Research Article

TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
1–12

DOI: 10.1177/03611981231155170
journals.sagepub.com/home/trr
SAGE

# Review of Critical Factors Influencing Longitudinal Track Resistance

**Max Potvin[1], Marcus Dersch[1], J. Riley Edwards[1], and Arthur de O. Lima[1]**


## Abstract

Longitudinal track resistance is one of the most critical parameters required to accurately analyze longitudinal load propagation and refine rail neutral temperature (i.e., stress-free temperature) maintenance practices. However, longitudinal track resistance has not been consistently defined and has been quantified using multiple methods that should not be conflated. This paper documents common definitions of longitudinal track resistance and the two methods regularly used for its quantification: track panel pull test (TPPT) and single rail break (SRB). Further, this paper documents the differences in mechanics between these methods, summarizes and discusses the critical factors influencing the longitudinal track resistance values found in the literature, and adds novel TPPT longitudinal track resistance values for timber sleeper track to address the current scarcity of data found in the literature. In summary, TPPT values provide insight into the mechanics of load propagation and pre-buckle analysis while the SRB values aid in the maintenance and restoration of rail neutral temperature after a rail break or destress. Additionally, the TPPT longitudinal track resistance values reported in the literature were independent of panel length, were influenced most by the presence of a vertical load, and were reduced by 25% when the ballast was disturbed. Finally, novel TPPT results indicated the longitudinal resistance of timber sleeper track was 19% lower than concrete sleeper track and that unfastened sleepers still transferred longitudinal load when the cribs were full and ballast was compacted.



## Keywords

rail, railroad infrastructure design and maintenance, ballast, crossties, fastner, general, infrastructure, loads


Railroads utilize continuous welded rail (CWR) in most of their primary corridors. CWR is defined as any segment of rail that exceeds 122 m (400 ft) (*1*). CWR, by definition, is installed with fewer joints and in longer segments thereby requiring less maintenance (*2*) which saves the railroad operators time and money. Other benefits of CWR include the rail providing an improved ride quality, lower friction, longer rail life, and more strength when compared with jointed track (*3*, *4*). It is also widely considered to be safer than jointed track (*5*). However, because continuous strands of CWR can routinely stretch for multiple kilometers between joints (*6*), new CWR-specific challenges arise. These include management of rail buckle risk and rail neutral temperature (RNT)—also known as the stress-free temperature.

To address or mitigate these challenges, the rail industry leverages lateral and longitudinal track resistance values. Lateral resistance is an absolutely critical parameter required to perform an accurate buckle analysis and has been studied by many authors previously, a few of whom that can be cited here are Mohammadzadeh et al. (*7*), Kerr (*8*), Allen et al. (*9*), Esmaeili et al. (*10*), and Shenton (*11*). However, longitudinal resistance, which has been studied less, is also considered to be one of the most critical parameters required for longitudinal load propagation analysis (*12–14*) and RNT maintenance practices (*15–17*) in CWR track. Together, both the lateral and longitudinal track resistance provide stability to the track structure.

Longitudinal track resistance has not been objectively and consistently defined, given that researchers have had

[1]Rail Transportation and Engineering Center (RailTEC), Department of Civil and Environmental Engineering, Grainger College of Engineering, University of Illinois at Urbana-Champaign, Urbana, IL

**Corresponding Author:**
Marcus Dersch, mdersch2@illinois.edu

different purposes for quantifying it—for example, bridge-track interaction (*18*), quantifying track stability and rail creep (*19*), as well as longitudinal force quantification (*20*)—and did not appear to consider how others had previously defined the term. Further, longitudinal resistance has been quantified using multiple methods that should not be conflated with each other, though this has not been explored and discussed previously. And while it is understood that vertical loading and uplift from the wave action of the rail affects the longitudinal and lateral resistance and stiffness of track (*14*), accurate quantification of the range of longitudinal resistance values is required before considering the impact of train loading. Therefore, this paper documents common definitions of longitudinal track resistance, why it is a critical parameter, and how it has been quantified. Further, this paper documents the differences in mechanics between the two primary longitudinal resistance quantification methods, summarizes the longitudinal track resistance values found in the literature, and adds novel longitudinal track resistance values for track conditions with minimal data in the literature. These values can be leveraged by others in conjunction with advanced analytical models to quantify more accurate component loading demands when accounting for the presence of a train, or to predict a gap given a rail break event when the rail is in tension or compression.

## Motivation

Between 1999 and 2018 there were 250 Federal Railroad Administration (FRA)-reportable derailments on mainlines and sidings in the United States caused by “defective or missing spikes or rail fasteners” (*14*). Dersch et al. (*14*) found that most fastening system failures are a result of a combination of vertical, lateral, and longitudinal loads and that there is a current disconnect between the demands and component’s design strength. This disconnect has led to a variety of fastening system failure modes (*14*). Researchers have leveraged longitudinal resistance and stiffness values found in the literature to quantify the longitudinal loads placed on infrastructure components (*13*, *14*, *21*) using various analytical models, with each concluding that more research quantifying longitudinal track resistance values was needed to accurately quantify demands under other track conditions.

Previous researchers (*22*, *23*) have analyzed the FRA reportable derailments in greater detail to better quantify the risk associated with a given accident cause. One method they have used is plotting the frequency (i.e., number of derailments per a given tonnage) and severity (i.e., the average number of cars derailed given an accident) of these reportable derailments. When reviewing the data presented in this fashion, derailment causes with

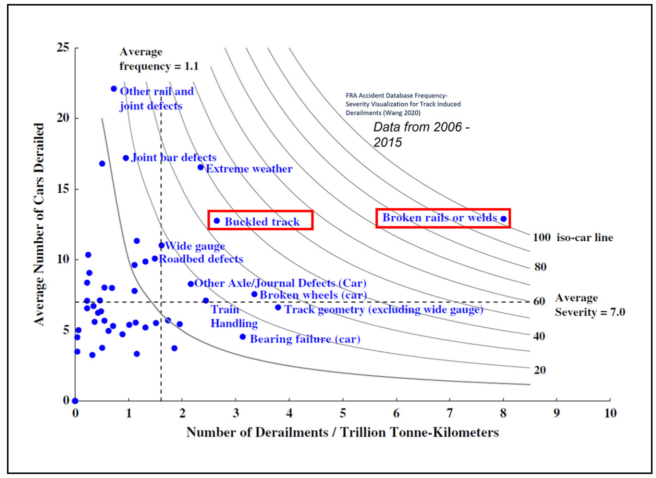


**Figure 1.** Frequency versus severity graph for Federal Railroad Administration accident cause codes (*23*).
*Note*: Dotted lines represent the average severity and average frequency of accidents. Iso-car contour lines are used to show levels of equivalent risk.

greater frequency and severity pose greater risks and thus should identify areas where research could focus. Most recently, Wang et al. (*23*) demonstrated that outside of extreme weather events (e.g., floods), buckled track and broken rails or welds were the two highest risk accident causes of freight derailments on Class 1 railroads between 2006 to 2015 (Figure 1). Therefore, there is the potential for more accurate longitudinal resistance values to improve current rail buckle analysis software (*12*, *24*) and RNT maintenance (*16*). Further, though not every rail break is a result of excess tensile axial stresses causing a pull-apart, each rail that breaks must have its RNT restored, which, if done improperly, could increase the probability of a pull-apart or buckle in the future.

