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Effect of Critical Factors Influencing Longitudinal Track Resistance Leveraging Laboratory Track Panel Pull Test Experimentation

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Abstract

There are, on average, 12.5 Federal Railroad Administration reportable derailments per year on U.S. mainlines and sidings caused by “defective or missing spikes or rail fasteners.” Because fastener failures are most commonly caused by a combination of vertical, lateral, and longitudinal loads, it is important to quantify all loads placed on the fasteners to reduce the number of failed fasteners and increase rail safety. Multiple researchers have developed analytical models that leverage longitudinal track resistance and stiffness to quantify the fastener demands. Therefore, to support the refinement of these analytical models that leverage longitudinal track resistance and stiffness, track panel pull tests (TPPTs) were executed in the laboratory to expand on the values within the available literature. These TPPTs quantified the effect of sleeper type (i.e., timber versus concrete), given that 88% of previous studies have focused on concrete. Further, these novel tests quantified the effect of the fastening system, crib ballast height, shoulder width, and ballast condition on the panel’s longitudinal resistance and stiffness. From these experiments and the resulting analysis of data, multiple conclusions were drawn. For example, concrete sleeper panels exhibit 20% higher resistance than timber sleeper panels, disturbing ballast reduced the longitudinal resistance by 13% and stiffness by approximately 80%, and the crib, shoulder, and bottom ballast provide approximately 65%, 5%, and 30% of the total longitudinal resistance, respectively.

Keywords

railroad infrastructure design and maintenance, ballast, crossties, longitudinal loads, track, lab experimentation

A review of Federal Railroad Administration (FRA) accident data from U.S. mainlines and sidings between 1999 and 2018 reveals an average of 12.5 derailments per year caused by “defective or missing spikes or rail fasteners” (*1*). To address these derailments and contribute to the rail industry’s goal of eliminating track-caused derailments in general, there is a need to improve the design methodology for fastening systems to mitigate failures. Because fastener failures are most commonly caused by a combination of vertical, lateral, and longitudinal loads (*2*), it is important to quantify all loads placed on the fasteners. Dersch et al. (*2*) reported that longitudinal loads contribute to many of the most commonly observed fastening system failures (e.g., broken spikes, rail seat deterioration, broken direct fixation hold-down rod), but longitudinal loads are the least quantified and have been the subject of comparatively little research (*3*). Therefore, to address this research void and quantify fastener loading demands, researchers have developed and leveraged analytical models (*2*, *4–7*). Many of these researchers are using longitudinal track resistance and stiffness values found in the literature. Based on a review of the literature by Potvin et al. (*8*), 14 of 16 (88%) studies that leveraged track panel pull tests (TPPTs) to quantify the longitudinal resistance and/or stiffness studied concrete sleeper

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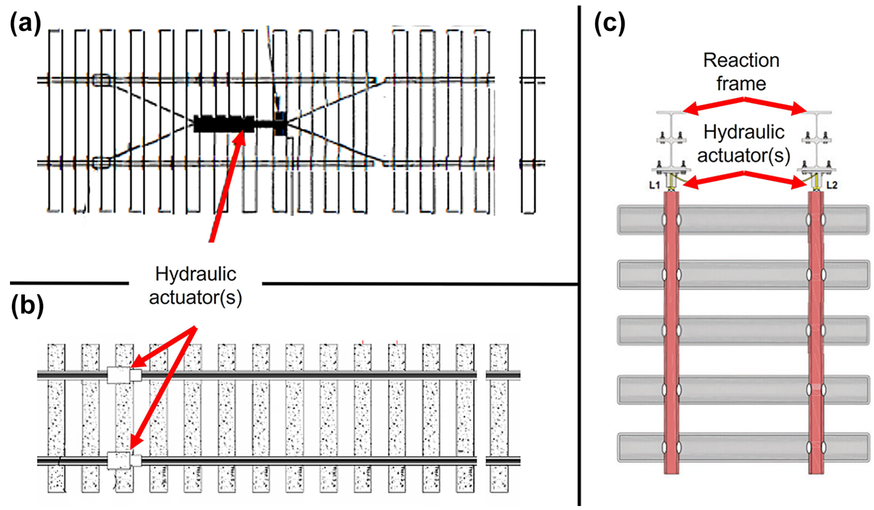


