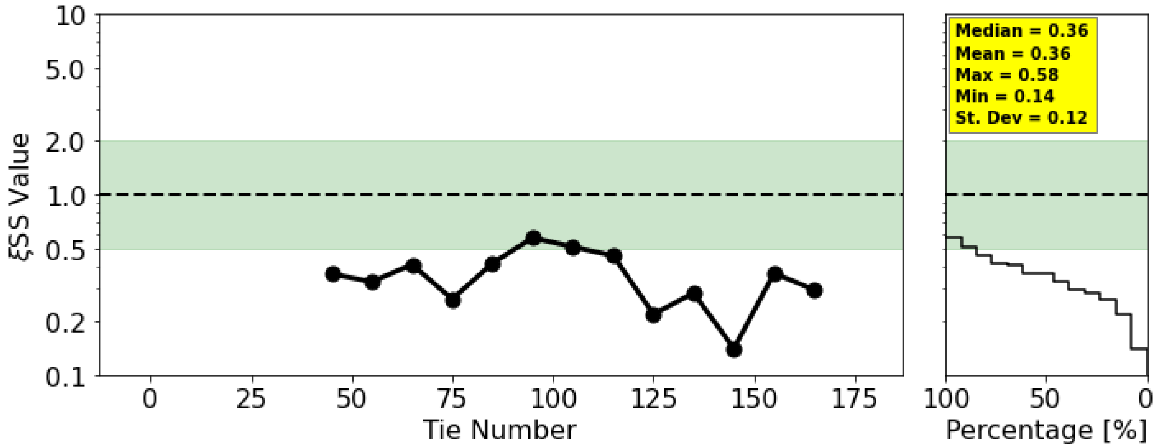


Figure 36. ξ_{SS} Along Track for Zone 3

3.3.4 Zone 3 Summary and Commentary

The results of Zone 3 suggest the track experiences settlement from ballast re-compaction. In this case, the RTLM over-projects settlement, with the greatest over-projections at locations with higher BFI. This suggests that BFI does not have a significant effect on settlement in situations where the settlement mechanism is ballast re-compaction. The SM/u relationship is also very low and probably indicates little relationship in ballast re-compaction situations.

3.4 Zone 4: Section 25

Zone 4 is in Section 25, where measurements were taken from September 2021 to May 2022. As with Zone 3, this zone also has a much larger analysis length, and instead of a single BFI and track modulus measurements, these values were measured every 10 ties in the middle of the section. This allowed for a more-detailed analysis of which factors affect localized variation in settlement along a single section of track.

3.4.1 Zone 4 Track Location Details and Measurements

Zone 4 is located within Section 25. It consists of wood ties with cut spikes and is located within a 5-degree curve. The ballast is degraded, has noticeable fines, and has surface mud pumping in certain regions. Figure 37 shows a photograph of the section.

The ballast and track were characterized using similar methods to those in Zone 3. Track geometry was measured using a Trimble push cart system, which measures the elevation of each tie in the section. This was similar to the TOR in previous sections. Measurement intervals were taken at 0, 0.1, 4, 23, 40, 78, 101, 132, and 141 MGT. The BFI and track modulus were measured, using the RABIT and L&H measurements, as in Zone 3.

Figure 37. Photograph of Zone 4

Figure 38 presents the BFI and track modulus results. The BFI results are more consistent, ranging from about 15 to 30, with surface mud pumping between Ties 200 and 280. The track modulus is also shown. It is fairly uniform, but lower than Zone 3, ranging from 1.4 kips/in/in to 7.1 kips/in/in, with a median value of 3.6 kips/in/in.

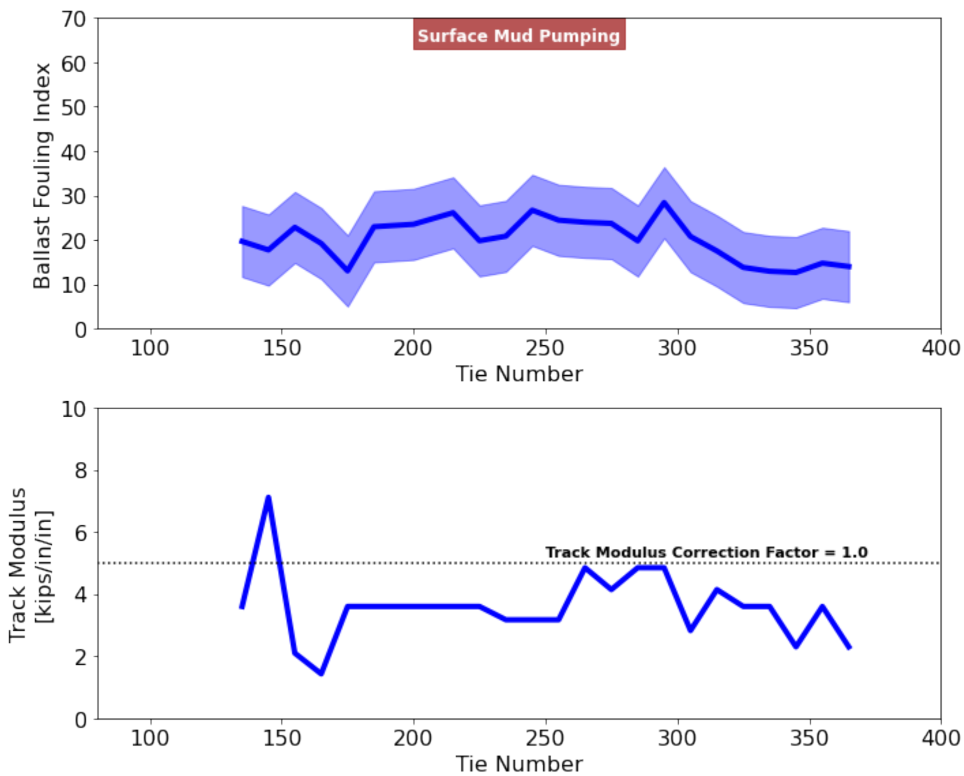


Figure 38. BFI and Track Modulus Values Along Zone 4

3.4.2 Track Settlement, Surface Profile, and Track Roughness

The change in rail elevation of Zone 4 over the surfacing cycle is shown in a layout that is similar to those used for the previous zones. The results in Figure 39 show a higher lift height than in the previous zones, exceeding 2 inches in certain locations. At the final 141 MGT measurement, the track settled back almost exactly to its pre-tamp elevation for distances of 300 ft from the starting point, or farther. At locations closer to the starting point, the track settlement rarely exceeded 1.4 inches, and residual lift remained.

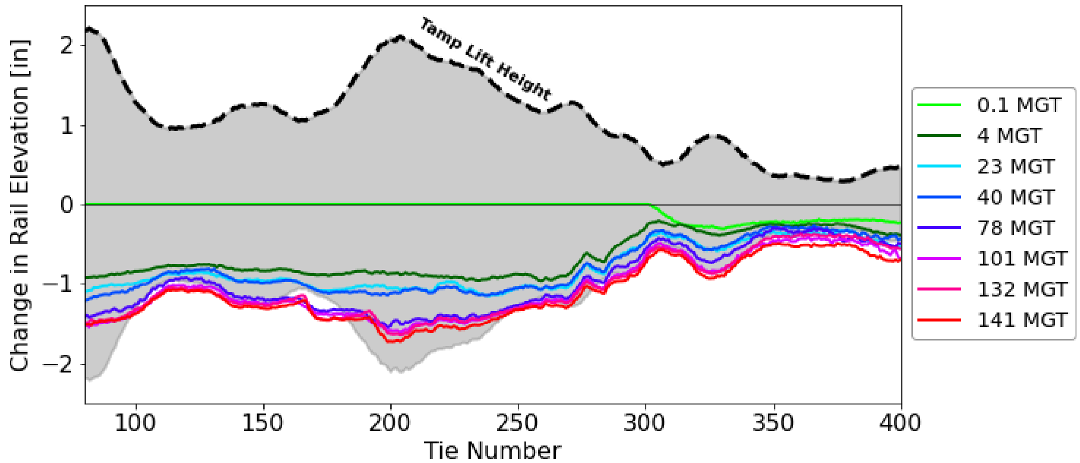


Figure 39. Change in Rail Elevations at Zone 4

Figure 40 shows that this diverging trend where lift height remains is apparent at about a lift height of 1.25 inches. Below this value, the track at 141 MGT has settled to its pre-tamped elevation (shown by the thick 45-degree black line). Above this value, the data has a different, shallower slope where a 2.0-inch lift height results in about 1.4 to 1.5 inches of settlement at 101 MGT.