## Longitudinal Track Resistance Definitions and Quantification Methods

Longitudinal track resistance is a measure of longitudinal force per unit distance provided by the ballast, sleepers, fasteners, and rail (*25*). The prevalent definitions of longitudinal track resistance are related to the method of quantification. Track panel pull test (TPPT) and single rail break (SRB) are the two most common methods used to quantify longitudinal track resistance. The following sections provide an overview of the definitions as presented in the literature as well as descriptions of both methods.

### Definitions

Longitudinal resistance from TPPT has primarily been derived in one of three ways, all leveraging the maximum force extracted from a load versus the displacement curve:

- for the total panel, for example kN (lb) (*20*),
- divided by the number of sleepers within the panel, for example kN/sleeper (lb/sleeper) (*26*), or
- divided by the length of the panel leading to a force per unit length of track, for example kN/mm (lb/in.) (*18*).

Because the force required to move a panel increases with the length of the panel and tighter sleeper spacing, it is necessary to standardize and normalize the values found in the literature. Furthermore, loads are applied to rails independently, and when a rail breaks in the field, only a single rail moves. Therefore, for consistency, all values in this paper are presented as a force per length per rail seat. For example, De Iorio et al. (*26*) report a longitudinal resistance value of 9.39 kN/sleeper (2,111 lb/sleeper) which, when accounting for a 0.6 m sleeper spacing and distributing the resistance over both rail seats, is converted to 7.82 kN/m (44.7 lb/in.) per rail seat (Equation 1). Because all TPPT longitudinal resistance values in this report will use values per rail seat, the term "rail seat" is hereafter omitted.

$$9.39\ \frac{kN}{sleeper} * \frac{1\ sleeper}{0.6\ m} * \frac{1\ sleeper}{2\ rail\ seats} = 7.82\ \frac{kN}{m} = f_{0_{TPPT}} \quad (1)$$

Similarly, SRB longitudinal resistance has also largely been calculated using one of three methods, leveraging a combination of key track variables (e.g., longitudinal rail force, rail gap on break, the RNT profile before the break, the influence zone caused by the break). These methods are listed below from most to least accurate and consist of:

1. quantifying the change in force caused by a rail break in a single rail over a sufficient length of track (Equation 2),
2. relating rail break gap size and temperature change at rail break ($dT$) (Equation 3), and
3. relating the influence zone ($L_d$) and $dT$ (Equation 4).

$$f_o = (m - \lambda) \quad (2)$$

$$f_o = [(dT^2 * EA\alpha^2)/RM] - \lambda \quad (3)$$

$$f_o = EA\alpha * dT/L_d \quad (4)$$

where

$f_o$ = SRB longitudinal resistance,

$m$ = the slope of the change in force over distance from longitudinal rail circuits,

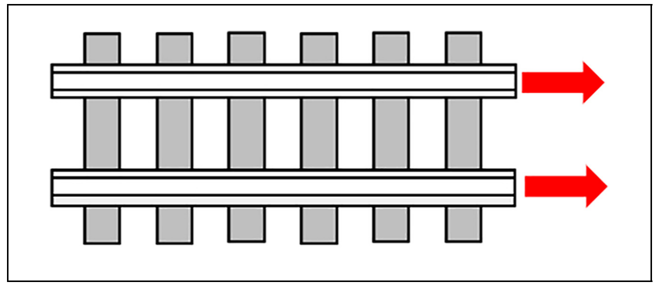

**Figure 2.** Example plan view schematic of track panel pull test.

$\lambda$ = the slope of the in-situ force over distance before the rail break,

$dT$ = the temperature differential between the pre-break RNT and rail break temperature,

$E$ = the modulus of elasticity for steel,

$A$ = the rail cross-sectional area,

$\alpha$ = the coefficient of thermal expansion of rail,

$RM$ = rail movement caused by the rail break, and

$L_d$ = the longitudinal zone of influence.

The non-broken rail is largely unaffected by the rail break (*4*). Therefore, the calculated values of SRB longitudinal resistance are not divided by two given they already represent a force per length per rail seat.

For research purposes, quantifying the change in force over a sufficient length of track is the most accurate method for calculation of longitudinal track resistance (Equation 2), given the other two methods require additional assumptions. Conversely, Equation 3 is the rail industry's preferred method, given that rail movement is a value that can be easily quantified in the field, as opposed to knowing the pre-break RNT or change in force over distance without the use of externally mounted gauges. This method, however, not only requires the knowledge—or estimation—of the pre-break RNT, but also assumes the RNT to be uniform before the break (i.e., $\lambda = 0$). Equation 4 is the least practical as it requires a known influence zone and $dT$ to determine the resistance.

## *Execution of TPPT*

The TPPT is the most common experimental method used to quantify longitudinal track resistance, primarily via laboratory testing. Performing a TPPT involves applying a longitudinal load to a track panel (typically four to 10 sleepers) (*18*, *19*, *26–29*) (Figure 2). Outliers to this relatively short panel setup were Mohammadzadeh et al. (*7*) who utilized a 108-sleeper panel and Liu et al. (*30*) who utilized a single sleeper push test arranged within a five-sleeper panel. All but one of the 15 studies that performed TPPTs used concrete sleepers, which is not surprising given that concrete is the most common sleeper material used in Europe and China where the

**Table 1.** Summary of Differences in Mechanics Between Track Panel Pull Test and Single Rail Break Longitudinal Resistance Tests

| Characteristic | Track panel pull test | Single rail break |
|---|---|---|
| Number of rails loaded | Two | One |
| Loading method | Quasi-static (>1 s) | Dynamic short impulse (<0.1 s) |
| Rail motion | Rigid body motion | Deformable body |
| Sleeper skew | Not present | Present |
| Torsional resistance | Not present | Present |
| Ballast movement | Particles within panel bounds experience rigid body motion | Particle movement is a function of distance from gap, engagement of fastener with sleeper, load duration, and so forth |
| Longitudinal resistance profile | Constant throughout | Changes along the length of the rail |

studies were performed. Although the specifics of any experiment are unique to each test, all TPPTs have the same scope of applying a symmetric force to both rails of a track panel and monitoring the panel displacement. The force is increased until it plateaus, or reaches a maximum value, as the panel begins to slide through the ballast. Researchers have noted that ballast plays a significant role in the track resistance (*26*). As such, a well-designed experiment must include resetting the ballast between loading applications to obtain repeatable results.