Figure 1. Example track panel pull test schematics for the field (*a*), (*b*) and the lab (*c*) with panel lengths varying from four to ten sleepers (*10*, *14*, *18*).

tracks (*9–19*). However, because 90% of North American track is constructed using timber sleepers (*20*), there is a need for additional longitudinal track resistance and stiffness data for timber sleeper tracks to support these analytical models.

TPPTs and single rail breaks (SRBs) are the two most common methods used to quantify the longitudinal track resistance and stiffness (*8*). Potvin et al. (*8*) recommends leveraging TPPT results, the values will be used to perform a load propagation analysis. Further, as longitudinal track resistance is a measure of longitudinal force per unit distance provided by the ballast, sleepers, fasteners, and rail (*10*), these are the parameters that should be considered when performing additional research.

To address this research need and supplement the available literature, novel TPPT research was conducted by the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois Urbana-Champaign (Illinois), which adds to the literature through testing of both timber and concrete sleeper panels. The results quantify the effect of the sleeper and fastener type as well as the crib and shoulder ballast level and ballast consolidation, and are compared to the relevant existing results found in the literature.

Methodology

Track Panel Pull Test Overview

TPPTs typically involve applying longitudinal loads to a track panel constructed with 4–10 sleepers (*11–15*, *18*) in the laboratory or field (Figure 1) to quantify the load versus displacement behavior of the track panel. Force is applied to the panel until a maximum or relatively steady-state resistance value is reached to quantify the maximum panel resistance. In their review, Potvin et al. (*8*) found that longitudinal resistance was independent of panel length when comparing the results from these typical panel lengths to the 108 sleeper panel executed by Mohammadzadeh et al. (*16*). While field tests have the advantage of quantifying the revenue service track conditions, laboratory tests can provide researchers with the flexibility to investigate more track configurations. In addition, in the lab, researchers can take more time than would be feasible with a revenue service track to replicate results. Regardless of the experimental location, care should be taken to ensure the ballast condition is well-documented, as it has a significant impact on the resistance (*8*, *10*, *17*).

Therefore, to achieve the objectives set forth in this research, while reducing experimental costs, a series of TPPTs leveraging a 10-sleeper panel was executed in a laboratory setting.

TPPT Longitudinal Track Resistance and Stiffness Calculations

At a minimum, when a TPPT is executed, the force applied to the panel and resulting panel displacement are recorded to determine the track panel longitudinal resistance and stiffness (Figure 2). Potvin et al. (*8*) discussed how various researchers defined longitudinal resistance differently and thus proposed that, for consistency, it be reported as a force per length per rail. Therefore, Equation 1 was used to quantify the longitudinal

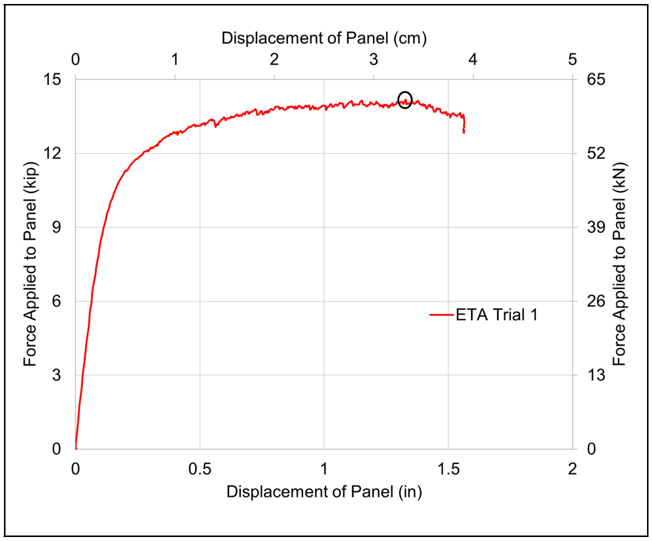


Figure 2. Example force versus displacement data from a track panel pull test with the maximum force circled.
Note: ETA = elastic fasteners or anchors on every sleeper.