This emphasizes once again the benefits of large lift heights where ballast particles can be "pushed" underneath the tie during the tamping process. It also suggests that the 50th percentile ballast size is about 1.25 inches, as this ballast size tends to correlate with the divergent trend.

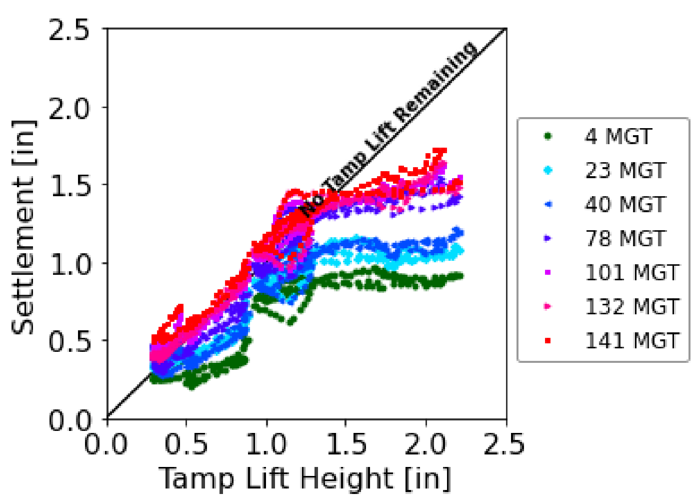


Figure 40. Relationship Between Tamp Lift Height and Settlement at Zone 4

[Figure 41](#) shows the 62-foot surface profile and the 200-foot standard deviation calculated similarly to Zone 3. As in the other situations, the results show few surface or roughness issues. This is likely because the settlement occurs from ballast re-compaction.

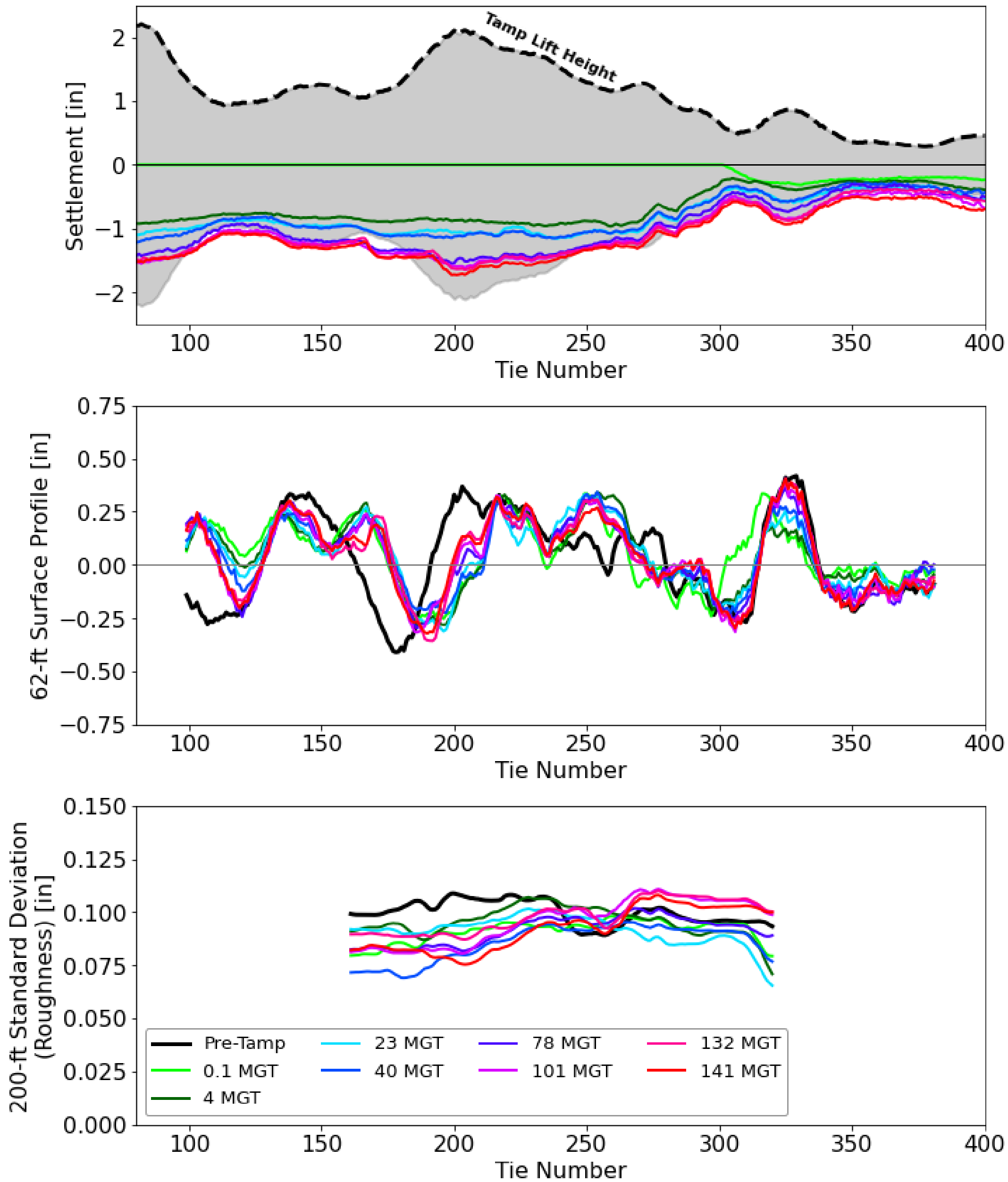


Figure 41. Zone 4 Settlement (upper), Surface Profile (middle), and Track Roughness (lower)

Figure 42 shows the relationship between settlement and surface profile degradation (SM/u) along the track. The graph shows a SM/u relationship ranging from 0 to 0.4. The region less than 300-foot has very low values, probably because of the fairly uniform settlement. The regions greater than 300-foot have higher values, most likely because the settlement is more non-uniform.

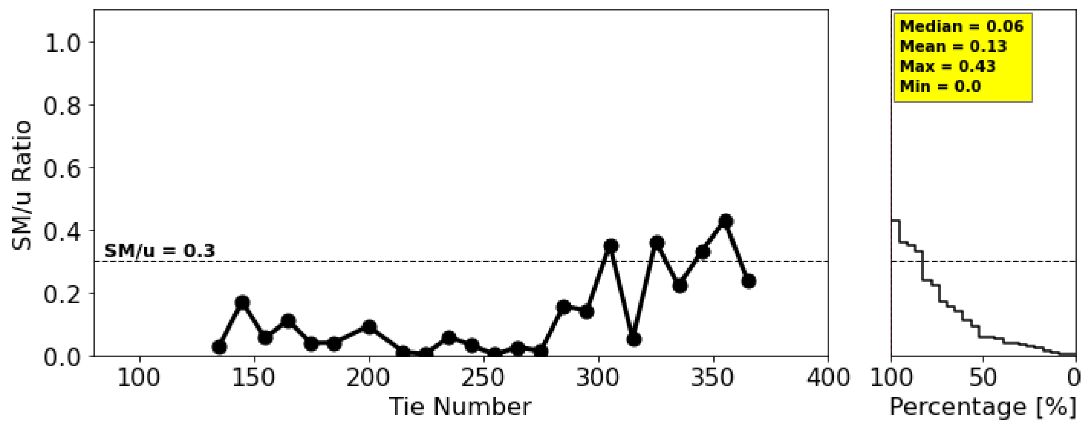


Figure 42. SM/u Values Along Zone 4 with Cumulative Distribution Function

3.4.3 Model Demonstration

Table 10 presents the inputs for the model demonstrations for Ties 135 to 365. As with Zone 3, the average value within each "tie-block" is used.