### Execution of SRB Test

Samavedam et al. (*31*) are the only researchers that are known to have quantified longitudinal resistance via a SRB test. In their experimentation, they instrumented 366 m (1,200 ft) of tangent CWR timber sleeper track at the Transportation Technology Center in Pueblo, CO (TTC). With the goal of simulating a rail break via a large longitudinal tensile force, the RNT was intentionally set high, and cuts occurred in the coolest part of the day to create large tensile loads at the time of break. To reset the track between tests, the track was deanchored over the zone of influence before pulling the rail back together. To give accurate force, displacement, and temperature profiles over the entire experimental section, 96 stress modules (i.e., rail strain gauge circuits that quantified the axial force), 96 longitudinal displacement transducers, and 52 temperature gauges were installed. Data were recorded before and immediately after the cut, after deanchoring, and after the rail temperature increased from solar heating. Rail cuts occurred when the axial tensile forces ranged between 400 and 860 kN (90–190 kips) and the longitudinal resistance values were quantified using Equation 2.

In addition to SRB conditions being more representative of an in-service rail break, another advantage of the SRB test is the ability to study directly the influence zone of a rail break given different track conditions. A typical value for an influence zone is in the order of tens to hundreds of meters (*16*), which is not typically feasible for a TPPT.

### Differences Between TPPT and SRB Experiments

Before reporting research results from the literature, further examination of the mechanics of both the TPPT and the SRB is needed. TPPT should be recognized in its context; it can provide valuable insight into force propagation for a non-broken rail (i.e., pre-buckle analysis). Further, as the test is more economical to construct and operate, TPPT results can inform the selection and range of variables for inclusion in more sophisticated and expensive SRB testing. However, the longitudinal resistance values from TPPTs should not be directly compared with values from a SRB test because of several important differences in their underlying mechanics (Table 1).

First, the TPPT loads both rails symmetrically while a SRB (un)loads one rail while the other remains largely unaffected (*4*), as previously mentioned. In response to the symmetric loading, the track panel will move as a rigid body, which is not representative of a revenue-service rail break. The asymmetric loading of the rails in a SRB will produce sleeper skew and thus engage a fastener's torsional resistance (*8*), which does not occur during a TPPT. By engaging the torsional resistance, the total longitudinal resistance experienced by one rail of the track will be higher than if it were not engaged.

Second, the loading rate of the TPPT is significantly different than the SRB. That is, the TPPT load is applied over multiple seconds, which ensures inertia does not affect the results, whereas the SRB releases a tensile or compressive member in less than 0.1 s, which could influence the slip interface. The TPPT's slower rate allows for the force (and energy) to fully transfer to all elements in the load path (i.e., from the rail to the fastener to the sleeper and to the ballast) and thus ensures slip occurs at the weakest interface (e.g., sleeper–ballast) (*14*). This was evident from every other sleeper (EOTA) TPPT experiments (discussed in more detail later in this paper) which demonstrated that sleepers that were not even fastened to the rail moved rigidly with the full panel, which does not always occur during a SRB test (Figure 3). Additionally, experience with SRBs indicates that slip can occur at the rail–

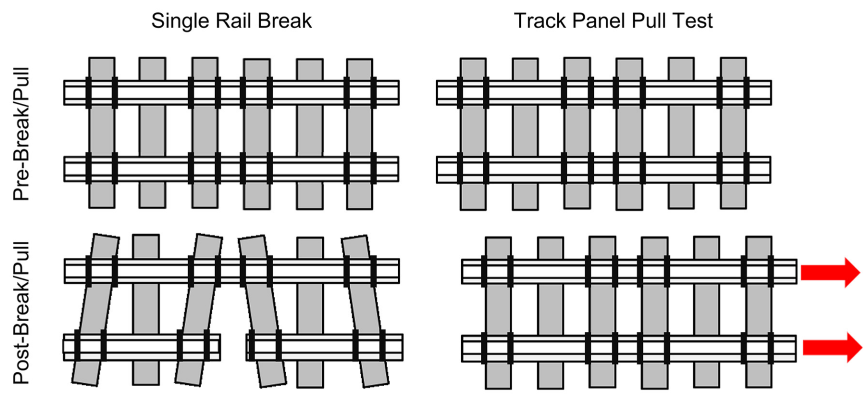


**Figure 3.** Comparison of example sleeper movement of timber sleeper track with variable spaced anchors leading to sleeper skew in the single rail break (SRB) test and rigid body motion in the track panel pull test (TPPT).

**Table 2.** Overview of Section Topics Including What Is Investigated and Key Notes (e.g., Number of Samples in Each Comparison or Length of Panels Investigated)

| Section | Quantification of | Notes | | |
|---|---|---|---|---|
| | Expected range | A total of 35 TPPT $f_{o,\text{panel}}$ values were found and reported from 15 studies | | |
| TPPT literature | Impact of vertical load | Present, n = 5 | Not present, n = 22 | |
| | Impact of panel length | Panels ranged from 4 to 108 sleepers | | |
| | Impact of ballast condition | Undisturbed, n = 13 | Disturbed, n = 3 | Frozen, n = 1 |
| | Impact of sleeper type | Only two timber TPPT studies were found | | |
| SRB literature | Impact of fastening system | Focused SRB studies with average value from multiple tests reported | | |
| Novel TPPT | Impact of fastening system | Three replicates were run for each test (i.e., ETA and EOTA) and the average reported | | |

*Note*: SRB = single rail break; TPPT = track panel pull test; ETA = every sleeper anchored; EOTA = every other sleeper anchored.

fastener and sleeper–ballast interfaces (*32*). This is likely because the impulse is too short to consistently allow for adequate force transfer from rail to fastener and from sleeper to ballast because of the mass of the sleepers and ballast, system damping, and reductions in friction (i.e., static to dynamic) at the rail–fastener interface.

These differences do not disqualify the utility of TPPT results but do require them to be placed in the proper context (i.e., longitudinal resistance values obtained via a TPPT should not be interchanged with the longitudinal resistance quantified via a SRB test). As a result, TPPT values are labeled differently ($f_{0_{TPPT}}$) than SRB results ($f_o$). In summary, TPPT values provide insight into the mechanics of load propagation and pre-buckling analysis while SRB values aid in RNT maintenance and restoration after a rail break.

## Literature Review of TPPT and SRB Longitudinal Resistance Values and Novel TPPT Results

The following sections provide an overview of the longitudinal resistance values found in the literature that leveraged TPPTs and SRBs as well as providing novel TPPT results executed for this study. Specifically, the TPPT literature section provides an overview of the longitudinal resistance values quantified by TPPTs, quantifies the impact of vertical load on resistance and location of slip interface, and quantifies the effect of panel length and ballast condition. Because TPPT longitudinal resistance investigations have almost exclusively focused on concrete sleepers, there is limited opportunity to quantify the impact of sleeper and fastener type—two of the key parameters expected to affect longitudinal resistance—on TPPT longitudinal resistance results. Therefore, novel TPPT tests were run to quantify the impact of fastener and sleeper type. Finally, SRB literature values are reported and compared with the TPPT results. All of this is summarized in Table 2.

### *TPPT Literature*

A review of the literature found 15 studies that quantified longitudinal track resistance using a TPPT with values ranging from 3.24 to 30 kN/m (18.5–171.3 lb/in.) and a median resistance of approximately 8 kN/m (45 lb/in.). The factor that had the most significant influence on longitudinal resistance was the presence (or lack) of a vertical load (Figure 4).