resistance in this study. Longitudinal panel stiffness represents the slope of the load–displacement curve before slip (i.e., the elastic region of the load versus displacement data). Thus, for this study, this was considered as the region from the beginning of the test to 1.25 mm (0.05 in.). This is a smaller displacement than used by previous researchers (*14*, *16*), but was chosen to provide a consistent definition between tests while also accounting for slip to occur at low load magnitudes for some of the load cases:

$$f_{0_{TPPT}} = F_{\max}/\left(L_{panel} \times 2\right) \quad (1)$$

where f_{0TPPT} is the longitudinal resistance calculated using the TPPT, $F_{\max}$ is the maximum force extracted from the load versus displacement data, and L_{panel} is the length of the panel.

RailTEC at Illinois TPPT Layout and Instrumentation

The TPPTs utilized Illinois' track loading system (TLS), a multi-axis load frame designed to load track panels constructed with a representative full-depth sub-structure: ballast, subballast, and subgrade support (Figure 3). Each panel was constructed with 136RE rail and AREMA 4A gradation ballast. The crib and shoulder height varied per the experimental matrix, but the shoulders, when constructed, were 305 mm (12 in.) wide and then tapered at a 2:1 slope. The timber and concrete panels were constructed and modified throughout the experimental matrix to achieve the desired goals as discussed (Table 1).

The timber panels were constructed with either elastic fasteners or anchors on every sleeper (ETA) or every other sleeper (EOTA). The concrete panels were constructed with elastic fasteners in which the rail would typically slip through the fastener at approximately 11.1 kN (2.5 kips) (*7*).

Axial loads were applied to the rails using a 156 kN (35 kip) hydraulic actuator. The actuator also recorded panel displacement through the in-line 152 mm (6 in.) linear variable differential transformer (LVDT). Additional instrumentation included (Figure 3*b*) 12 potentiometers used to measure the global panel and the relative component displacements (e.g., rail relative to sleeper or sleeper relative to ground) to identify the interface at which slip occurred. Six longitudinal load circuits were also installed (three along each rail) to quantify the force propagation through the rail.

As discussed previously, the ballast compaction state is critical to the longitudinal panel resistance. To further quantify its effects, each panel was pulled through both compacted and disturbed ballast. All panel tests were executed in a displacement-controlled procedure at a loading rate of 102 mm/min (4 in./min). Loading rates up to 510 mm/min (20 in./min) were initially investigated to quantify the impact of loading rate to better capture differences in mechanics between the TPPT and SRB, as documented by Potvin et al. (*8*), but the results did not indicate a difference. Therefore, the more controlled loading was used for all tests.

After the track panel was pulled through compacted ballast, it was immediately pushed back through the disturbed ballast to its initial position at the same rate. Thus, for each load cycle, the panel longitudinal resistance was quantified for the compacted and disturbed state. After each cycle, the shoulder and crib ballast were then recompacted using a vibratory compactor as described by Potvin et al. (*8*). That is, 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 of the constructed track. The tamper provided approximately 700 blows per minute (bpm) with each blow providing 17 kN (3800 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. Further, the disturbed ballast was achieved by running the test through compacted ballast. That is, the interlock and high density created by the compaction were broken by shearing the panel through the ballast section. It could be hypothesized that tamping the ballast could further reduce the ballast density and interlock, further reducing the longitudinal resistance. Three trials of each panel configuration were performed to quantify and mitigate variance.

