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Improving lateral track strength after ballast maintenance

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Abstract

Purpose – MxV Rail conducted multiple single tie push tests (STPTs) between 2020 and 2023 to assess the changes in lateral tie resistance from tonnage accumulation, dynamic track stabilizers (DTS), tie type and ballast condition. High lateral tie resistance is necessary for preventing lateral misalignments and track buckles. Therefore, understanding how various factors affect the lateral tie resistance will aid in the development of track buckling risk assessments and ballast maintenance best practices.

Design/methodology/approach – The test involved tamping a section of track that consisted of both concrete and wood ties and then increasing the lateral tie resistance, using either tonnage during speed restrictions or a DTS. The STPTs and top-of-rail (TOR) elevation measurements were taken at multiple stages, including immediately after tamping and then after different tonnage increments or DTS. The results from this test were then added to a compiled measurement from previous tests, and the results from all the tests were used to develop general guidelines for ballast maintenance best practices and trade-off considerations.

Findings – The results showed multiple factors affect the lateral track strength and therefore the susceptibility to misalignments and track buckles. The disturbance from ballast tamping can reduce the lateral track strength by 20–80% (~45% median) and can be compacted from either tonnage (25–50% regain in strength after 0.1 m gross ton or MGT) or DTS (33–78% regain in strength). The amount of ballast (shoulder width and crib height), tie type and ballast characteristics all have a meaningful role in lateral track strength.

Originality/value – This paper is based on the testing programs conducted by authors at MxV Rail.

Keywords Lateral track strength, Single tie push test (STPT), Track buckle, Tamping, Shoulder width, Crib height

Paper type Research paper

1. Introduction

Track buckles and thermal misalignments are problems for railroads in the summer and can result in reduced capacity from speed restrictions and operational disruptions from track buckles. An important aspect of maintaining a strong track structure to avoid track buckles is the lateral track strength or ability of the ballast to resist lateral tie movement. It is well known that the lateral track strength can be significantly reduced after track surfacing and other ballast maintenance and also varies based on the tie type and ballast structure. Measuring the lateral track strength to mitigate risk relies on a disruptive test called the single tie push test (STPT) and is not suitable on a system-wide level. Therefore, railroads rely on other types of testing and modeling to estimate lateral track strength changes and make operational decisions.

In an effort to better understand how track maintenance can reduce the lateral track strength and the options available to strengthen the track after maintenance, MxV Rail conducted multiple STPT studies between 2020 and 2023 to assess the changes in lateral tie resistance

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from tonnage accumulation, dynamic track stabilizers (DTS), tie type and ballast condition. In addition, MxV Rail modified existing lateral track strength estimation models (Kish & Samavedam, 2013) to include testing from the previous decade.

2. Background

2.1 Track buckles

One of the main functions of ballast is to minimize tie movement (AREMA, 2022), including lateral track misalignments and track buckles. Track buckling occurs when the build-up of compressive longitudinal rail forces exceeds the buckling strength of the track structure, resulting in lateral track deformations, often at a localized weaker location of the track. This can result in misalignments as great as 0.7 m (30 in.) or more (Wilk & Kleman, 2023). Thus, preventing buckles is an important step toward minimizing train derailments and the significant maintenance effort required to realign the track.

Multiple factors may affect the track-buckling process, including (1) rail temperature, (2) rail neutral temperature (RNT), (3) track geometry, (4) vehicle forces, (5) vehicle-induced track uplift, (6) rail properties, (7) longitudinal track stiffness, (8) fastener rotational resistance and (9) tie/ballast interface resistance (Kish & Samavedam, 2013). Often (but not always) buckles are a result of some combination of high longitudinal rail forces (e.g. high rail temp, low RNT or high vehicle forces) and/or low lateral track strength (e.g. lateral misalignments, low rotational strength and low tie/ballast interface strength).

This paper focuses on the relative track strength as it relates to the tie/ballast interface. This interface component is important because track maintenance, in general, tends to disturb the ballast by breaking up the compacted ballast structure, which leads to a sharp reduction in strength of the tie/ballast interface (Wilk, 2023). To compensate for the strength reduction that occurs after maintenance, speed restrictions are often enacted – typically for the first 0.1 m gross ton (MGT) – in order to minimize in-train forces until the tonnage from train operations recompacts the ballast and it regains some of its lost interface strength. Other compaction tools, such as DTS, can be used in place of the speed restriction tonnage to reduce the number of trains required to recompact the ballast before speed restrictions can be removed.

In addition to changes in ballast compaction (i.e. density), many of the other important tie/ballast interface strength components can be measured (e.g. adding ballast), and they are also relatively easier to measure than many other buckling parameters, such as RNT. Therefore, a more comprehensive understanding of the tie/ballast interface strength can lead to better identification of higher-risk locations and provide options to increase the lateral track strength.

2.2 Tie ballast interface strength

The tie/ballast interface strength is the resistance of the ballast against lateral tie movement. The ballast resistance is provided by the interlocking of discrete ballast particles with each other and by the ability of the ballast particles to engage the tie. Ballast that consists of compacted, angular and textured crushed rock that can indent into the ties will provide significantly greater resistance than will smooth, rounded ballast (Tutumluer, Qamhia, & Wilk, 2024).

The lateral resistance of a tie can be directly measured using STPTs. These tests are conducted by removing the fastening system, lifting the rail and laterally pushing the tie with an actuator. Because this direct measurement involves significant track disruption, it can only be used in limited situations and cannot be an output from a track inspection vehicle.

The tie/ballast interface resistance is affected by many factors but can be simplified as: Resistance = f(ballast interlock ability, ballast density and amount of ballast). The ballast interlock ability is determined by the ballast characteristics (i.e. particle shape and texture), tie/ballast interface friction (i.e. tie/ballast particle engagement), tie weight, tie loading and tie lift-off from vehicles or hanging ties. Ballast with angular and textured characteristics has historically been recommended for ballast (AREMA, 2022), and a few previous studies have shown the relationship between ballast characteristics (e.g. angularity and texture) and increased lateral track strength (Moaveni, Wang, Hart, Tutumluer, & Ahuga, 2013; Davis, Jimenez, LoPresti, Tutumluer, & Qian, 2011) since more angular and textured ballast particles will have stronger engagement with other ballast particles and the tie. The tie/ballast interface friction refers to the ability of the ballast to engage the tie, and there have been a few studies characterizing the bottom tie/ballast frictional interface for both wood and concrete ties (Samavedam, Kish, Purple, & Schoengart, 1993; Kish & Samavedam, 2013). While not characterized, Kish & Samavedam (2013) mention that the tie/ballast frictional interface for both wood and concrete ties will change over time as the surfaces degrade and that adding texture to the sides of concrete ties (i.e. scalloping) or pads to the bottom of ties can improve the interface strength. Increased tie weight will increase the lateral strength because of the tie/ballast interface strength. The higher weight of concrete ties is one reason concrete ties tend to have greater lateral strength than wood ties, but interface friction can also have a role. Tie loading/liftoff is a vehicle effect where the additional vertical loading from the vehicle will locally increase the lateral strength but may reduce the lateral track strength underneath the carbody if the tie "lifts off" (Kish & Samyedam, 2013).