Table 10. Zone 4 Model Demonstration Inputs

Tie Number	Distance (feet)	ξ_{BFI}	ξ_t	ξ_{SS}	ξ	$\xi\sigma$
135	89.5	1.20	3.24	1.10	1.21	0.86
145	105.7	1.18	3.48	1.96	0.68	0.86
155	121.7	1.23	3.40	0.92	1.44	0.86
165	131.7	1.19	3.15	0.96	1.54	0.86
175	154.5	1.13	3.38	1.34	1.21	0.86
185	170.7	1.23	4.05	1.01	1.21	0.86
200	194.7	1.24	5.09	0.87	1.21	0.86
215	219.1	1.26	4.77	0.89	1.21	0.86
225	235.6	1.20	4.54	0.94	1.21	0.86
235	251.9	1.21	4.30	0.98	1.27	0.86
245	268.1	1.27	3.79	1.00	1.27	0.86
255	284.3	1.24	3.43	1.05	1.27	0.86
265	300.4	1.24	3.42	1.31	1.02	0.86
275	316.6	1.24	3.37	0.99	1.13	0.86
285	332.5	1.20	2.83	1.29	1.02	0.86
295	348.7	1.28	2.59	0.97	1.02	0.86
305	364.8	1.21	2.10	0.59	1.33	0.86
315	380.9	1.18	2.25	0.80	1.13	0.86
325	396.9	1.14	2.67	0.90	1.21	0.86
335	413.2	1.13	2.43	0.85	1.21	0.86
345	429.5	1.13	1.92	0.66	1.41	0.86
355	445.7	1.15	1.72	0.76	1.21	0.86
365	462.0	1.14	1.67	0.67	1.41	0.86

Figure 43 displays the measured data and RTLM projections at various MGT intervals along the track. Figure 43(a) shows the projections without the site-specific correction factor, while Figure 43(b) shows the projections with the site-specific correction factor. The results show a better match without the site-specific correction factor than was the case with Zone 3. This is likely due to the more consistent BFI along the track.

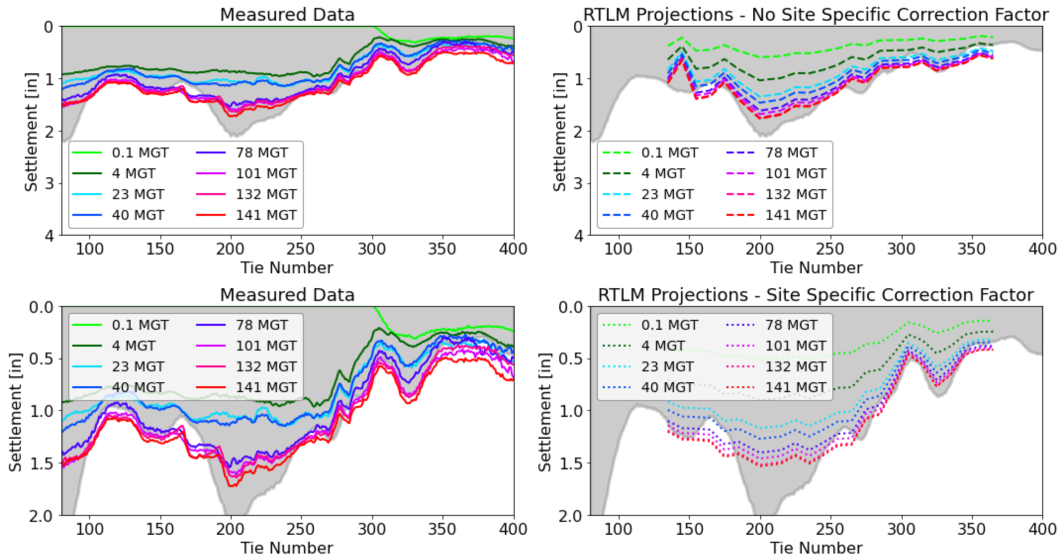


Figure 43. Zone 4 Model Demonstration Using (a) No Site-Specific Correction Factor and (b) Including Site-Specific Correction Factor

Figure 44 shows the same data as Figure 43, but with 1) the measured data, 2) RTLM projections without the site-specific correction factor, and 3) RTLM projection with the site-specific correction factor for each MGT interval. This emphasizes the good projections even without the site-specific correction factor.

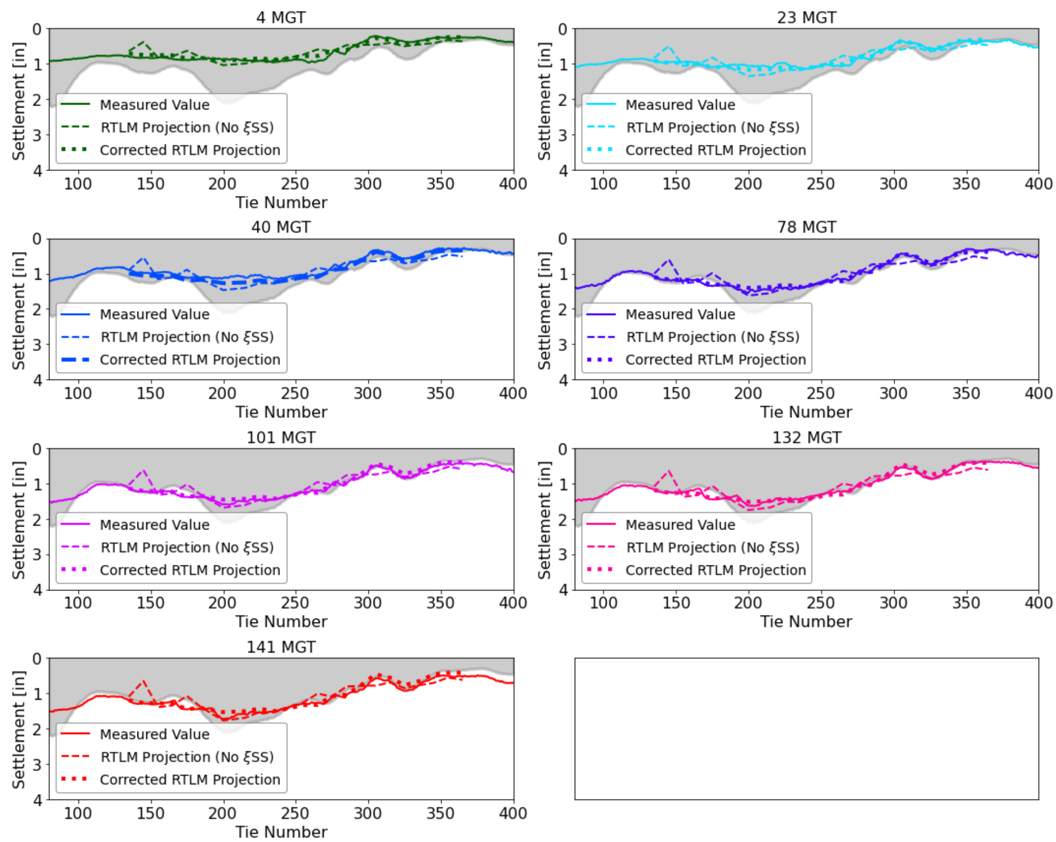


Figure 44. Zone 4 Model Projection by MGT Measurement Interval

[Figure 45](#) plots the measured and projected (with site-specific correction factor) settlement at each tie with MGT. The results again show that the logarithmic settlement trend agrees well with the data. The red line indicates the tamp lift height and the data shows the settlement tends to stabilize at values less than the tamp lift height.