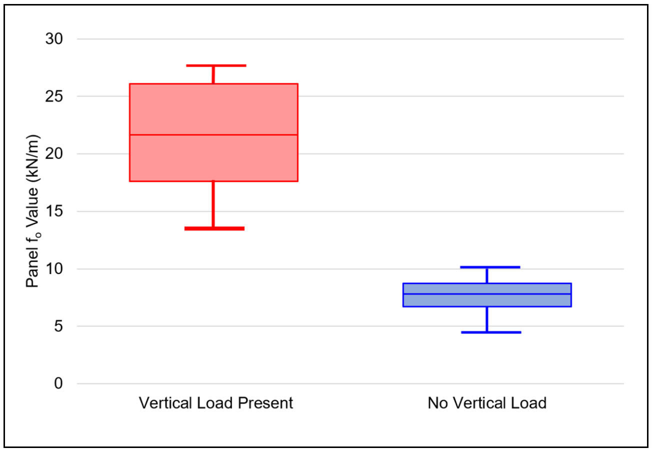


**Figure 4.** Variance in longitudinal resistance values across the literature separated by presence of vertical load (vertical load present: n = 5, no vertical load: n = 22).

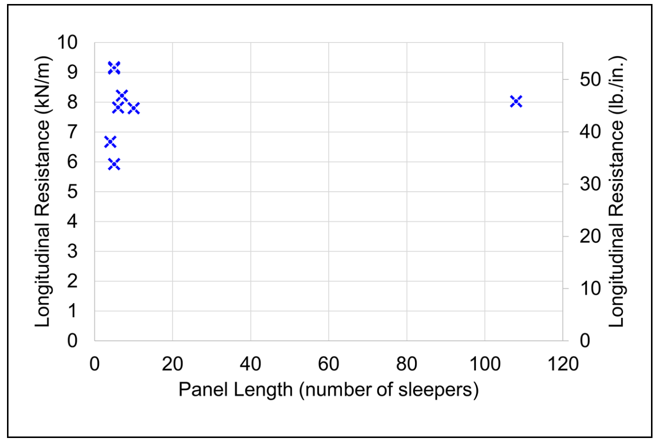


**Figure 5.** Longitudinal resistance for various panel lengths.

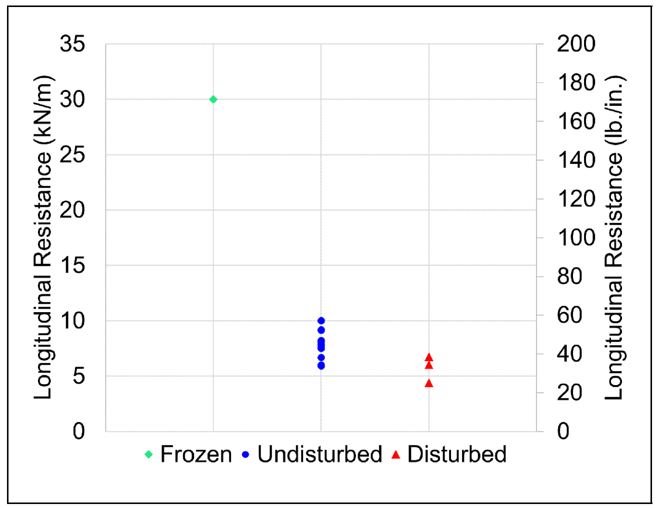


**Figure 6.** Longitudinal resistance values with various ballast conditions.

Not only did the value of median longitudinal resistance more than double with the presence of a vertical load (i.e., from 7.5 kN/m [42.8 lb/in.] to 15.5 kN/m [88.5 lb/in.]), but the location of slip also moved from the sleeper–ballast interface with no vertical load to the rail–fastener interface when a vertical load was present. Dersch et al. (*14*) documented that slip of the rail through a fastener occurs at approximately 11.1 kN (2,500 lb) while slip of the sleeper through the ballast occurs at just 3.6 kN (800 lb) when no vertical load is present. However, in every study that reported the application of a vertical load, slip occurred at the fastener (*18*, *33*). This is likely because the vertical load strengthens the sleeper–ballast interface by increasing the ballast engagement across the sleeper, thus increasing the force needed to overcome friction. Two other investigations, by Zand and Moraal (*29*) and Van (*24*), that studied loading the track panel in all three principal directions provide evidence that increasing vertical load results in increased longitudinal resistance. Further, Dieterman et al. (*33*) reported a linear relationship between applied vertical load and longitudinal slip capacity. The longitudinal resistance values for unloaded track ranged from 5 to 8.33 kN/m (28.5–47.5 lb/in.). The range in values likely stemmed from different sized concrete sleepers and variations in ballast types and conditions (*33*). When testing an unballasted track and forcing slip to occur at the rail–fastener interface, Dieterman reported values of 24 kN/m (137 lb/in.) with no vertical load present and 30 kN/m (171.2 lb/in.) with an 80 kN/m (455 lb/in.) vertical load.

The impact of panel length was investigated using eight of the longitudinal resistance values from panels that were constructed using concrete sleepers, had no vertical load and undisturbed ballast (Figure 5).

The panel lengths in this subset of data ranged from four to 108 sleepers. The median longitudinal resistance of this subset of data was 8.03 kN/m (45.9 lb/in.) which is also the value of the 108-sleeper panel. Therefore, it appears that TPPT longitudinal resistance is independent of panel length. Thus, shorter panels can be used to acquire accurate data when quantifying the longitudinal resistance using TPPTs while minimizing cost.

The effect of ballast condition was investigated using 19 of the longitudinal resistance values from panels that were constructed using concrete sleepers, had no vertical load and ballast that was either frozen, undisturbed, or disturbed (e.g., previous testing without vibration or compaction) (Figure 6).

Though the number of samples are very low for the frozen and disturbed ballast conditions (i.e., one and three, respectively), there appears to be a quantifiable impact on longitudinal resistance. The median longitudinal resistance is 8.0 kN/m (45.9 lb/in.) for undisturbed ballast and 6.0 kN/m (34.3 lb/in.) for disturbed ballast, a 25%

reduction. This aligns with expectations that disturbed ballast would have a lower strength, given there would be less interlock between particles and the ballast section would have a lower density. And while it is only a single data point, the longitudinal resistance of frozen ballast is more than three times greater than that of undisturbed ballast. Though tested in a different configuration, this aligns with the findings of Liu et al. (*30*) that ballast resistance was very sensitive to temperature variation and that freezing could increase the resistance of the ballast. Therefore, load transfer will be affected by ballast condition, as will the gap size when a rail break occurs.

Queiroz (*28*) and Samavedam et al. (*25*) are the only two studies in the literature that performed TPPTs on non-concrete sleepers. Of the various sleeper types studied by Queiroz (*28*), prestressed concrete sleepers had the largest resistance followed by concrete bi-block, timber, and steel. Samavedam et al. (*25*) found that crib ballast level significantly affected the longitudinal resistance with a 50% reduction in crib height leading to an approximate 50% reduction in longitudinal resistance. They also confirmed that unconsolidated ballast reduced the longitudinal resistance by approximately 25% (i.e., from 10.16 kN/m to 7.44 kN/m [58.0 lb/in. to 42.5 lb/in.]).