Ballast "density" refers to how tightly packed the ballast particles are, and this is a function of tonnage. Ballast maintenance (e.g. tamping) involves disturbing the compacted ballast and results in a looser ballast structure. As the ballast compacts from tonnage or a DTS, the ballast particles will recompact and improve the engagement with other ballast particles and tie, resulting in an increased lateral strength (Trevizo, 1991; Kish, Clark, & Thompson, 1995; Kish, Sussmann, & Trosino, 2003; Read, Thompson, Clark, & Gehringer, 2011).

The amount of ballast refers to the shoulder width and crib height. The more crib ballast provides more tie/ballast surface contact and confinement, increasing the lateral strength. The shoulder width provides end bearing resistance to the tie, so a higher shoulder provides more lateral strength. There has been previous work separating the three interface components of the tie bottom (tie/ballast interface strength and tie weight), tie side (tie/ballast interface strength and crib height) and tie end (ballast characteristics and shoulder width). Kish & Samavedam (2013) summarized as 30/50/20 (bottom/side/end) for wood ties and 40/45/15 for concrete ties.

For measurement purposes, the amount of ballast can be measured either visually or by track inspection vehicles. The ballast density can be approximated by tonnage accumulation after maintenance. Tie lift-off situations can be estimated by knowing the vehicle type and whether the tie is hanging. Tie type (or weight) can also be documented. The interlocking ability of the ballast particles and tie/ballast interface can be measured (Moaveni *et al.*, 2013), but because the method requires track disturbance, it cannot currently be incorporated into inspection vehicles. However, conservative assumptions can still be made, regardless of whether the ballast and tie are new or degraded.

2.3 Post-ballast maintenance speed restrictions

Track maintenance that disrupts the ballast interlock (e.g. tamping) can temporarily reduce the track's capability to resist lateral track movements, such as misalignments and buckles. During a weakened track state, railroads apply restrictions to the maximum allowable speed of trains with the goal of reducing vehicle forces until the ballast can recompact and regain its strength capability. Each railroad has a different speed restriction policy, but, in general, they all release the speed restriction and have resumed posted speeds after approximately 0.1 MGT. However, the optimal tonnage accumulation before resuming posted speeds may depend on the actual situation.

3. Test layout

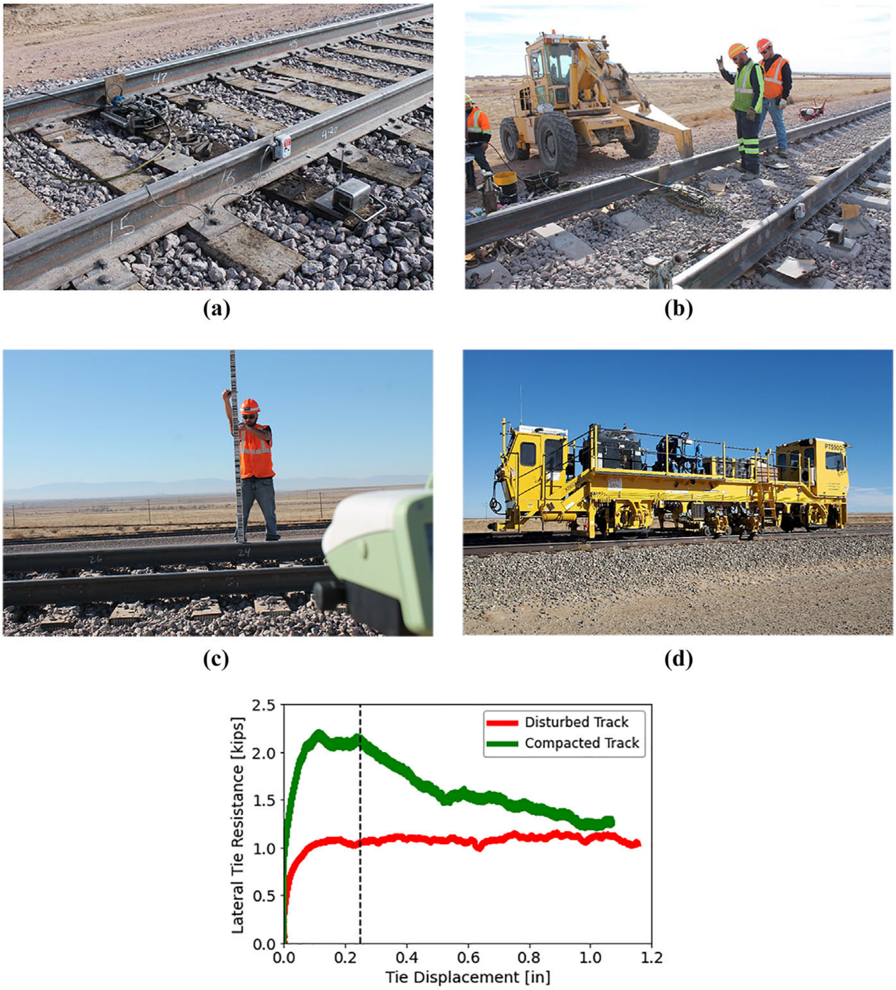
This paper presents the results from two separate but related tests: Test #1 and Test #2. The details are described in the following subsections.

3.1 Instrumentation and monitoring

In order to assess ballast compaction, both the lateral tie resistance and track settlement were measured. The lateral tie resistance was measured by performing STPTs at various tonnage/stabilization intervals after tamping. Top-of-rail (TOR) elevations measured unloaded track settlement at multiple intervals. Figure 1(a) and (b) show photographs of STPTs in wood and concrete ties, and Figure 1(c) shows a TOR elevation measurement.

3.2 Test #1: dynamic track stabilizer vs 0.1 MGT speed restriction tonnage

Test #1 occurred between 2020 and 2022 at Section 36 of the High Tonnage Loop (HTL), located within the Transportation Technology Center (TTC) near Pueblo, CO, USA.