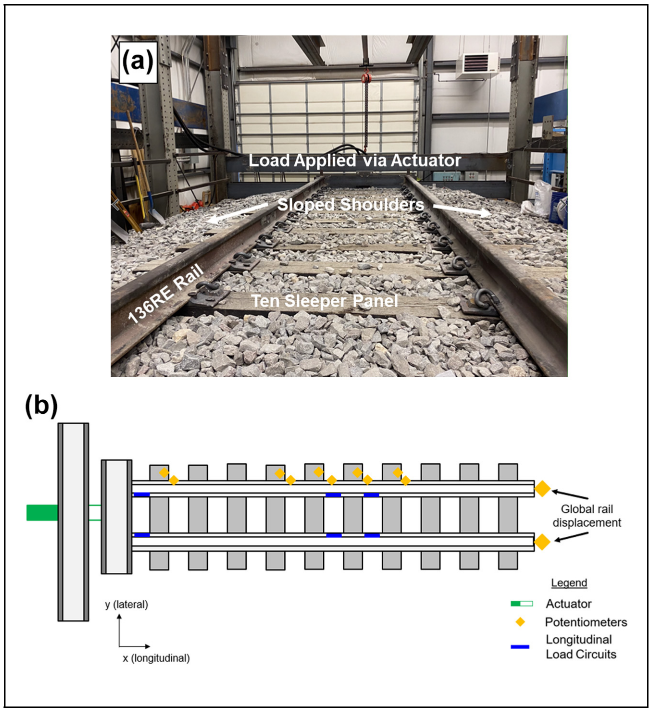


Figure 3. Timber sleeper track panel constructed with 136 RE rail, AREMA 4A ballast, full cribs and shoulders, 460 mm (18 in.) plates with four spikes per plate, and elastic fasteners (*a*) and track panel instrumentation overview (*b*).

- shoulder width;
- crib height;
- ballast condition (disturbed and "frozen");
- sleeper type.

To achieve these objectives, the comprehensive experimental matrix developed consisted of 13 unique panel configurations (Table 2). Each panel configuration was tested three times with compacted and disturbed ballast conditions for a total of 78 total tests.

Each configuration provided an opportunity to investigate the effect of disturbing the ballast. The effect of the fastening system and shoulder width was investigated using the timber panels. The effect of ballast height was investigated using both timber and concrete panels by performing tests when the crib and shoulders were full, half-full, and empty. The effect of a "frozen" ballast condition was meant to simulate either frozen ballast or a mud-spot that was dried, thus significantly increasing the strength of the ballast. To execute this "frozen" test configuration, the crib ballast was removed and replaced with bracing between all sleepers and in front of the panel to ensure the panel could not slip through the ballast, thereby encouraging slip to occur at the rail–fastener interface.

To better communicate the results of all 10 of the non-frozen configurations, each is represented pictorially

Table 1. Track Panel Details for Laboratory Experimentation

	Panel type	
	Timber	Concrete
Ballast		
Type	AREMA 4A	
Crib height	Variable	
Compaction	Variable	
Shoulder width (mm [in.])	305 [12]	
Shoulder height	Variable	
Sleepers		
Quantity	10	9
Spacing (mm [in.])	495 [19.5]	610 [24]
Fastening system		
Anchor slip force (kN [kip])	44.5 [10]	Not applicable
Length of rail plate (mm [in.])	460 [18]	Not applicable
Quantity of spikes per rail plate	4	Not applicable
Elastic fastener toe load (kN [kip])	22.2 [5], *when applicable*	22.2 [5]

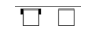
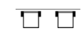
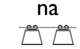
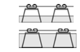
Experimental Matrix

As mentioned previously, the primary objectives of this study were to quantify the effect of various track parameters on longitudinal track resistance and stiffness, which included the following:

- fastening system;

(Legend, Table 2). The frozen configurations, which yielded repeatable results, were not included in Table 2 because the data were extreme outliers, relative to the other test results; this is discussed in greater detail in the results section. Concrete and timber sleepers are represented by trapezoids and squares, respectively. Elastic