## SRB Literature

As mentioned above, Samavedam et al. (*31*) are the only researchers who have quantified longitudinal resistance via the SRB methodology. Using instrumentation that was placed over 366 m (1,200 ft) of tangent CWR track at TTC, they quantified the longitudinal resistance of timber sleeper track with two fastening system arrangements: every sleeper anchored (ETA) and every other sleeper anchored (EOTA). The average longitudinal resistance with EOTA was 3.0 kN/m (17 lb/in.) which was approximately 57% of the resistance with ETA, 5.3 kN/m (30 lb/in.). These longitudinal resistance values are lower than the TPPT values at the same location reported by Samavedam et al. (*25*) and thus provide empirical evidence that TPPT data should not be conflated with SRB data without additional information.

While the literature provided quantifiable values to assess the influence of load level and ballast condition, additional research is needed to better understand the impact of sleeper type, fastening system type and condition, ballast fouling, and moisture levels.

## Novel Laboratory TPPT Experimentation

To expand on previous research into longitudinal resistance values, additional TPPT experimentation was conducted by the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign (Illinois). This work adds to the literature by testing a timber sleeper panel, which is representative of the more than 90% of rail track in the United States that is constructed with timber sleepers (*34*). These tests were performed on Illinois' Track Loading System (Figure 7), a multi-axis load frame designed to test track panels with realistic ballast, sub-ballast, and subgrade support. Axial loads were mechanically applied to the rail using a hydraulic actuator with a 156 kN (35 kip) load cell and 152 mm (6 in.) Linear Variable Differential Transformer mounted on the actuator.

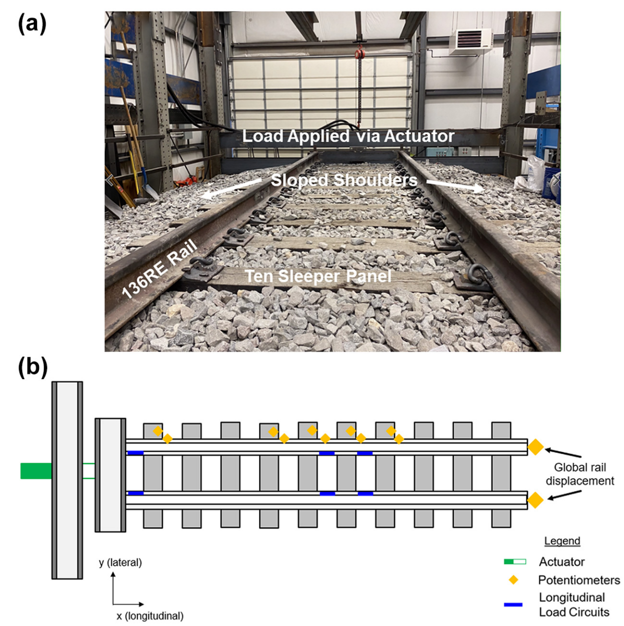


**Figure 7.** (*a*) Timber sleeper track panel constructed with 136 RE rail, AREMA 4A ballast, full cribs and shoulders, 460 mm (18 in.) plates with four spikes per plate and elastic fasteners, and (*b*) overview of track panel instrumentation.

The Illinois track panel consisted of 136RE rail and 10 2.6 m (100 in.) timber sleepers, spaced at 500 mm (20 in.) on center. All the sleepers had 457 mm (18 in.) plates with four spikes per plate. Further, sleeper anchor patters were either ETA or EOTA, the two most common arrangements used in North America. The panel had full ballast cribs and 300 mm (12 in.) ballast shoulders from the sleeper end with a 2:1 slope. TPPTs were conducted in displacement-control (i.e., the actuator applied the load to the panel at a constant 101 mm/min. [4 in./min.] rate of displacement). It was assumed that every test fully disturbed the ballast and thus, between each trial, a tamping rammer vibratory compactor was used to recompact the ballast in each crib and on the shoulders before running the subsequent test. The compaction was completed using a tamping rammer with a 328 mm by 280 mm (12.9 in. by 11 in.) shoe that could fit in the cribs

**Table 3.** Summary of Longitudinal Resistance and Longitudinal Stiffness Values From Present Study

| Recorded value | Every tie anchored (ETA) | | | | Every other tie anchored (EOTA) | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | Average | 1 | 2 | 3 | Average |
| Longitudinal resistance, $f_o$ (kN/m) | 6.2 | 6.2 | 6.4 | 6.3 | 6.3 | 6.0 | 6.0 | 6.1 |
| $f_o$ (lb/in.) | 35.5 | 35.4 | 36.4 | 35.8 | 36.1 | 34.5 | 34.5 | 35.0 |
| Longitudinal stiffness, $k_a$ (kN/m) | 16.2 | 16.0 | 14.9 | 15.7 | 15.5 | 14.0 | 14.4 | 14.7 |
| $k_a$ (lb/in.) | 92.8 | 91.6 | 85.3 | 89.9 | 88.6 | 80.2 | 82.4 | 83.7 |

*Note*: ETA = every sleeper anchored; EOTA = every other sleeper anchored.

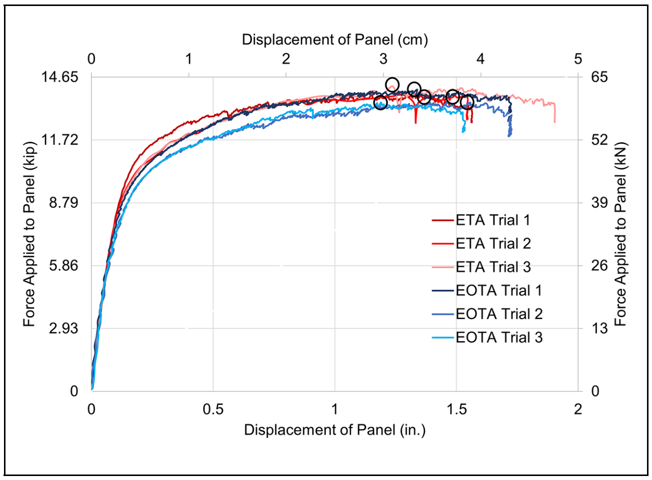


**Figure 8.** Load versus displacement for each track panel pull test (TPPT) trial from present study.

of the constructed track. The tamper provided approximately 700 blows per minute (bpm) with each blow providing 17 kN (3,800 lb). The tamper was operated at approximately 10 ft per minute. This provided sufficient force and vibration to ensure the ballast was recompacted and at the same level within the cribs and on the ends of the sleepers.

Three replicates were performed for each experimental condition to quantify the load and displacement variability (Figure 8). Each trial's maximum load is marked with a black circle in Figure 8 and the longitudinal resistance was calculated using Equation 1 (Table 3). To provide additional value, the panel stiffness ($k_a$) was also quantified and is presented in Table 3, given that this is a critical value as mentioned by Dersch et al. (*14*). The stiffness was calculated by taking a linear regression of the data from the origin through 50% of the maximum observed load. This value was selected as it provided a representative elastic response that could then be used for future load transfer analyses.