(a) (b)

(c) (d)

(e)

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Figure 1. Photograph of the single tie push test (STPT) setup in (a) wood and (b) concrete ties, (c) photograph of top-of-rail (TOR) survey elevation measurement, (d) a photograph of a dynamic track stabilizer (DTS) and (e) a typical STPT load-displacement curve

Two rounds of testing occurred. The first round involved tamping the section and measuring the increase in lateral tie resistance after 0.1 MGT of speed restriction tonnage. The second round involved tamping and then measuring the increase in lateral tie resistance from a DTS. Three different zones were used: Zone #1, consisting of wood ties, and Zones #2 and #3, consisting of concrete ties. The test layout is shown in Figure 2. Zone #1 has about 20-STPT tested ties, while Zones #2 and #3 each have about 10 STPT-tested ties. The DTS (Figure 2) applied a down-pressure of 40 Bar (580 psi, 4 MPa) in Zones #1 and #2 and a heavier down-pressure of 60 Bar (870 psi, 6 MPa) in Zone #3. It should be noted that the speed restriction tonnage round of testing only involved Zone #1 and #2.

3.3 Test #2: tonnage increments

Test #2 occurred in November 2023 during the initial compaction runs of the new Facility for Accelerated Service Testing (FAST) track. MxV Rail performed STPTs at increments of 0 MGT, 0.01 MGT, 0.03 MGT, 0.05 MGT and 0.11 MGT to define the increase in lateral tie resistance as a function of early tonnage accumulation. For the 0.0 and 0.11 MGT increments, ten wood ties were pushed. For the 0.01, 0.03 and 0.05 MGT increments, six wood ties were pushed.

Completed in November 2023, the new FAST track is a 2.8-mile loop that supports railroad research and testing. The tests were conducted on tangent track with mixed hardwood ties, cut spikes and new ballast on a newly constructed fill. The cribs were generally full, and the shoulder was approximately 15 in. wide. A short train consisting of three locomotives and 28 FAST cars loaded to 315,000 pounds gross rail load was used to compact the track. The train speed ranged from 15 to 25 mph.

3.4 Other studies

The results of the current test were included in a larger database from the previous studies (Wilk, 2021a, b; Wilk, 2024; Kish, 2020; Trevizo, 1991; Kish *et al.*, 1995, 2003; Read *et al.*, 2011; McHenry, 2017).

3.5 Dynamic track stabilizers (DTS)

The DTS is a machine that attempts to replicate the ballast compaction process from train operations with vibration. The vibration produced in the machine is transferred downwards through the track structure into the ballast.

In the 1990s and 2000s, multiple DTS tests were performed using heavier DTS models (Trevizo, 1991; Kish *et al.*, 1995; Li & Shust, 1999; Kish *et al.*, 2003; Read *et al.*, 2011). In the current test, a newer model DTS (that can be moved by truck) was used Figure 1(d). The weight and down-pressures in the newer DTS are lower than in the previous DTS models, making them more versatile than their heavier counterparts. However, there was a desire to ensure that a similar ballast compaction benefit could be achieved in the lighter models. Additionally, it was important to understand the effect of different tie types and DTS down-pressures. As a note, 80–90 bar down-pressures (1,160–1,305 psi, 8–9 MPa) have been tested frequently in previous tests.

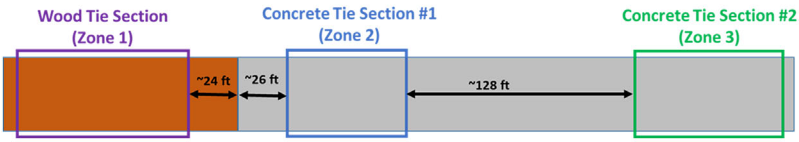

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Figure 2. Layout for Test #1

3.6 Data analysis

During an STPT test, the collected data involves a force-displacement curve. An example load-displacement curve is shown in Figure 1(e) and shows examples of compacted track (green) and disturbed track (red). In compacted track, the peak force typically occurs within 0.1–0.25 in. and then softens to a limiting resistance at about an inch. In in the disturbed track, the peak force also occurs within 0.1–0.25 in. but then remains near constant as the displacement increases.

The maximum lateral tie resistance (kips) is the maximum value within the initial 0.25 in., and the 0.25 in. emphasize initial movement. If the study involves comparing a factor other than shoulder width or crib height, the values are normalized by an 18-in. shoulder width and full crib height using the values used later in Section 6.2. If the analysis involves different tie types, the values may be again normalized by tie spacing and output lb/in.

Typically, a number of STPTs are conducted within a section due to the natural variation in lateral tie resistance, so the average value from that section is considered representative. This study focuses on the change in lateral tie resistance, so the change is represented as a percent increase.

4. Test 1 results: comparing compaction from tonnage and DTS

This section compares compaction ability between train operations under speed restriction tonnage and a DTS.

4.1 Lateral tie resistance increase from tonnage and DTS

The increase in lateral tie resistance from compaction – either by speed restriction tonnage (Round 1) or DTS (Round 2) – was calculated by taking the percentage increase from the post-tamping state. Figure 3 compares the percentage increase from the recent test (with speed restriction tonnage in blue and DTS in red) for the three test sections. The results show a slightly greater lateral tie resistance (4–11%) from the DTS, which agrees with historical measurements. This particular test also suggests that the track with concrete ties has a greater relative compaction (16%) from the DTS than the track with wood ties.

To provide historical context, Figure 4 compiles all the test results from the available literature (Wilk, 2021a). The tests are separated by tie type (wood and concrete), and the down-pressure (if known) is shown in the legend. There are many other factors that may affect lateral tie resistance, such as ballast condition, tie texture, etc. but these were not consistently documented in previous tests, so they cannot be compared.