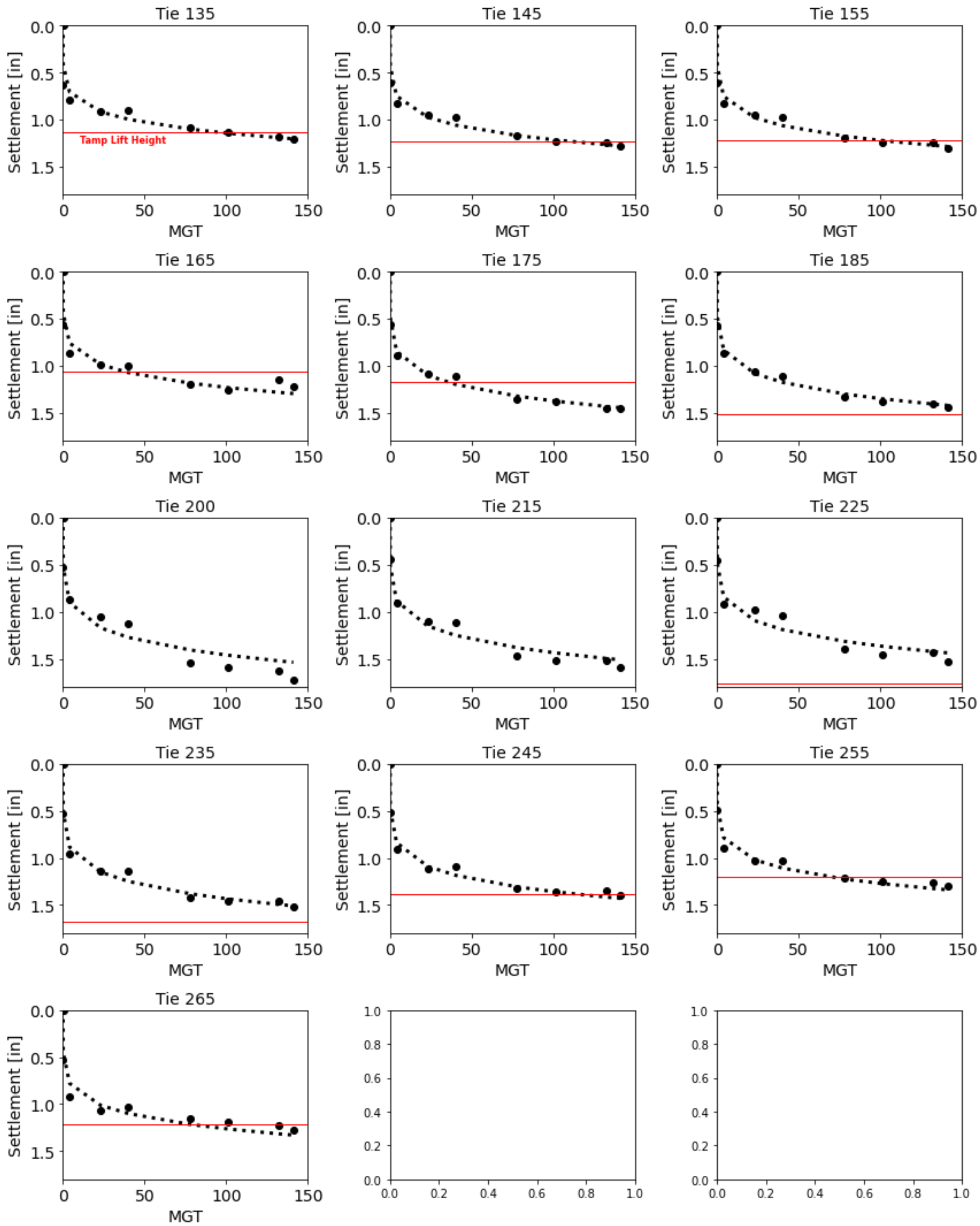


Figure 45. Zone 4 Model Projection by MGT for Each Tie Interval

The site-specific correction factor (ξ_{SS}) can be used as proxy for accuracy. Figure 46 shows the values of the measured ties along with some basic statistical values. The median value is 0.96, with a range from 0.59 to 1.96. This indicates that the non-corrected RTLM projection generally matches well with the measured settlement in Zone 4.

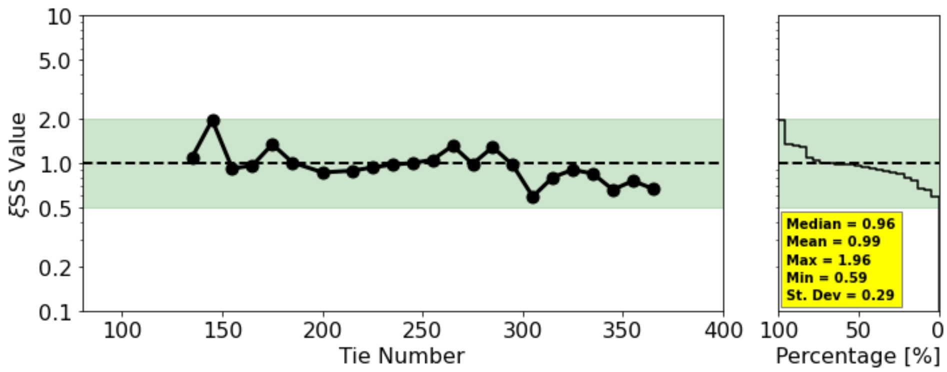


Figure 46. ξ_{SS} Along Track for Zone 4

3.4.4 Zone 4 Summary and Commentary

The results of Zone 4 suggest that the track experiences settlement from ballast re-compaction. In this case, the RTLM projections without the site-specific correction factor (ξ_{SS}) agree well with the measured settlement. The SM/u relationship is also very low, and this likely indicates little relationship in ballast re-compaction situations.

3.5 Summary

All four zones had some unique aspects. However, while it is important to look at those unique aspects in detail, it is also important to look at the overall range in values.

Figure 47 plots box graphs of the SM/u relationship of all four zones, with Zone 1 split between wood and concrete tie sections. The results show that Zones 1, 3, and 4, in which the settlement mechanism is considered ballast re-compaction, all have SM/u values that are generally below 0.3, with Zones 3 and 4 below 0.1. This indicates that settlement from ballast re-compaction does not need to translate into surface profile or roughness. Zone 2 is the exception, with a SM/u value near 0.8. This difference is attributed to its location in a localized dip where the adjacent track had stabilized, and the settlement mechanism is due to wet fouled ballast conditions.

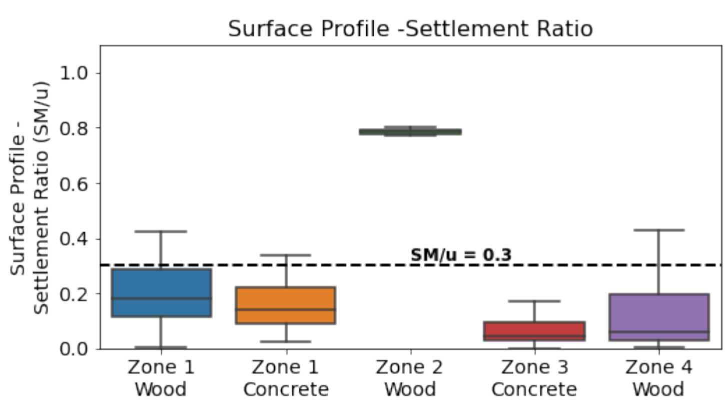


Figure 47. Range of SM/u Values for All Four Zones

Figure 48 plots the box graphs of the site-specific correction factors for all four zones, with Zone 1 split between wood and concrete tie sections. The ξ_{SS} factor is a proxy for accuracy. The ξ_{SS} = 1.0 meaning the RTLM projection has perfect accuracy, ξ_{SS}>1 meaning the RTLM under-projects the measurement, and ξ_{SS} < 1 meaning the RTLM over-projects the measurement. The results show that Zones 1 and 4 projections had accurate projections, with the median very near 1.0, and low amounts of scatter. Zone 3 projections had over-projected the measured settlement, and there was significant scatter. This may be partly due to the high BFI values. But even if low BFI are assumed, the ξ_{SS} values would still be low. This may be due to better tamping compaction or some other tamping factor.

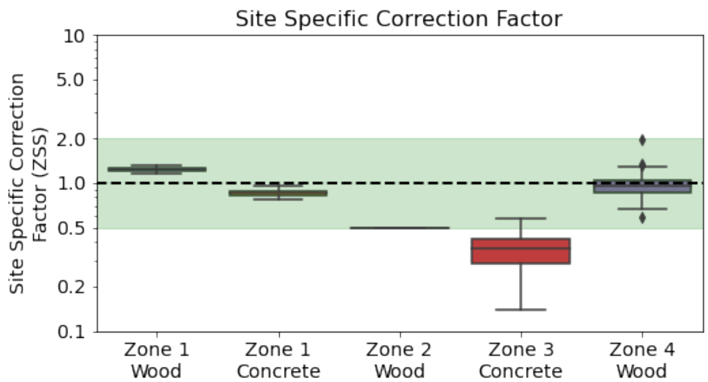


Figure 48. Range of Site-Specific Correction Factor for All Four Zones

In summary, the following remarks can be made:

- Zones 1, 3, and 4 showed signs that most settlement occurred from re-compaction of the upper ballast layer to its original pre-tamping elevation.
  - The modified settlement RTLM projections matched measured settlement data well for the ballast re-compaction locations. The general logarithmic trend (b=0.15) consistently matched the measured data with MGT. The overall settlement magnitude matched well with RTLM settlement projections (ξ_{SS} values near 1.0) for Zones 1 and 4. RTLM settlement projections in Zone 3 were consistently overestimated (low ξ_{SS} values).
  - Ballast re-compaction locations tend to have low SM/u values since most of the track is settling back to its pre-tamping elevation. Additional surface profile would be expected in localized locations that continued to settle after adjacent locations stabilized.
- Zone 2 had different settlement mechanisms (wet fouled ballast) than Zones 1, 3, and 4, and therefore had different observations.
  - The settlement trend with MGT did not have a smooth logarithmic trend and would stabilize and settle with wetting and dry cycles. The RTLM projections were not able to replicate this change in behavior, even when using different climates and VTM values.
  - Zone 2 showed a much higher SM/u value because the settlement occurred locally, with the adjacent regions stabilized. This means that the settlement at the middle of the dip would relate well to the change in surface profile.

4. Settlement Model Parameter Analysis

The HTL data collection and model demonstration at multiple sites showed the RTLM projections generally matched well for locations where the primary settlement mechanisms were upper ballast re-compaction (Zones 1, 3, and 4). Despite the general agreement, it is still important to assess the accuracy of the individual input parameters (e.g., tamp lift, BFI, tie type, and VTM).