The data indicate repeatable tests with acceptable variability; the maximum difference between the longitudinal resistance of any given trial and the average value was 3%. Therefore, the average longitudinal resistance for the ETA and EOTA arrangements for the timber sleeper track were 6.3 kN/m (35.8 lb/in.) and 6.1 kN/m (35.0 lb/in.), respectively.

The most noteworthy finding from this laboratory experimentation is the similarity of longitudinal resistance values between the ETA and EOTA configurations (i.e., only a 3% difference). This can be contrasted with the approximately 57% difference recorded in the SRB study of Samavedam et al. (*31*). The TPPT results do not indicate that fastening system affects resistance, yet the SRB tests do, which provides further evidence that results from each test method (i.e., TPPT versus SRB) should not be conflated with one another. One additional outlier is when comparing the TPPT results for timber sleepers, good ballast, and ETA, where the present study values are 38% lower than those reported by Samavedam et al. (*25*) (i.e., 6.29 kN/m [35.9 lb/in.] versus 10.16 kN/m [58.0 lb/in.]). The Samavedam TPPT value is actually an outlier relative to all other reported results in that it is greater than all values that do not include an applied vertical load—including concrete sleepers. Furthermore, because the report does not detail the methods, the actual cause of the difference cannot be determined. The recent experimental TPPT data indicate that longitudinal resistance is largely independent of anchoring pattern when the anchors are fully engaged with the sleepers, the cribs are full, and ballast is well compacted. Therefore, the load is transferred from an anchored sleeper, through the ballast and unanchored sleeper, to the next anchored sleeper. When the longitudinal force was applied, the panel (sleepers and crib ballast) sheared through the ballast, rather than the rails slipping through the fasteners. This indicates that the fastener capacity for resisting longitudinal load is higher than the ballast capacity, as was expected by Dersch et al. (*14*). Given this, it can be hypothesized that the ballast level will be a critical factor on longitudinal resistance. This aligns with the data reported by Samavedam et al. (*25*) in that when the crib ballast level was reduced by 50%, the longitudinal resistance was also reduced by 50%. In total, the median longitudinal resistance of timber sleeper track found in

**Table 4.** Summary of Track Panel Pull Test (TPPT) Longitudinal Resistance Values

| Sleeper type | Vertical load[a] | Ballast condition | Fastening system[b] | Author | Panel length | $f_{o,panel}$ (kN/m) | $f_{o,panel}$ (lb/in.) |
|---|---|---|---|---|---|---|---|
| Track panel pull test (TPPT) | | | | | | | |
| Concrete | Yes | Good | EF | Dieterman et al. (33) | Unspecified | 17.60 | 100.5 |
| | | | | | | 27.60 | 157.6 |
| | | | | Nobakht et al. (20) | 5 | 26.10 | 149.0 |
| | | | | | | 18.78 | 107.3 |
| | | | | | | 25.03 | 142.9 |
| | | | | Zand and Moraal (29) | 5 | 27.12 | 154.9 |
| | | | | | | 21.67 | 123.7 |
| | | Disturbed | EF | Kerokoski (18) | 10 | 13.50 | 77.1 |
| | | | | | | 15.50 | 88.5 |
| Concrete | No | Good | EF | Dieterman et al. (33) | Unspecified | 6.00 | 34.3 |
| | | | | | | 10.00 | 57.1 |
| | | | | De Iorio et al. (26) | 6 | 7.82 | 44.7 |
| | | | | ERRI (35) | Unspecified | 7.58 | 43.3 |
| | | | | Esveld (36) | Unspecified | 9.17 | 52.3 |
| | | | | Kerokoski (18) | 10 | 7.80 | 44.5 |
| | | | | | | 8.20 | 46.8 |
| | | | | Markine and Esveld (12) | Unspecified | 7.50 | 42.8 |
| | | | | Mohammadzadeh et al. (7) | 108 | 8.03 | 45.9 |
| | | | | Nobakht et al. (20) | 5 | 9.13 | 52.1 |
| | | | | Queiroz (28) | 7 | 8.22 | 46.9 |
| | | | | UIC (21) | Unspecified | 10.00 | 57.1 |
| | | | | Xiao et al. (19) | 4 | 6.67 | 38.1 |
| | | | | Zakeri and Yousefian (27) | 5 | 5.92 | 33.8 |
| | | | | Zand and Moraal (29) | 5 | 9.17 | 52.4 |
| | | Various conditions | Not applicable | Liu et al. (30)[c] | 1 | 8.8–19.6 | 30–67 |
| | | Disturbed | EF | Kerokoski (18) | 10 | 6.72 | 38.4 |
| | | | | Xiao et al. (19) | 4 | 4.38 | 25.0 |
| | | | | UIC (21) | Unspecified | 6.00 | 34.3 |
| | | Frozen | | UIC (21) | | 30.00 | 171.3 |
| Timber | No | | EF | Queiroz (28) | 7 | 6.31 | 36.0 |
| | | Good | EOTA | Present study | 10 | 6.15 | 35.1 |
| | | | EOTA | Samavedam et al. (25) | 4 | 8.41 | 48.0 |
| | | | ETA | Present study | 10 | 6.29 | 35.9 |
| | | | ETA | Samavedam et al. (25) | 4 | 10.16 | 58.0 |
| | | Disturbed | ETA | Samavedam et al. (25) | 4 | 7.44 | 42.5 |
| | | | E3TA | Samavedam et al. (25) | 4 | 6.48 | 37.0 |
| | | Disturbed, 50% crib | EOTA | Samavedam et al. (25) | 4 | 3.24 | 18.5 |
| Bi-block | No | Unspecified | EF | Queiroz (28) | 7 | 7.70 | 44.0 |
| Steel | No | Unspecified | EF | Queiroz (28) | 7 | 5.70 | 32.5 |
| | | | | Single rail break | | $f_o$ (kN/m) | $f_o$ (lb/in.) |
| Timber | No | Good | EOTA | Samavedam et al. (31)[d] | Not applicable | 2.98 | 17 |
| | No | Good | ETA | Samavedam et al. (31)[d] | | 5.25 | 30 |

[a]It has been hypothesized (29, 33) that there is a linear relationship between magnitude of vertical loading and longitudinal resistance so the binary “loaded” and “unloaded” may be oversimplified.
[b]EF = elastic fastener; EOTA = every other sleeper anchored; ETA = every sleeper anchored; E3TA = every third sleeper anchored.
[c]Liu et al. (30) pushed a single sleeper within a four-sleeper panel and thus the resistance continued to increase as other unfastened sleeper engaged the fastened sleeper within the panel and thus the values are outliers on the high side.
[d]The Samavedam results are the only SRB tests. All other results come from a TPPT.

the literature and as reported in this study was 19% lower than the median concrete sleeper value reported in the literature (i.e., 6.5 versus 8.0 kN/m [37.0 versus 45.9 lb/in.], respectively). The stiffness results showed similar trends with only a 6% decrease in panel stiffness between ETA and EOTA (i.e., removing half of the anchors) from 15.7 to 14.7 kN (89.9 to 83.7 lb/in.), respectively.