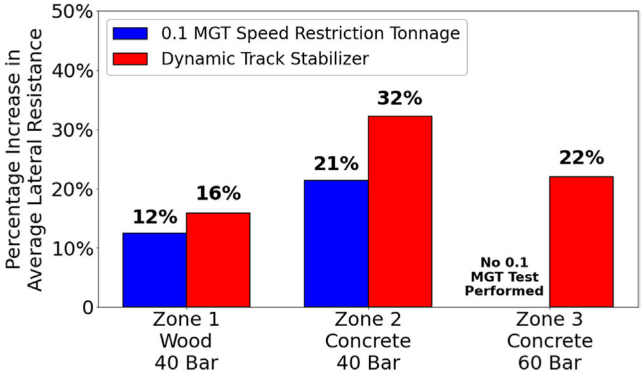

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Figure 3. Percentage increase in average lateral tie resistance from 0.1 MGT of speed restriction tonnage and DTS in Test #1

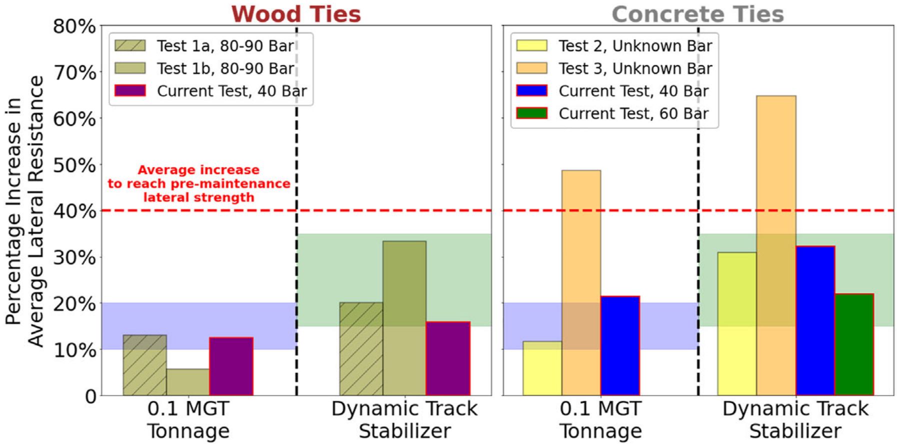

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Figure 4. Percentage increase in average lateral tie resistance from all available literature

While the results show wide variation in lateral resistance increases, general patterns can still be observed. For example, the DTS consistently produced a similar or greater increase in lateral tie resistance than did speed restriction tonnage for all tie types and down-pressures. This observation is important as it demonstrates the effectiveness of DTS systems. The shaded regions in the graph show the general range of lateral resistance increases, with the slow order tonnage increases ranging from 10 to 20% and the DTS increases ranging from 15 to 35%. With regard to tie type, Test #3 appears to be an outlier. If that test is not considered, concrete ties show a slightly greater lateral resistance than do wood ties (5%), but the difference is less significant than in the current test (16%). Lastly, there is not a recognizable pattern regarding the effect of down-pressures.

4.2 Track settlement from tonnage and DTS

Track settlement is a more direct method of assessing ballast compaction than STPT but is not a direct measure of lateral tie resistance. For the 2021 test, TOR elevations were measured at multiple intervals: (1) pre-tamp, (2) post-tamp, (3) post-stabilization and (4) at 22 MGT. The tamp lift height can be calculated from the difference between the pre- and post-tamp. The initial settlement from DTS is calculated from the difference between post-tamp and post-stabilization. The long-term settlement assumes 22 MGT of tonnage.

The settlement at a location is highly dependent upon the tamp lift height; therefore, it is important to reduce the influence of the tamp lift height parameter as much as possible. One way to do this is to plot the settlement by the tamp lift height and fit a linear regression line. To normalize by tamp lift height, a 25 mm (1.0 in.) tamp lift is assumed, and the anticipated settlement is calculated using the linear regression equation. Figure 5 presents the settlement assuming a lift height of 25 mm (1.0 in.) both initially (Figure 5a) and long-term (Figure 5b).

The initial settlement in Figure 5a generally shows greater or equal settlement with the DTS than with the tonnage. This agrees with the lateral tie resistance measurements. The concrete tie sections did seem to have greater settlement than the wood tie section for the DTS, which, again, agrees with the lateral tie resistance values. However, the previous studies did not measure settlement; thus, it is unclear if this is consistent with historic values.

For the long-term settlement at 22 MGT shown in Figure 5b, the trends are similar to those in Figure 5a (initial settlement), and the DTS locations show slightly greater settlements than the tonnage. As mentioned earlier, the trends of the short- and long-term settlements should be

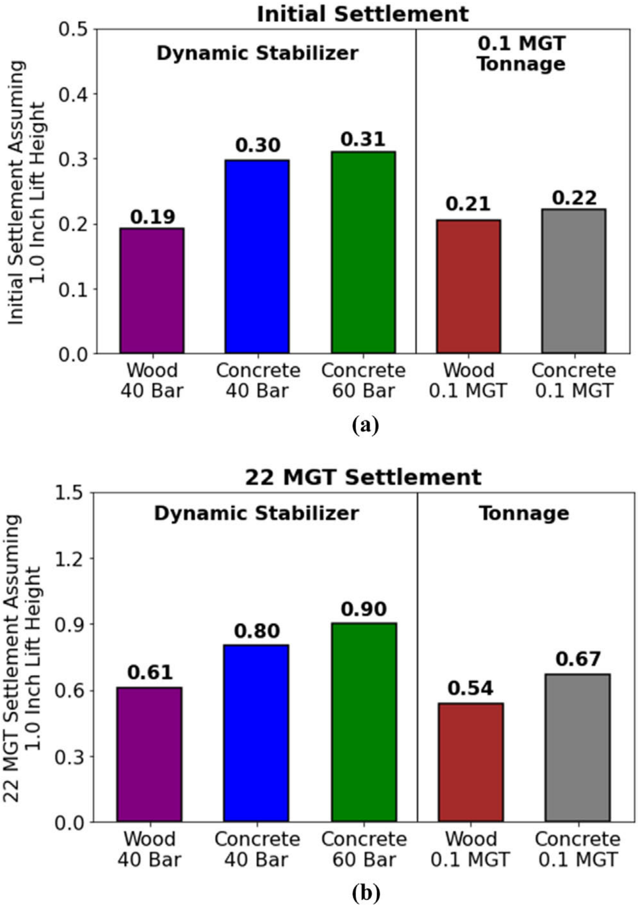

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Figure 5. Track settlement assuming 25 mm (1.0 in) lift height (a) initially (post-DTS or 0.1 MGT) and (b) long-term ~22 MGT