This section investigates the relationships between BFI, tamp lift height, VTM, and tie type parameter to settlement to determine if some of the correction factor equations should be re-assessed. Only the modified settlement model is used because surface profile data is limited. This study should also acknowledge that the dataset involves multiple locations within the same track and geographic region (i.e., arid sandy subgrade), and studies in different regions may suggest different results.

4.1 General Correlations

The first step is to perform a general correlation analysis. Correlations are helpful when exploring relationships between parameters, but interpretation is necessary as well. The parameters explored include settlement (23 MGT), lift height, BFI, VTM, and tie type. The correlations were performed by combining all zones (except for Zone 2 because it did not settle only from ballast re-compaction), and also by analyzing each zone individually. When combined, a settlement value between 20 to 25 MGT is used. This analysis also uses the measured Zone 1 (Section 36) VTM values from Phase I [1].

Figure 49 shows correlation heatmaps, and Figure 50 shows a Pairplot for: settlement, lift height, BFI, VTM, and tie type. For the correlation heatmap, a value of 1.0 indicates a perfect correlation, a value of -1.0 indicates a perfect inverse correlation, and a value of 0.0 indicates no correlation. Figure 49(a) is the combined data from Zones 1, 3, and 4. Figure 49(b)–(d) shows the Zone 1, 3, and 4 datasets separately. The Pairplot shows scatterplots of each of the relationships.

The general results show tamp lift height has the strongest correlation with settlement with a Pearson's correlation of 0.82. This is also observed in the three independent datasets, with a range between 0.68 and 0.97.

BFI showed a weak general correlation (0.20). However, separating by dataset shows that there is a weak to non-existent relationship with Zone 3 (0.14) and a mid-strength relationship with Zone 4 (0.53). Further observation shows that BFI has no correlation with tamp lift height in Zone 3 (0.00) and a mid-strength relationship with tamp lift height in Zone 4 (0.56). This likely means that, for situations where BFI shows correlation with settlement, the correlation may actually be with tamp lift height, which is correlated with settlement.

VTM shows a weak inverse relationship with settlement (-0.26), but this may be an artifact of the datasets, as it does not appear strongly for the individual datasets (0.40, -0.09, and 0.11). The relationship with settlement in Zone 1 is likely due to the VTM correlation with tie type and tamp lift height. The change in VTM along the track may have to do with other parameters (e.g., the fastening system), and VTM has been more of an indicator of track settlement for other mechanisms, such as mud pumping and subgrade settlement.

The tie type shows a general inverse correlation (there are higher settlements with wood ties). This inverse correlation may also be a result of the fact that the greatest settlements are in Zone 4 (Section 25), which consists only of wood ties. Zone 1 (Section 36) shows a correlation of 0.73 higher settlement for concrete ties. However, this is again likely due to the correlation with tamp lift height (0.67).

In summary, the primary relationship with settlement for the three analyzed zones is tamp lift height. All other correlations with settlement appear to be artifacts from being correlated also with tamp lift height, and not just with settlement itself. If the settlement mechanism is not ballast re-compaction (e.g., Zone 2), the correlating parameters will likely be different.

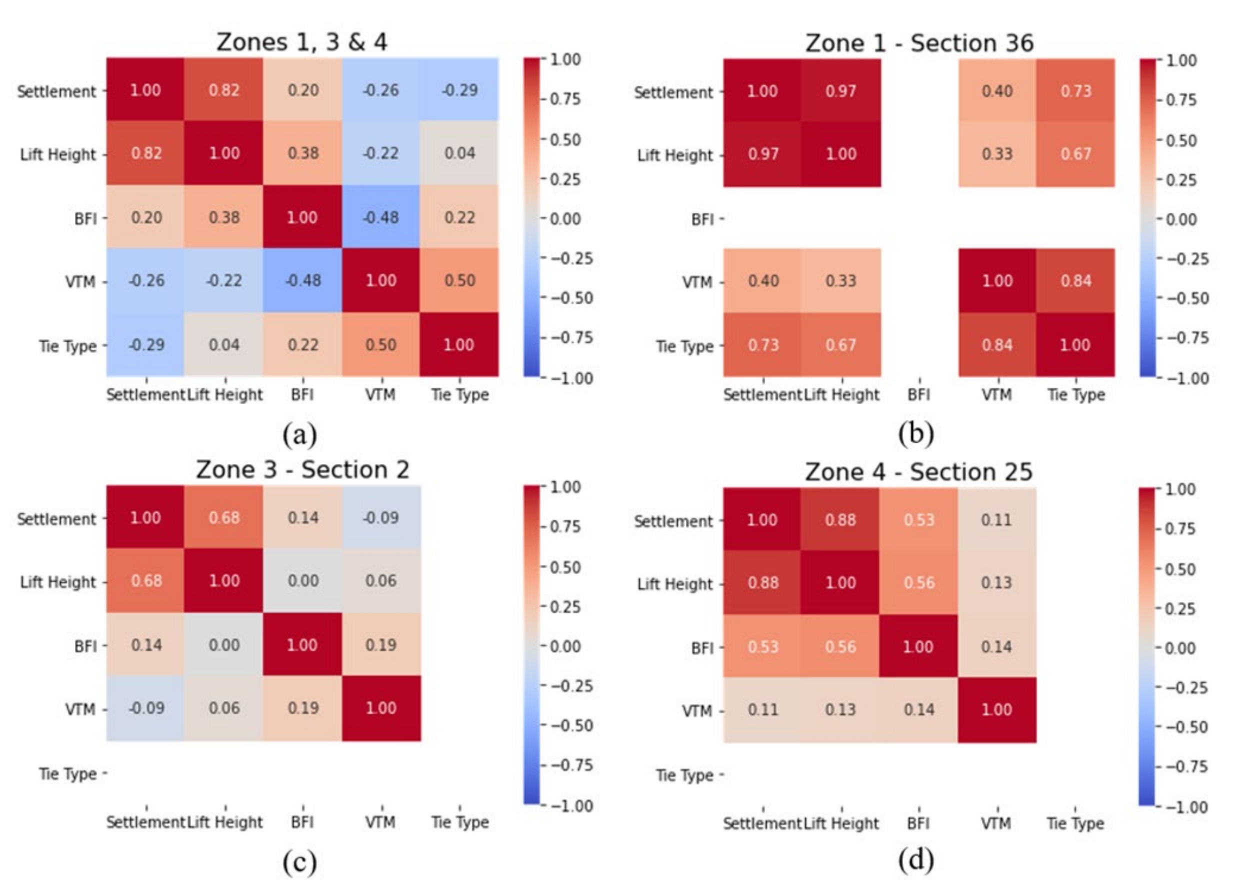


Figure 49. Correlation Heatmap Between Parameters for (a) Zones 1, 3, and 4, (b) Zone 1, (c) Zone 3, and (d) Zone 4