## Summary of Longitudinal Resistance Values

All values obtained from the literature and from the present study are summarized in Table 4. The values are placed in their proper context by documenting the slip interface, presence or absence of vertical load, sleeper and fastener type, ballast condition, longitudinal resistance, and source. As discussed above, values from SRB tests are expected to differ from TPPTs. Therefore, though the values from the SRB have been included, all values should be used in their proper context.

With the introduction of torsional resistance, sleeper skew, and other items mentioned previously, one might expect that SRB longitudinal resistance values would only increase. However, the only SRB experimentation that has been performed (*31*) reports longitudinal resistance values below almost every reported TPPT value in the literature and in the present study, regardless of sleeper type. Of specific interest is that the SRB longitudinal resistance value for the EOTA condition by Samavedam et al. (*31*) is lower than even the timber sleeper EOTA track with half-filled cribs performed by Samavedam et al. (*25*) at the same location. This likely indicates that the SRB dynamic loading alters the load transfer mechanics compared with the TPPT.

## Conclusions

Longitudinal track resistance is one of the most critical input parameters that is required for longitudinal load propagation analysis and RNT maintenance practices. Improved accuracy in the quantification of longitudinal resistance can lead to fewer broken components and more appropriate CWR repairs after a rail break or destressing event. Therefore, this paper proposed a unified definition of longitudinal track resistance using force per length of rail per rail seat. Additionally, this paper discussed the two primary methods used to quantify the longitudinal track resistance and then detailed the differences in the mechanics and utility of each. Lastly, this paper, which is the first among a series of papers on this topic, summarized the longitudinal track resistance values found in the literature and added novel values for timber sleeper track which are presently underrepresented in the literature. Additional longitudinal resistance values from more extensive TPPTs and SRB trials are presented in subsequent papers to this.

Based on the material presented, the following conclusions were made:

1. Values from TPPT and SRB, the two primary methods for quantifying longitudinal resistance, should be used appropriately as different load transfer mechanics map to different applications:
   a. SRB values should be used for RNT maintenance practices and rail stress management
   b. TPPT values should be used for load propagation analysis
2. The literature indicated that SRB longitudinal resistance values were consistently lower than corresponding TPPT values
3. The literature review found that the TPPT longitudinal track resistance was:
   a. most significantly affected by the presence of a vertical load which also moved the interface of slip from the sleeper–ballast to the rail–fastener interface (i.e., median resistance increased by more than 100% when a vertical load was present)
   b. independent of panel length
   c. reduced by 25% when the ballast was disturbed
4. Novel TPPT results presented in this study indicate that:
   a. unfastened sleepers still transfer load when cribs are full and ballast is compacted, leading to negligible difference in longitudinal resistance between ETA and EOTA. This is in direct conflict with the SRB results indicating anchoring pattern (i.e., fastener engagement) has a significant impact on longitudinal resistance
   b. the longitudinal resistance of timber sleeper track was 19% lower than concrete sleeper track

No target design longitudinal resistance or stiffness value is yet available, however, the results from this study provide insight into how changes in track condition affect the longitudinal resistance. In practice, as presented by Dersch et al. (*14*), changes in longitudinal track resistance and stiffness can affect the force placed on a fastening system by between 6% and 24%. Further, as longitudinal resistance increases, the gap resulting from any rail break will decrease, so if the wrong longitudinal resistance value is assumed, the actual restored RNT would be different than the target value. Additional work is therefore needed to study the impact of longitudinal resistance and stiffness on track component loading and CWR stress management to reduce the accidents caused by failed components and buckle derailments.

### Acknowledgments

The authors would like to acknowledge the following project industry partners for supplying insight, recommendations, and materials to this study: BNSF, Union Pacific Railroad, Norfolk Southern Corporation, the U.S. DOT Volpe Center. Additional thanks to Dr. Andrew Kish for his consultations and insight into the topic of longitudinal resistance and rail neutral temperature.

### Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: M. S. Dersch, A. de O. Lima, J. Riley Edwards; data collection: M. Potvin, M. Dersch; analysis and interpretation of results: M. Potvin, M. Dersch; draft manuscript preparation: M. Potvin, M. Dersch, J. Riley Edwards.

All authors reviewed the results and approved the final version of the manuscript.

### Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

### Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research effort is funded by the Federal Railroad Administration (FRA), part of the United States Department of Transportation (U.S. DOT). J. Riley Edwards has been supported in part by grants to the Illinois Rail Transportation and Engineering Center (RailTEC) from CN and Hanson Professional Services.

### ORCID iDs

Marcus Dersch https://orcid.org/0000-0001-9262-3480
J. Riley Edwards https://orcid.org/0000-0001-7112-0956
Arthur de O. Lima https://orcid.org/0000-0002-9642-2931