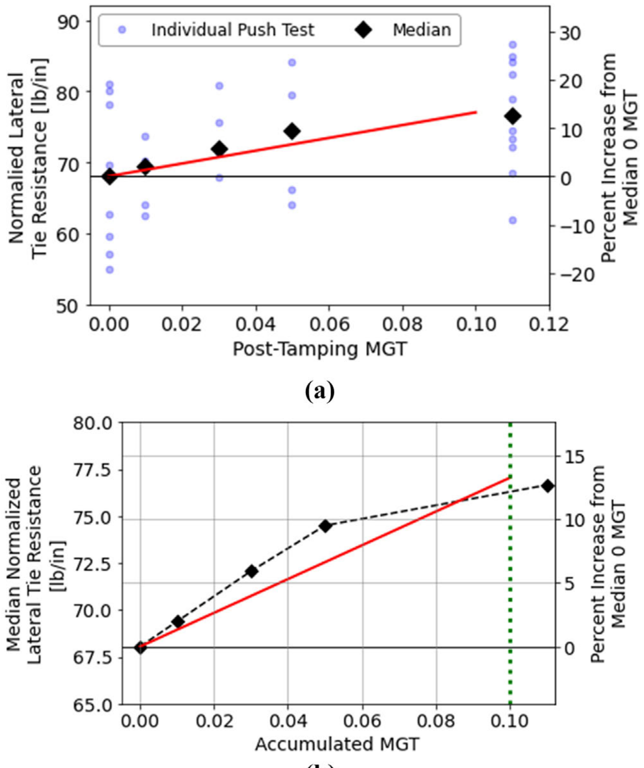
similar because the DTS should only influence the initial compaction. For both the DTS and tonnage situations, the remaining settlement is induced by train tonnage, so they should behave similarly, assuming that DTS and slow order tonnage had similar levels of initial compaction.

5. Test 2 results: lateral resistance increase from speed restriction tonnage

This section presents the increase in lateral tie resistance from tonnage under speed restrictions. The test section consisted of new mixed hardwood ties, cut spikes and new granite ballast following #4a AREMA specifications (AREMA, 2022).

5.1 Lateral resistance trend below 0.1 MGT

Figure 6(a) compiles the tie push results measured at different tonnage increments, with the left *y*-axis displaying the normalized lateral tie resistance (by shoulder width, crib height and tie spacing) and the right *y*-axis showing the percent increase from the median 0 MGT value. The blue dots indicate the individual tie pushes, while each black diamond represents the



(a)

(b)

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Figure 6. Change in normalized lateral tie resistance values from tie pushes at different tonnage increments: (a) shows all data and (b) shows the median trend

median value for each tonnage increment. The widespread of blue dots showed a wide range of resistance, but it is the median value that is considered representative because lateral misalignments or buckles are resisted by a group of ties, rather than by individual ties. The average could also be used to provide similar results and trends.

While there is scatter of approximately 25-lbs/in. at each tonnage increment, the median shows a gradual increase up to 0.1 MGT. Figure 6(b) emphasizes the median trend. The increase from 0.0 to 0.1 MGT is 12.7%, which is slightly below the median from previous tests (16.8%) but still within the common range of 10–20%.

5.2 Relationship between lateral tie resistance and track settlement

Figure 7 shows the relationship between lateral tie resistance (left *y*-axis) and track settlement (right *y*-axis). The increase in lateral tie resistance with tonnage is due to the densification of the individual ballast particles, thereby increasing the interlocking ability of the particles. Since both settlement and an increase in lateral strength are dependent on increased ballast density, a similar relationship between the two parameters is anticipated.

5.3 Full relationship between tonnage and lateral resistance

From previous tests, the trend after 0.1 MGT was observed to be nonlinear with diminishing increases in lateral tie resistance with further tonnage increases. At approximately 10 MGT, the

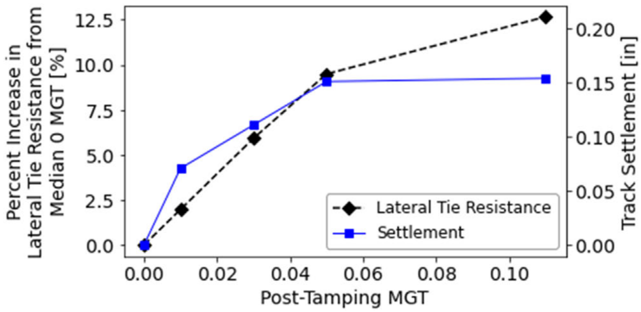

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Figure 7. Relationship between increase in tie resistance and track settlement up to 0.1 MGT

lateral tie resistance can increase, but the increase is generally small, and for the purpose of this study, the 10+ MGT tests are grouped together. The current test showed generally linear behavior within the initial 0.1 MGT (or 0.05 MGT) of traffic.

Due to the different trends, the equation is split into three parts: 0–0.1 MGT, 0.1–10 MGT and 10+ MGT. There are significant amounts of test data at 0.1 MGT (16.8% median) and 10+ MGT (44.4% median), so those two increments are used as bounds between the parts. The nonlinear portion between 0.1 MGT and 10 MGT is fit with a logarithmic trend (similar to track settlement). Table 1 presents the equations.

Figure 8 plots the results of the current test (black diamonds), the results of the previous three tonnage increment tests, and the presented equations. The data are split between three panels to emphasize different tonnages. While there is significant scatter between the tests, likely due to other influences on lateral tie resistance such as ballast characteristics, the results show that the proposed relationship (thick black line) generally agrees with the current and past test results. The additional test results at 10+ MGT made the trend more conservative than

Table 1. Equations of increase in lateral tie resistance with tonnage

Part	Trend	Equation
0 to 0.1 MGT	Linear	166.15*MGT
0.1 to 10 MGT	Nonlinear	$27.17*\mathrm{MGT}^{0.2136}$
10+ MGT	Constant	44.4

Source(s): Authors' own work

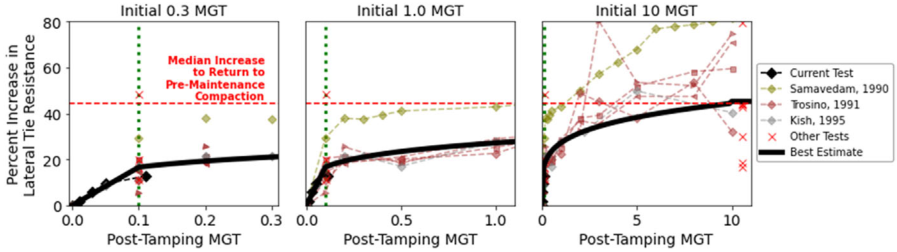

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Figure 8. Full trend plotted against available data from multiple sources

using just the three studies, but the additional data from other tests should make the trend more representative.

The data also emphasizes that the increase in lateral tie resistance tends to be relative to the 0 MGT lateral tie resistance value. This means inherently stronger tracks will see a greater absolute increase from tonnage and can be attributed to differing ballast interlock abilities. Ballast with more interlocking ability will see a greater absolute increase in lateral tie resistance from tonnage.