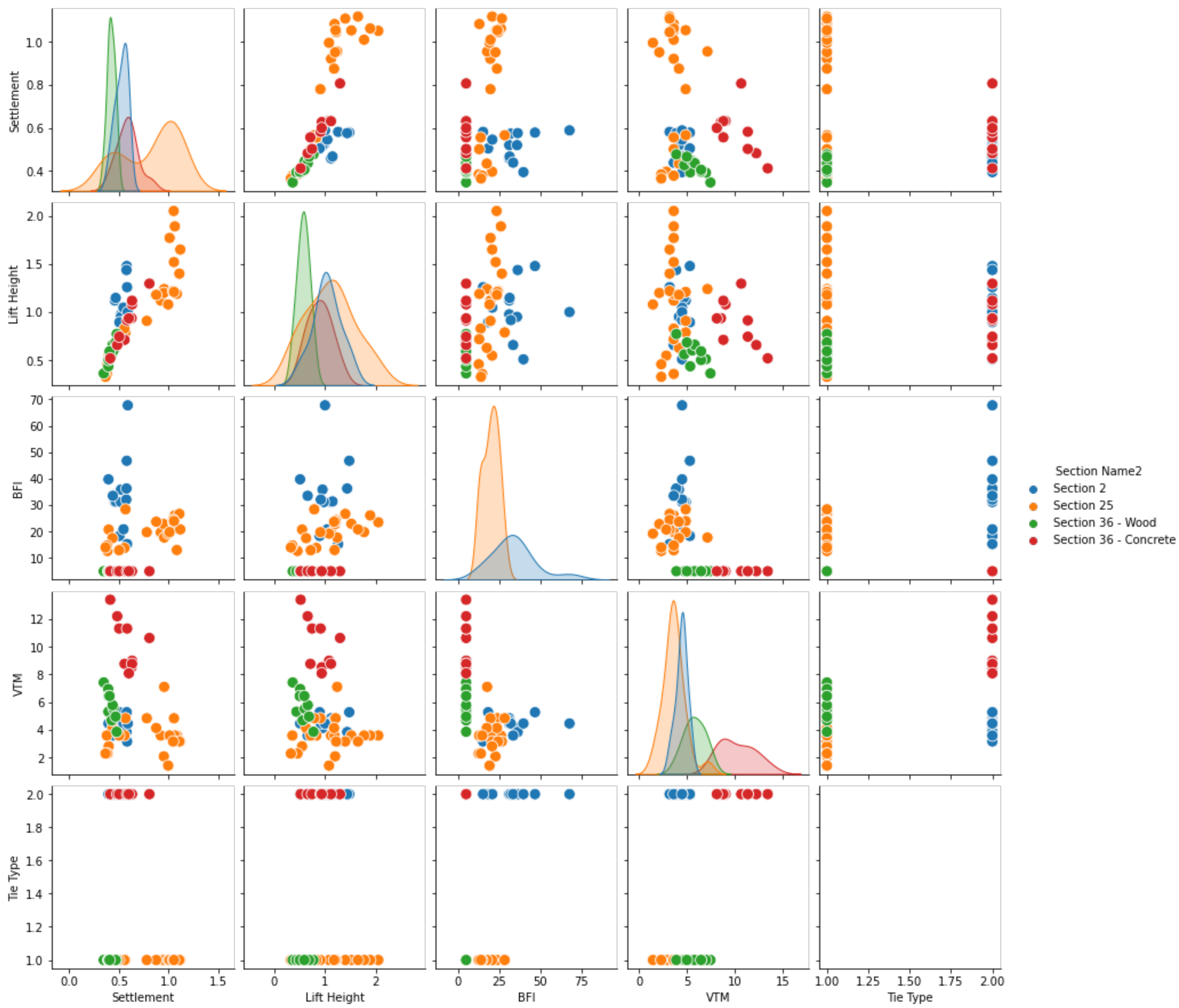


Figure 50. Pairplot of all Parameters for Zone 1 (Section 36), Zone 3 (Section 2), and Zone 4 (Section 25)

4.2 Error Analysis (Site-Specific Correction Factor)

The heatmaps showed that 1) tamp lift height is the primary correlating factor with settlement and 2) other potential correlating factors (e.g., BFI, VTM, and tie type) may just be artifacts of those factors also being correlated with tamp lift height. To further investigate the influence of the various parameters, an analysis involving removing different parameters and comparing the errors (i.e., site-specific correction factor, (ξ_{SS})) was performed.

The analysis involved calculating the ξ_{SS} for Zones 1, 3, and 4 using a variety of different analysis assumptions. This primarily involved assuming a single representative value, typically median, for a particular parameter. The goal of this approach is to assess how it changes the median and standard deviation ξ_{SS} values in a meaningful way. The analysis includes:

- Analysis 1 (Standard): Standard RTLM projections.
- Analysis 2 (No BFI): Assume all ties in Zone have median BFI of that zone.

- Analysis 3 (No VTM): Assume all ties in zone have median VTM of that zone.
- Analysis 4 (No Lift): Assume all ties in zone have median lift height of that zone.
- Analysis 5 (No Tie): Assume ξ_σ from tie type is 1.0 for both wood and concrete ties.
- Analysis 6 (Lift Only 1): Use assumptions of Analysis 2, 3, and 5 so only tamp lift height has individual tie variation.
- Analysis 7 (Lift Only 2): Assume 1.0 for tie type, BFI, and VTM correction factors for all zones.

Figure 51 shows the median ξ_{SS} value for each zone and analysis case, while Figure 52 shows the coefficient of variation (CV) ξ_{SS} value. Ideally, the median should be as close to 1.0 as possible. However, care must be taken with interpretation because there are multiple factors that can influence the median. Analyzing the median of all zones separately, as well as in a combined situation, provides a more comprehensive view than analyzing individual situations in detail. Calculating the CV consisted of dividing the standard deviation by the mean. This should provide a more representative indicator of variation than just standard deviation alone. For these situations, a low CV is desired as it shows the factors used in the calculation can represent variations in actual measured settlement.

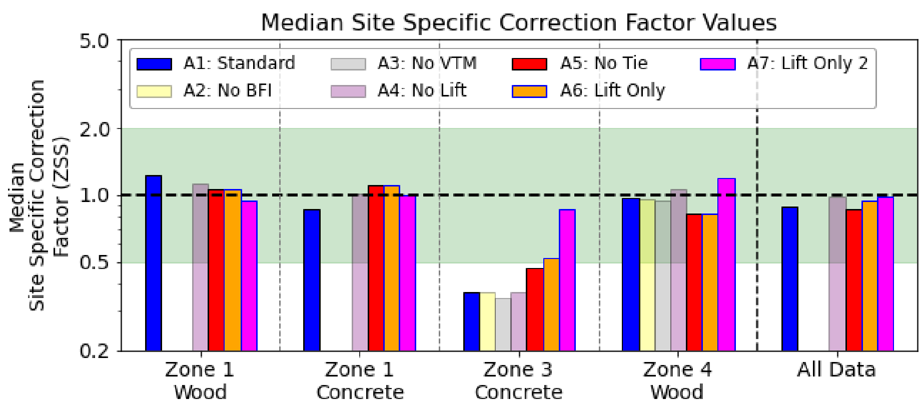


Figure 51. Median Site-Specific Correction Factor for Parameter Analysis

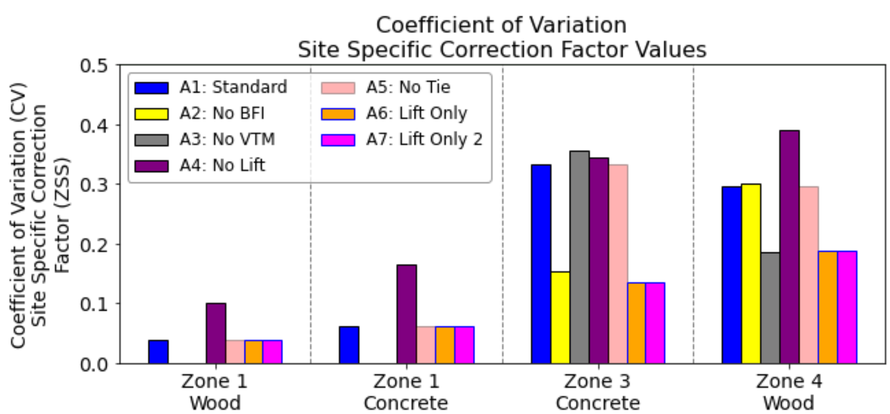


Figure 52. Coefficient of Variation of Site-Specific Correction Factor for Parameter Analysis

To aid analysis interpretation, the goal of the analyses are listed below:

- Analysis 2 to 4: These analyses replace the tie-by-tie variation with the median for the three factors (i.e., BFI, VTM, and lift height). Therefore, the median is not expected to change, but the CV should indicate whether the RTLM projections from parameter accurately represent measured settlement variation. If the CV increases, the removal of the factor causes more tie-by-tie inaccuracy and indicates the factor should be included. If the CV decreases, the inclusion of the factor produces more tie-by-tie inaccuracy so should not be used.
- Analysis 5: This analysis removes the tie type correction factor and assumes 1.0. Since the ties in each zone are the same (except for Zone 1, which is split up), only the median will change. If tie type is an important factor, the wood tie locations should become lower, while the concrete tie locations should become higher. If tie type is not an important factor, the wood tie median ξ_{SS} should be higher, while the concrete tie should be lower.
- Analysis 6 and 7: These analyses remove the tie-by-tie variation of BFI, VTM, and tie type. The primary difference is whether the median values should be used, or if all non-tamp lift correction factors should be 1.0. In these cases, both the median (close to 1.0 for as many cases as possible) and low CV indicate success.

The results, which are only applicable to ballast re-compaction mechanisms, can be summarized as follows:

- While not conclusive, the removal of BFI (A2, yellow) and VTM (A3, gray) either show no change or a reduction in CV. This, along with the low Pearson correlations, suggests that tie-by-tie variation in these two parameters does not affect the tie-by-tie variation in settlement.
- The increase in CV for the removal of lift height (A4, purple) generally shows an increase in CV. This, along with the high Pearson correlation, suggests that the tamp lift height is a key parameter that relates to ballast settlement.
- The removal of tie type (A5, red) shows a decrease in median for the wood ties (Zone 1, Wood & Zone 4) but an increase in median for the concrete ties (Zone 1, Concrete & Zone 3). This means the concrete tie factor overestimates settlement ($\xi_{SS} < 1$), while the wood tie factor underestimates settlement ($\xi_{SS} > 1$). Since concrete tie factor is above 1 and the wood tie factor is below 1, it is likely that tie type has no influence, or at least has a reduced influence, on settlement during ballast re-compaction than what is assumed in the RTLM equations.
- Using only lift height as a parameter (A6 and A7), both situations show good results, with medians around 1.0 and low CVs. The A7 analysis (BFI, VTM, and tie type correction factors equal 1) has the median closest to 1.0 for all zones, suggesting that even the median BFI and VTM should not be used for ballast re-compaction situations.