### References

1. Federal Railroad Administration Track Safety Standards. *Federal Register*, Vol. 63, No. 119, 1998, p. 34037.
2. Albinović, S., and M. Hebib-Albinović. Continuously Welded Rail (CWR) Track Buckling and Safety Concepts. *Proc., 2nd International Conference on Road and Rail Infrastructure-CETRA*, Dubrovnik, Croatia, Department of Transportation Faculty of Civil Engineering, Zagreb, Croatia, May 7–9, 2012, pp. 649–655.
3. Kish, A., and G. Samavedam. *Risk Analysis Based CWR Track Buckling Safety Evaluations*. U.S. Department of Transportation's Volpe Center, Cambridge, MA, 2001.
4. Harrison, H. Managing the Longitudinal Forces in Heavy Haul Track. *Proc., International Heavy Haul Association*, Brazil, 2005, p. 6.
5. Railways: Use of Continuous Welded Rail. UK House of Lords Debates, 5 November 1969, Vol. 305, 1969, pp. 335–339. https://api.parliament.uk/historic-hansard/lords/1969/nov/05/railways-use-of-continuous-welded-rail.
6. Federal Railroad Administration. Track Safety Standards; Continuous Welded Rail (CWR); Final Rule. *Federal Register*, 2009. https://www.federalregister.gov/documents/2009/08/25/E9-20253/track-safety-standards-continuous-welded-rail-cwr.
7. Mohammadzadeh, S., M. Esmaeili, and F. Khatibi. A New Field Investigation on the Lateral and Longitudinal Resistance of Ballasted Track. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol. 232, No. 8, 2018, pp. 2138–2148.
8. Kerr, A. *Effect of Torsional Fastener Resistance on the Lateral Response of a Rail-Tie Structure*. Federal Railroad Administration Report No. FRA/ORD-78/35. U.S. Department of Transportation, Cambridge, MA, 1978.
9. Allen, D., G. Fry, and D. Davis. *Development of a Model for Describing Nonlinear Lateral Resistance of Track Ballast*. Report No. TD-16-029. Transportation Technology Center, Inc., Pueblo, CO, 2016.
10. Esmaeili, M., R. Nouri, and K. Yousefian. Experimental Comparison of the Lateral Resistance of Tracks With Steel Slag Ballast and Limestone Ballast Materials. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol. 231, No. 2, 2017, pp. 175–184.
11. Shenton, H. W. III. Analysis of Crosstie Track in Lateral Plane Using New Track Equations. *American Society of Civil Engineers Journal of Transportation Engineering*, Vol. 123, No. 3, 1997, pp. 202–208.
12. Markine, V., and C. Esveld. *Analysis of Longitudinal and Lateral Behaviour of a CWR Track Using a Computer System Longin*. Delft University of Technology, The Netherlands, 1998, p. 10.
13. Trizotto, M., M. S. Dersch, J. R. Edwards, and A. Lima. Analytical Elastic Modeling of Rail and Fastener Longitudinal Response. *Transportation Research Record: Journal of the Transportation Research Board*, 2021. 2675: 164–177.
14. Dersch, M. S., M. T. Silva, J. R. Edwards, and A. de Oliveira Lima. Analytical Nonlinear Modeling of Rail and Fastener Longitudinal Response. *Transportation Research Record: Journal of the Transportation Research Board*, 2022. 2676: 695–707.
15. Kerr, A. D. X. Miscellaneous Track Problems and Analyses. In *Fundamentals of Railway Track Engineering* (A. D. X. Kerr., ed.), Simmons Boardman, Omaha, NE, 2003, pp. 318–336.
16. Kish, A. Best Practice Guidelines for CWR Neutral Temperature Management. *Proc., American Railway Engineering and Maintenance-of-Way Association Annual Conference*, Indianapolis, IN, AREMA, Landover, MD, 2013, pp. 1004–1028.
17. Potvin, M., M. Trizotto, M. Dersch, J. R. Edwards, and A. de Oliveira Lima. A Review of Parameters Affecting Rail Break Gap Size Using Analytical Methods. *Proc., Joint Rail Conference*, Urbana, IL, ASME, Washington, D.C., 2021, p. 6.
18. Kerokoski, O. Determination of Longitudinal and Transverse Railway Track Resistance. *Proc., Joint Rail Conference*, Vol. 1, Urbana, IL, ASME, Washington, D.C., 2010, pp. 157–165. https://asmedigitalcollection.asme.org/JRC/proceedings/JRC2010/49064/157/347184. Accessed June 12, 2020.
19. Xiao, J., H. Liu, P. Wang, G. Liu, J. Xu, and R. Chen. Evolution of Longitudinal Resistance Performance of Granular Ballast Track With Durable Dynamic Reciprocated Changes. *Advances in Materials Science and Engineering*, Vol. 2018, 2018, pp. 1–11. https://www.hindawi.com/journals/amse/2018/3189434/.
20. Nobakht, S., J. A. Zakeri, and A. Safizadeh. Investigation on Longitudinal Resistance of the Ballasted Railway Track Under Vertical Load. *Construction and Building Materials*, Vol. 317, 2022, p. 126074.
21. UIC. Track/Bridge Interaction Recommendations for Calculations. 2001. https://global.ihs.com/doc_detail.cfm?item_s_key=00671424. Accessed June 16, 2020.

22. Liu, X., M. R. Saat, and C. P. L. Barkan. Analysis of Causes of Major Train Derailment and Their Effect on Accident Rates. *Transportation Research Record: Journal of the Transportation Research Board*, 2012. 2289: 154–163.
23. Wang, B. Z., C. P. Barkan, and M. Rapik Saat. Quantitative Analysis of Changes in Freight Train Derailment Causes and Rates. *Journal of Transportation Engineering, Part A: Systems*, Vol. 146, No. 11, 2020, p. 04020127.
24. Van, M. A. *Stability of Continuous Welded Rail Track*. Doctoral thesis. Technische Universiteit Delft, The Netherlands, 1997. https://repository.tudelft.nl/islandora/object/uuid%3Acf107693-5eed-410b-a879-450aec6ec383.
25. Samavedam, G., A. Kish, A. Purple, and J. Schoengart. *Parametric Analysis and Safety Concepts of CWR Track Buckling*. Final Report. Federal Railroad Administration, Washington, D.C., 1993.
26. De Iorio, A., M. Grasso, F. Penta, G. P. Pucillo, S. Rossi, and M. Testa. On the Ballast–Sleeper Interaction in the Longitudinal and Lateral Directions. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol. 232, No. 2, 2018, pp. 620–631.
27. Zakeri, J. A., and K. Yousefian. Experimental Investigation Into the Longitudinal Resistance of Ballasted Railway Track. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol. 235, No. 8, 2021, pp. 969–981.
28. Queiroz, R. C. *Longitudinal Track-Ballast Resistance of Railroad Tracks Considering Four Different Types of Sleepers*.Sao Paulo State University, Brazil, 2006. http://www.railway-research.org/IMG/pdf/275.pdf.
29. Zand, J. van 't, and J. Moraal. *Ballast Resistance Under Three Dimensional Loading*. Delft University of Technology, The Netherlands, 1998. https://esveld.com/Download/TUD/Ballast%20tests.pdf. Accessed April 4, 2021.
30. Liu, J., P. Wang, G. Liu, J. Dai, J. Xiao, and H. Liu. Study of the Characteristics of Ballast Bed Resistance for Different Temperature and Humidity Conditions. *Construction and Building Materials*, Vol. 266, 2021, p. 121115. https://www.researchgate.net/publication/344910894_Study_of_the_characteristics_of_ballast_bed_resistance_for_different_temperature_and_humidity_conditions.
31. Samavedam, G., J. Gomes, A. Kish, and A. Sluz. Investigation on CWR Longitudinal Restraint Behavior in Winter Rail Break and Summer Destressing Operations. *Federal Railroad Administration*, 1997. https://railroads.dot.gov/elibrary/investigation-cwr-longitudinal-restraint-behavior-winter-rail-break-and-summer-destressing. Accessed September 24, 2020.
32. Dersch, M., M. Potvin, and J. R. Edwards. Longitudinal Track Resistance: What it Is and Why it Matters. *Proc., FRA Track & Railroad Workplace Safety Symposium*, St. Louis, MO, April 7, 2022.
33. Dieterman, H. A., M. A. Van, A. J. P. Van Dam, and C. Esveld. Longitudinal Forces in Railroad Structures. *Rail Engineering International*, Vol. 1, 1990, pp. 16–19.
34. Wolf, H. E., S. Mattson, J. R. Edwards, M. S. Dersch, and C. P. L. Barkan. Flexural Analysis of Prestressed Concrete Monoblock Crossties: Comparison of Current Methodologies and Sensitivity to Support Conditions. Presented at 94th Annual Meeting of the Transportation Research Board, Washington, D.C., 2015. https://railtec.illinois.edu/wp/wp-content/uploads/Wolf-et-al.-2014-Flexural-analysis-of-prestressed-concrete-monobloc.pdf Accessed February 13, 2023.
35. ERRI DC. *Improved Knowledge of Forces in CWR Track (Including Switches)*. Research Project D202, European Rail Research Institute (ERRI), December 1997.
36. Esveld C. *Modern Railway Track*. Digital. La Couronne, Nouvelle-Aquitaine, France: MRT-Productions, 2014.

*The opinions expressed and material presented in this paper represent the position of the authors and not necessarily those of the sponsors.*