Below 0.1 MGT, the linear trend matches the current test and one data point from Kish *et al.* (1995). Based on the results of the current test, it could be argued that the linear/nonlinear threshold starts at 0.05 MGT instead of 0.1 MGT; however, 0.1 MGT was chosen because this threshold was conservative. If a threshold of 0.05 MGT is desired, the equation in Table 1 can be modified by calculating the increase in lateral strength at 0.05 MGT from Part 2 (14.33%) and creating a linear trend for tonnages lower than 0.05 MGT. Physically, the threshold between the linear and nonlinear trend likely varies between 0.05 and 0.1 MGT, depending on the ballast and track type.

6. Other parameters

This section summarizes influences of tie/ballast interface strength parameters other than compaction. The results, derived from STPT testing, are normalized by ballast section (corrected to assumed full crib and 0.45-m (18-in.) ballast shoulder) and are also normalized by tie spacing (divide STPT lateral tie resistance by tie spacing).

6.1 Tie type

Tie type influences lateral strength because heavier concrete ties induce more bottom friction. Figure 9 presents the median results of the various studies, which included wood, concrete and engineered polymer composite (EPC) ties under compacted (10+ MGT) and post-surfacing conditions.

The results show that concrete ties generally provide higher resistance than wood ties, even when normalized by tie spacing, and the strength results tend to be similar to the results at the upper end for wood ties. There is more variation in the results for wood ties, due to the greater number of studies, and this variation is attributed to ballast characteristics. The EPC ties show resistance values similar to those for wood ties. In that case, the variation is attributed to tie side texture. The results also show that surfacing reduces the track strength by about 40% (but can range anywhere from 16 to 80%).

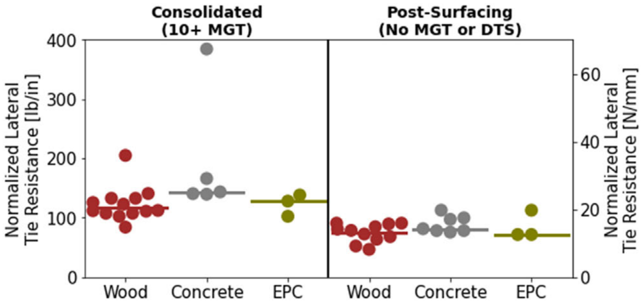

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Figure 9. Normalized lateral tie resistance results of different tie types in compacted and post-surfaced conditions

6.2 Amount of ballast

The amount of ballast in the ballast section is influential because more ballast will provide more overall resistance. Shoulder width and crib height are the influential parameters, and both of these can be reliably measured by vehicle-based track inspection methods. The influence of shoulder width, crib height and bottom interface has been characterized previously (Kish & Samavedam, 2013), and results from the current test have agreed with the previous equation.

The equation reads as follows and would be the lateral tie resistance adjustment factor based on the ballast section.

$$F_{BS} = \beta_1 + \beta_2 * C_d + \beta_3 * \frac{S_W}{18} \tag{1}$$

where F_{BS} = ballast section correction factor; C_{d} = the crib height as a percentage of tie height (1.0 = full crib, 0.5 = half crib and 0.0 = empty crib); SW = shoulder width (in inches) and β_1, β_2 and β_3 = factors (see Table 2) based on tie type. The equation assumes that only ballast up to 0.45 m (18 in.) in the shoulder provides resistance and that larger shoulders provide minimal additional resistance.

Figure 10a shows a diagram of contributions from the different location components. Figures 10b and 10c show the percent changes from shoulder width and crib height for wood and concrete ties. As an example, a location with a reduced ballast section (i.e. a 6-in. shoulder and a two-thirds filled crib) can reduce lateral strengths by about 30%.

6.3 Ballast characteristics

The ballast characteristics provide the "locking" ability of the ballast. This locking ability can be measured using the angularity index, surface texture index, flat and elongated index and gradation (Moaveni *et al.*, 2013; Davis *et al.*, 2011). Figure 11 shows the general relationship between the indices and lateral resistance. The results in Figure 11 also suggest that high-quality ballast may provide additional track strength in higher track buckle risk situations.

The ballast particle characteristic measurements involve sampling and detailed visual assessment and cannot be incorporated into vehicle-based track inspection methods. For this reason, the values are simplified into "new" and "degraded" ballast, and the results are shown in Figure 12 and Table 3. These values are recommended as "baseline values" for any lateral tie resistance estimations. The values also assume a high-quality rock, such as granite or traprock (rather than limestone or slag).

The differences between new and degraded ballast in Figure 12 suggest that the lateral track resistance will gradually reduce over time due to the degradation of the ballast particles. However, the exact reason for this reduction is unclear. While abrasion should round the particles and thereby decrease ballast interlocking, particle breakage and general changes in gradation can also increase the ballast interlocking.

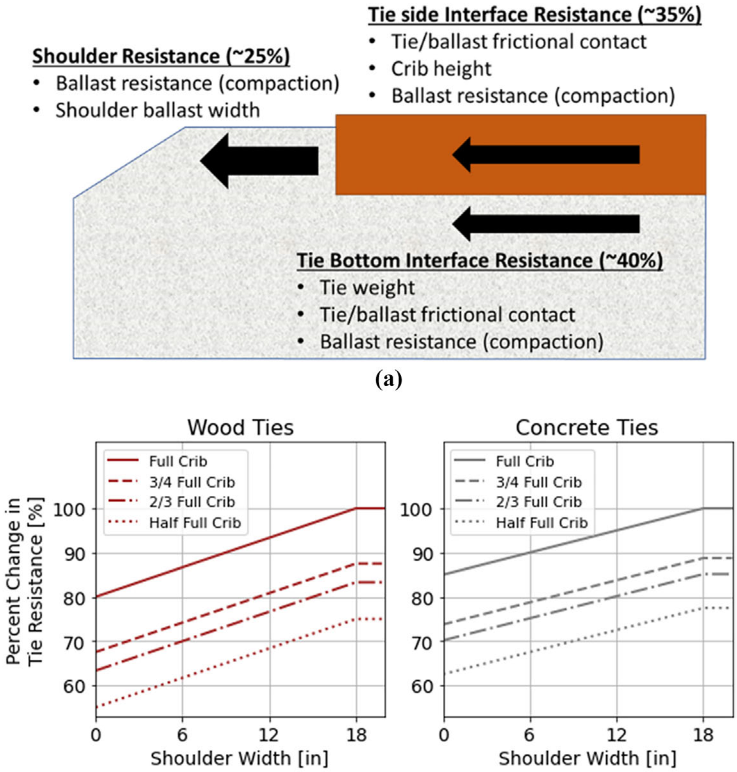
6.4 Tie-ballast interface friction

Typically, tie/ballast interface friction involves the indentation of ballast particles into the tie. But the interface friction can also be influenced by tie texture, tie pads and tie movement. Because the interface friction parameter is difficult to isolate and measure, it is currently