This indicates that for situations of ballast re-compaction, the modified RTLM settlement projections are well-suited, but BFI, VTM, and tie type should be assumed to be 1.0.

4.3 Settlement Mechanism and Other Experience

One significant finding from the study is that the parameters relating to track settlement will vary based on the settlement mechanism. If the settlement mechanism is ballast re-compaction, as it was in Zones 1, 3, and 4 of this study, tamp lift height is the primary correlating parameter and it was determined that BFI, VTM, and tie type should have little effects.

If the settlement mechanism is something other than ballast re-compaction (e.g., settlement because of mud pumping or subgrade), other parameters such as BFI, VTM, and even tie type, may play a larger role. The influence of BFI, while not perfect, was the primary correlating factor in the field measurements in Phase I [1].

This suggests that the categorization of settlement mechanisms is an important step in accurately forecasting mechanistic-based track geometry degradation. This study does not have the solutions for this next stage but a roadmap to achieve it may include:

- Determination of various possible settlement mechanisms occurring in track. This may also include other rail characteristics such as insulated joints (IJs)
- Determination of measurable indicators that can identify each settlement mechanism at a particular location
- Determine measurable indicators that best project settlement/track geometry deterioration and develop separate forecasting models for each settlement mechanism

5. Conceptual Model Use

The model demonstration showed that the RTLM settlement model is well suited for estimating the settlement curves when the settlement mechanism is ballast re-compaction. However, for scenarios where the settlement mechanism is not just ballast re-compaction, while the RTLM may estimate the average behavior, it does not capture all the necessary variables to reliably forecast a single location. For this reason, trending analyses that fit the individual location may be better suited for short-term forecasts to identify locations that may exceed track geometry thresholds in the near future.

One limiting assumption of trending analysis methods is that the track and loading conditions must remain constant. This means that, while trending analyses may be suitable for short-term forecasts, they are not suitable for long-term forecasts or for situations where there is a change to the track structure (e.g., maintenance) or to external conditions (e.g., seasonal climatic changes or change in axle loads).

A potential niche of the mechanistic-based RTLM track geometry degradation projections is to evaluate how changes in ballast and external conditions may affect track degradation. This section will be viewed as an exploratory view into this RTLM use case. Future studies should test this use case.

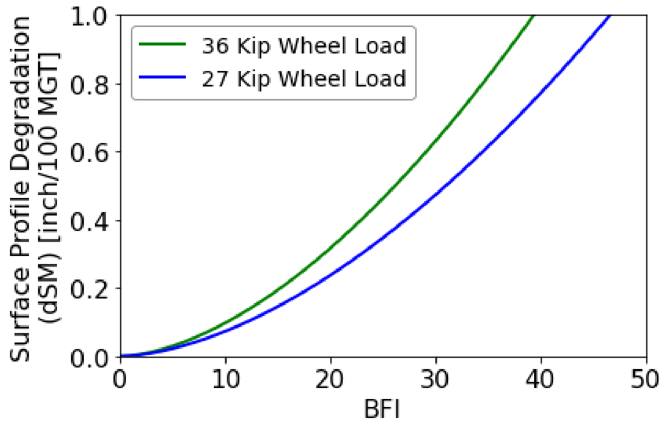
The exploratory examples in this section assume the change of a single location over time.

5.1 Change in Wheel Load

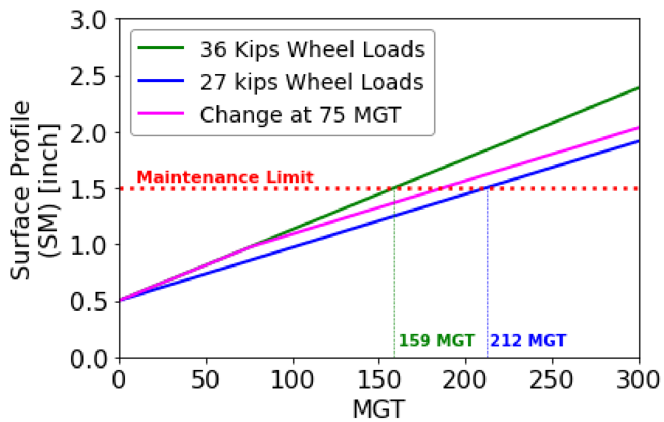
The first case is estimating how changes in wheel load affect track geometry degradation. This could be relevant as commodities shift from heavier coal cars to intermodal cars.

The first example explores how the change in wheel load from 36-kips to 27-kips affects the track geometry degradation over time. The assumption of this situation are concrete ties (ξ_{σ} = 1.3), VTM of 5 kips/in/in (ξ_{VTMS} = 1.0), BFI of 30, a site-specific factor of 1.5, and the a- and b-constants of 1.7 and 0.00091188. The 36-kips wheel load has a ξ_W of 1.09 and the 27-kip wheel load has a ξ_W of 0.81, meaning a reduction of about 25 percent.

Figure 53(a) shows the BFI-dSM curve for the two different wheel load conditions. Figure 53(b) presents the surface profile with MGT. This case assumes a post-tamping SM of 0.5 inches. The research team presented both the 36-kip and 27-kips wheel load situations along with a change from 36-kips to 27-kips at 75 MGT. Assuming a maintenance limit of 1.5 inches, the change from 36-kips to 27-kip wheel loads increases the necessary surfacing cycle from 159 to 212 MGT, a 33 percent increase.



(a)



(b)

Figure 53. Comparison of 36- and 27-Kip Wheel Loads for (a) BFI-dSM Curves and (b) Over MGT

5.2 BFI Degradation and Ballast Maintenance

The second case estimated the increase in track degradation from ballast degradation. Ballast will degrade after repeated loadings from train operations, producing larger BFI values. It is commonly observed that the track geometry degradation will also increase.

Figure 54 shows this process conceptually. The location is similar to the previous example, but assumes an initial BFI of 10, wheel loads of 27-kips, and a site-specific factor of 2.5. A simplistic ballast degradation trend is assumed, which has an increase of 3 BFI over a 150 MGT surfacing cycle and an additional 2 BFI increase from tamping events, summing to an increase of 5 BFI every surfacing cycle. The results show a steady increase in BFI and the track geometry degradation also increases with each surfacing cycle.

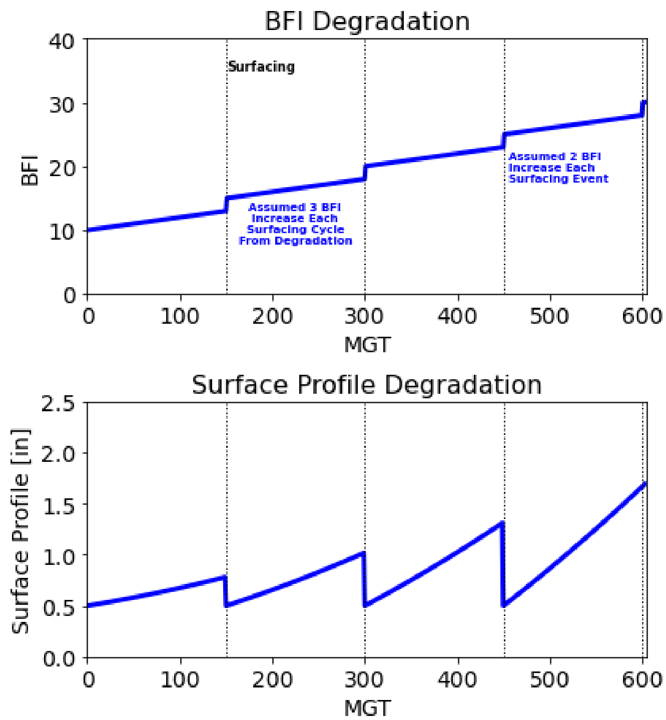


Figure 54. Conceptual BFI and SM Degradation

A second use case for changes in BFI is the influence of a ballast maintenance operation such as undercutting. Undercutting removes the high-BFI ballast and replaces the ballast section with new low-BFI ballast. This is generally considered a "ballast renewal" that reduces track geometry issues in the area. Figure 55 shows the assumed BFI and RTLM projections.