Table 2. Beta values for tie bottom, side and end components

Tie type	Bottom (β_1)	Side (β_2)	End (β_3)
Wood	0.3	0.5	0.2
Concrete	0.4	0.45	0.15

Source(s): Authors' own work



(a)

(b)

(c)

Source(s): Authors' own work

Figure 10. (a) Diagram of contributions from the different location components, (b and c) percent changes from shoulder width and crib height for wood and concrete ties

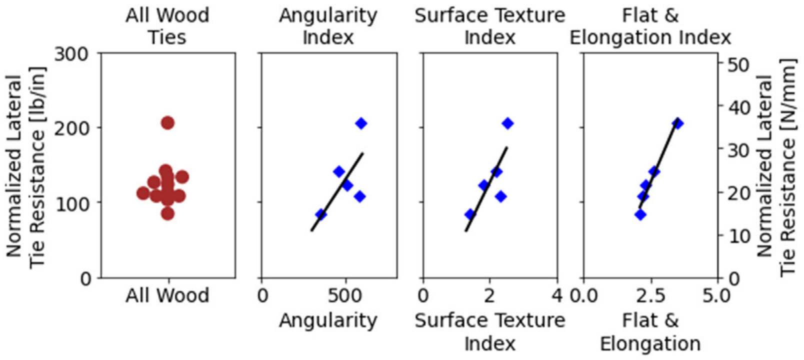


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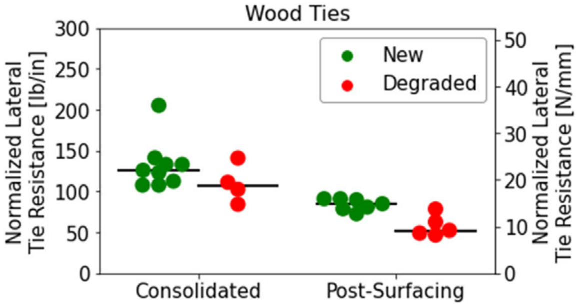
Figure 11. Relationship between ballast particle indices and lateral resistance



Source(s): Authors' own work

Figure 12. Baseline lateral tie resistance values based on ballast condition

Table 3. Baseline values in lb/in. (N/mm)

Density	Ballast	Wood	Concrete
Post-surface	New	84.9 (15)	Limited data
Post-surface	Degraded	52.4 (9.2)	80.0 (14)
Consolidated	New	125.8 (22)	Limited data
Consolidated	Degraded	106.9 (19)	142.3 (25)

Source(s): Authors' own work

included with ballast characteristics (see Section 6.3). It can be reasonably assumed, however, that tie pads increase resistance because of their strong engagement at the tie-ballast interface. And tie movement (e.g. lateral curve breathing, longitudinal tie bunching and vertical pumping) produces a weaker interface friction because it will not allow the ballast particles to engage with the tie. Therefore, the values in Table 3 can be adjusted accordingly.

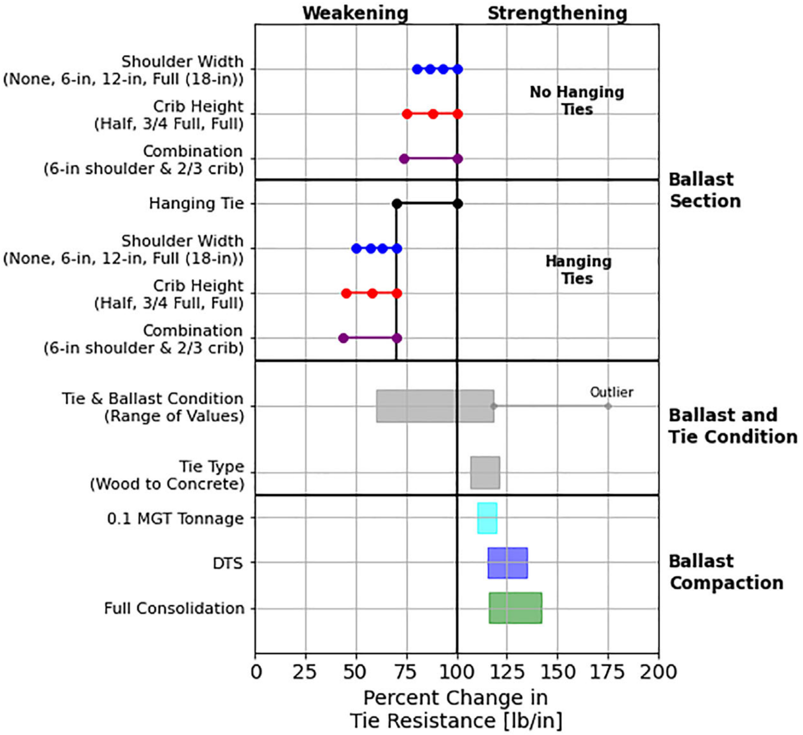
6.5 Tie uplift and hanging ties

The bottom of a tie can lose contact with the top of the ballast through two different mechanisms: (1) tie uplift and (2) hanging ties. Tie uplift is when the weight of the vehicle causes the rail between the axles to uplift, which often causes the tie to uplift as well. This tie uplift mechanism can occur from longer train car lengths and heavier car weights, and situations in which tie uplift from train cars can occur are generally known (Kish & Samavedam, 2013). The effect of tie uplift on lateral tie resistance is the removal of the bottom interface component ($\beta 1$ in Section 6.2), which entails a reduction in lateral tie resistance of 30–40%.

Hanging ties occur when the ballast underneath the tie settles and the bottom of the tie no longer contacts the ballast, generally in unloaded situations. The effect of hanging ties is more difficult to identify, but hanging ties are often located at locations with surface profile defects, so track geometry thresholds can be used for identification. To be conservative, hanging ties can be assumed off any fixed structure, such as a bridge, turnout or roadway crossing.

6.6 Summary of parameters

Figure 13 shows the influence of the lateral tie resistance parameters in relation to each other. The results are presented as the percentage change from a baseline of new ballast, wood ties and full ballast section. The results show that, while many of the factors have similar



Source(s): Authors' own work

Figure 13. Influence of each lateral tie resistance parameter from baseline of new ballast, wood ties and full ballast section

influences, there does not appear to be a single dominant influence for all the factors. This means that higher-risk instances will likely involve a multiple of situations (e.g. recently maintained, low ballast section and hanging ties). Alternatively, this also means that there are multiple options for increasing the lateral tie resistance.

7. Discussion

This section discusses the results from Sections 4 through 6 and provides interpretation that can be used for practical applications.

7.1 Compaction and lateral strength

Regaining ballast compaction after maintenance is important for reducing track buckling risks. Tamping reduces the lateral strength by about 40%. Speed restriction tonnage can increase lateral strength by 10–20% (regaining 25–50% of loss), and DTS increases lateral strength by 15–35% (regaining 37.5–87.5% of loss).

With regard to track buckle risk, the amount of recompaction needed (if any) to reasonably prevent buckles will vary by situation because of the influence of other track buckle strength components (e.g. fasteners, RNT and rail temperature). However, since it is difficult to measure the other track buckle parameters, this also makes identifying high-risk situations difficult. Therefore, speed restrictions and re-compaction are useful as a "blanket risk reduction method" until the other track buckle parameters can be more reliably measured and the high-risk situations that require ballast re-compaction can be identified. In addition, it is unclear how initial compaction affects non-buckling aspects such as misalignments.

7.2 Different ballast maintenance

All the available STPT studies used tamping as the ballast maintenance method. Tamping is expected to disrupt the tie/ballast interface from the lift as well as disturb the ballast with the tamping tines.

Other maintenance activities are anticipated to disrupt the ballast in different manners; therefore, each will have different post-maintenance lateral tie resistances. Tie replacement will fully disturb the tie/ballast interface of replaced ties (but will likely have minimal impact on non-replaced or adjacent ties). Thus, the lateral resistance will vary from tie to tie. The implications of this, besides an average or conservative assumption, are not well known. Undercutting, track lifting or new construction will fully disrupt the track and likely have lower post-maintenance strength values.

Shoulder ballast cleaning itself should only disturb the ballast in the shoulder as well as the ballast underneath the tie end from the scarifier, which is the smallest contributor of strength (~20%). In addition, shoulder cleaning is often performed in fouled ballast, which can provide higher lateral resistances when dry. However, if cleaning is in tandem with tamping, there could be additional disruption and lower lateral strength values.

7.3 Measurable and non-measurable parameters

Measuring the lateral tie resistance with STPTs involves significant track disruption. Therefore, it is helpful to be able to estimate the lateral resistance using other measurable parameters, especially outputs from track inspection vehicles. However, while some parameters (e.g. tie type, compaction, ballast section and even tie movement and hanging ties) can be easily measured and documented, this is not the case for other factors, such as ballast condition and tie/ballast friction, which cannot be reliably measured at scale. Unfortunately, these two factors have a significant influence on lateral resistance. To account for this uncertainty, degraded conditions could be conservatively assumed, and then higher values used in the track with more confidence in the ballast and tie condition.

Given the limitations of current technologies, it is unlikely that the ballast and tie/ballast interface characterization will become reliable and scalable in the near future. Visual technologies may be able to assess surface ballast particles, but there is always the uncertainty of different particles underneath the surface cover.

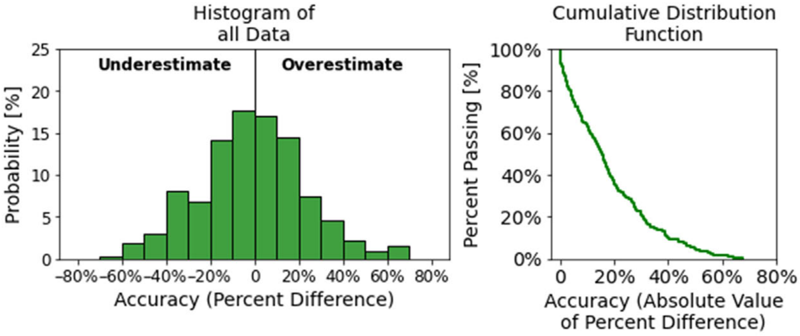
7.4 Lateral tie resistance model

If tie type, compaction, ballast section and whether a tie is hanging are all known, existing datasets can provide reasonable estimates of lateral tie resistance. This would involve assuming a base value based on ballast and tie characteristics (Section 6.3) and then adjusting based on compaction (Section 5), ballast section (Section 6.2) and hanging ties (Section 6.5). Additional adjustments can be made for situations with different track maintenance, tie movement or ballast fouling, but there are no measurable studies of those factors. As a note, while the track buckle strength is anticipated to be lower in curves, curvature was not found to be an important factor in the lateral tie resistance.

Figure 14 shows the difference between estimated (modeled) and measured lateral tie resistance. The results show about 60% of cases are within 20% accuracy, and 90% of cases are within 40% accuracy.

7.5 Track buckle risk

This paper laid out the various parameters affecting the lateral tie strength in the metric of "lateral tie resistance" and how they are anticipated to vary. This is useful in the tie/ballast



Source(s): Authors' own work

Figure 14. Accuracy of estimated versus measured STPT

context but requires additional analysis to compare tie/ballast parameter influence against other track buckling parameters, such as fastener rotational resistance, RNT, misalignment, train forces and rail temperature. A detailed analysis using a track buckling model is needed to do side-by-side comparisons.

8. Conclusions

Ballast maintenance is necessary for maintaining a healthy track structure and proper track geometry, but it can temporarily reduce the lateral track strength until the ballast can be recompacted from speed restriction tonnage or DTS. Between 2020 and 2023, MxV Rail compared the lateral tie strength increase from the two recompaction methods and found speed restriction tonnage (0.1 MGT) generally increased the strength from 10 to 20%, while the DTS increased from 15 to 35%. This means the DTS can be useful for ballast recompaction purposes and will reduce the need for speed restrictions. If speed restrictions are used, an equation is proposed by authors that relates the percent increase in lateral track strength with tonnage.

In addition to recompaction, there are multiple parameters that can affect the lateral tie resistance, including type of maintenance, tie type, ballast section, ballast particle characteristics, tie lift-off, tie/ballast interface and fouling. The range and influence for the majority of these parameters have been tested and documented.

Based on measurable parameters, it is recommended to assume a degraded ballast and tie condition, unless known otherwise, and then use adjustment factors to account for compaction, ballast section, hanging ties and tie movement. There are multiple options for ensuring a strong track structure besides ballast compaction. These options include maintaining an appropriate ballast section (0.45-m [18-in.] shoulders and full crib), selecting ballast with good particle characteristics, reducing hanging ties by maintaining track geometry and avoiding tie movement.

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