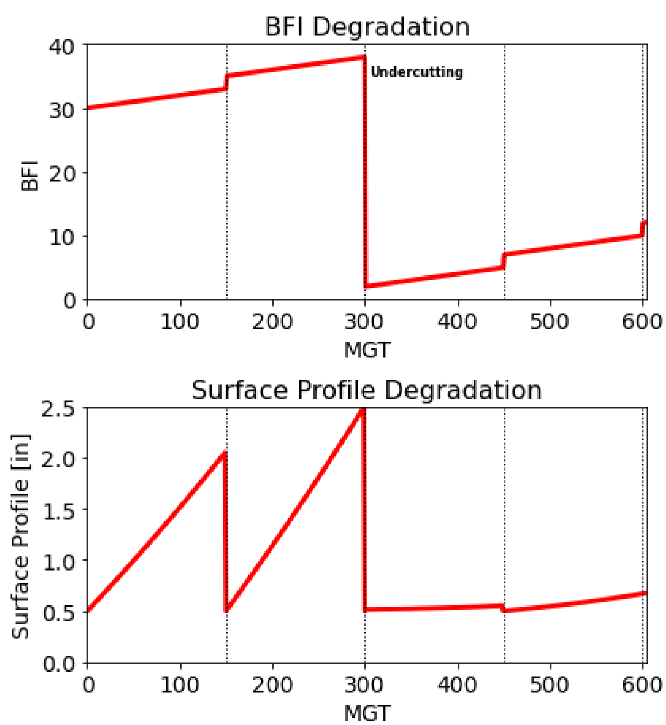


Figure 55. Conceptual Change in SM Degradation from Undercutting

5.3 Seasonal or Yearly Precipitation

The third case estimated the change in track geometry degradation from changes in climate. This could be relevant in multiple situations. This situation compares degradation rates if a climate has a distinct “wet” and “arid” season, or if there is significant degradation during a seasonal wet period. The same concept could be used to model where the seasonal precipitation may vary from year to year, or variations due to long-term climatic shifts from climate change as some regions become wetter and some regions become drier.

Figure 56 shows the variable SM degradation from a consistent “wet” and “arid” climate, along with a seasonal change where the location is “arid” for parts of the year and “wet” for another.

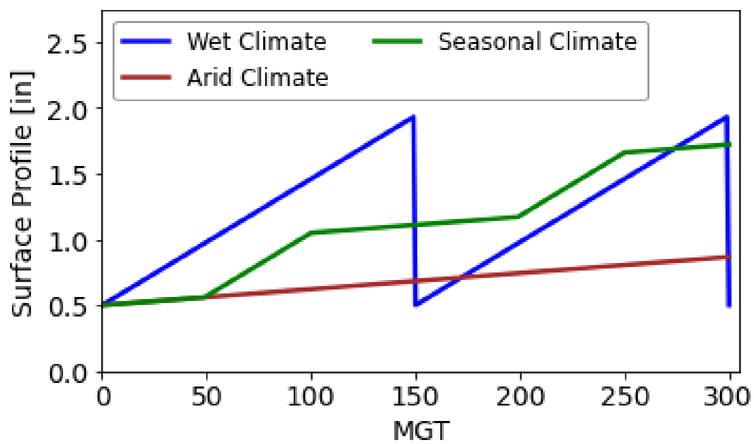


Figure 56. Conceptual Change in SM from Different Climatic Conditions

5.4 Summary and Conclusion

This exploratory look into the uses of the mechanistic aspects of the surface profile degradation RTLM shows multiple potential use cases projecting medium-range (months to years) changes in degradation resulting from changes in loading, ballast condition, and climate. Although these mechanistic aspects need further verification, even rough projections may be powerful tools when the method is applied to long stretches of track over multiple locations, instead of just to individual track locations. This emphasis on multiple locations is because the mechanistic factors should be viewed as an “average” change in behavior instead of a rule for an individual location.

6. Conclusions

Field measurements from the HTL at TTC aided in the demonstration of a modified version of the RTLM. Four different zones provided a variety of settlement mechanisms along with tie types, BFI levels, track modulus, and tamp lift heights. The testing at the four zones occurred between 2020 and 2022.

Section 2) presented modifications of the RTLM. Key findings of the modified RTLM included:

- The original settlement RTLM retains the logarithmic settlement curve trend. A modified surface profile degradation model assumes a linear degradation.
- The settlement model (the original RTLM model) was modified to include tamp lift height and a site-specific correction factor. The research team added the tamp lift height because lift height has a strong relationship with settlement from ballast re-compaction. The site-specific correction factor addressed settlement differences that could not be accounted for by the existing measurable parameters (e.g., BFI and track modulus) and serves as a proxy for accuracy.
- The model may be well suited for stochastic analyses, and initial explorations showed that the known variation in key parameters may produce significant variation in settlement magnitudes.

Sections 3 and 4 presented the demonstration RTLM against field results. Only the settlement model is used. Key findings of the model demonstration include:

- It was important to identify the primary settlement mechanism because it predicts the success of the RTLM settlement model.
  - The most common settlement mechanism during HTL testing was ballast re-compaction (Zones 1, 3 and 4), in which the upper ballast re-compacts to its pre-tamping elevation. This re-compaction could be identified by comparing lift height with settlement as they should eventually be equal to each other. The settlement RTLM was well suited for these situations as the settlement has the logarithmic trend that is assumed by the settlement RTLM.
  - A second ballast settlement mechanism is settlement from a degraded ballast location (Zone 2). The exact mechanism of settlement is more complicated, but the settlement trends tend to be linear, can vary by moisture levels, and often exceed the tamp lift height.
  - Other settlement mechanisms, such as subballast, subgrade, and lateral movement, exist but were not measured in this study. Additional factors may include high-force regions such as joints or turnouts.
- For the ballast re-compaction situations (Zones 1, 3, and 4), the following findings were made:
  - Tamp lift height was the primary correlating factor with settlement. Other factors such as BFI, track modulus, and tie type did not have any noticeable relationship. For this reason, the BFI, track modulus, and tie type correction factors should be assumed as 1.0 in ballast re-compaction scenarios.

- When using only tamp lift height, the accuracy of the modified settlement RTLM for all ties in Zones 1, 3, and 4 was quite high (median site-specific correction factor, ξ_{SS} = 0.98). The coefficient of variation (CV) for the zones ranged from 0.03 to 0.19.
    - The relationship between settlement and surface profile was low, with very low SM/u values (0 to 0.2). This low ratio was due to the nearly uniform ballast settling, which will not produce large surface profile deviations.

- These are the following findings for the degraded ballast situation (Zone 2):
  - Moisture (climate) was the primary correlating factor with the post-compaction settlement rate. The projected magnitudes and settlement trends did not agree well with the measured values, but the existing framework allowed for the factor to be explored.
  - The accuracy of the modified settlement RTLM was not good for this situation, and the surface profile model may be better suited.
  - The relationship between settlement and surface profile was high, with an SM/u ratio of 0.8. This indicates that the settlement occurred in a localized dip instead of over an entire area.

An exploratory analysis investigating how the surface profile RTLM could be used to project possible changes in degradation rate based on changes in axle load, BFI degradation, and climate. This type of analysis should be explored further and verified with actual measured scenarios.

Forecasting track geometry degradation based on mechanistic inputs from track inspection vehicles is a complicated task that involves multiple settlement mechanisms and important parameters. This report presents two different model types, a "settlement" model and a "surface profile" model. The "settlement" model characterized the ballast re-compaction mechanism well, which is the most common situation in track, but is also the least likely to produce track geometry exceptions. The "surface profile" model is better suited for degraded ballast settlement mechanisms using track inspection vehicles. Additional work is required for different settlement mechanisms such as degraded ballast and subgrade, and even rail and loading influences such as IJs.

7. References

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Abbreviations and Acronyms

ACRONYM	DEFINITION
AN	Abrasion Number
AAR	Association of American Railroads
AREMA	American Railway Engineering and Maintenance-of-Way Association
BFI	Ballast Fouling Index
CV	Coefficient of Variation
dSM	Degradation Rate
FRA	Federal Railroad Administration
GPR	Ground Penetrating Radar
MCO	Mid-chord Offset
MGT	Million Gross Tons
RTLM	Railway Track Life Cycle Model
SeiBIT	Seismic Ballast Inspection Tool
FI	Selig's Fouling Index
SD	Standard Deviation
SRI	Strategic Research Initiatives
SM	Surface Magnitude
TOR	Top-of-Rail
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.
VTM	Vertical Track Modulus