Table 2. Track Panel Pull Test Experimental Matrix With Legend

Configuration	Sleeper type	Crib ballast height	Fastener	Shoulder width	Objectives	Legend
1	Timber	Full	Spikes and elastic fasteners	12 in.	A, F	
2	Timber	Full	Spikes and ETA	12 in.	A, F	
3	Timber	Full	Spikes and EOTA	12 in.	A, B, C, D, F	
4	Timber	Full	Spikes and EOTA	0 in.	A, B, F	
5	Timber	Half	Spikes and EOTA	12 in.	C, E, F	
6	Timber	Empty	Spikes and EOTA	12 in.	C, E, F	
7	Timber	Empty	Spikes and ETA	12 in.	A, C, E, F	
8	Timber	"Frozen"	Spikes and ETA	12 in.	A, D, E, F	na
9	Timber	"Frozen"	Spikes and EOTA	12 in.	D, E, F	na
10	Concrete	"Frozen"	Elastic fasteners	12 in.	D, E, F	na
11	Concrete	Empty	Elastic fasteners	12 in.	C, E, F	
12	Concrete	Half	Elastic fasteners	12 in.	C, E, F	
13	Concrete	Full	Elastic fasteners	12 in.	C, E, F	

A | Effect of fastening system
B | Effect of shoulder width
C | Effect of ballast height
D | Effect of "frozen" ballast condition
E | Effect of sleeper type
F | Effect of disturbed ballast condition
Quantity of replicates, and determination of final matrix, will be determined on Completion of shakedown testing

Note: ETA = elastic fasteners or anchors on every sleeper; EOTA = elastic fasteners or anchors on every other sleeper; na = not applicable.

fasteners are shown on top of the sleeper, while anchors are shown in contact with the side of the sleeper. EOTA has one sleeper with anchors while ETA has both sleepers anchored in the two-sleeper depiction. The crib ballast level is shown in gray (fully ballasted cribs and shoulders have gray up to the top of the sleeper, half-ballasted cribs and shoulders have gray up to half of the sleeper's height, empty cribs and shoulders have no gray, and track without shoulder has the sides of the sleepers exposed [white] with filled-in cribs).

Experimental Results

A load versus displacement figure was developed for every test run. Representative load versus displacement curves for each normally consolidated ballast tests were plotted to visualize how the forces, displacements, and stiffnesses compare (Figure 4).

From a visual perspective, the concrete sleeper panels provide a greater resistance than a similar timber panel (i.e., the full crib and shoulder ballast concrete sleeper panel is greater than the full crib and shoulder ballast timber sleeper panel). In fact, the data indicate that a concrete sleeper panel with half-filled cribs and shoulders could exhibit a greater resistance than a timber sleeper panel with full cribs and shoulders. Further, it appears that the stiffness of the panel is primarily affected by the quantity and location of the ballast. That is, when the cribs and shoulders are full, the stiffness of the panel is largely independent of the sleeper or fastener type. However, when the ballast levels are reduced, the stiffness also reduces. This indicates that the ballast plays a major role in load transfer before slip occurs, as well as setting the limit of the slip. These data also indicate that each panel generally exhibits a bilinear behavior, which aligns with Samavedam et al. (*21*). Some of the load versus displacement curves exhibit increasing force with increasing displacement, rather than reaching a peak. This behavior is most evident in the cases with empty to partially full cribs and, thus, it is hypothesized that this is occurring when the sleepers dragging through the ballast move ballast into the cribs and thus increase the total resistance of the panel (e.g., this would be similar to a plow having increased resistance as more material is being moved).

From the load and displacement data recorded from all tests, the maximum force was identified and then the resistance and stiffness calculated as discussed previously. A summary of 10 of the panel configurations' calculated resistance and stiffness values are summarized below (Table 3) with the average values from each configuration highlighted in Figure 5.

When considering compacted ballasted tests, as expected, the concrete sleeper panel with fully ballasted cribs provided the highest resistance value of 8.0 kN/m (45.5 lb/in.). This value is very similar to the median reported concrete sleeper TPPT resistance value of 7.5 kN/m (42.8 lb/in.) reported by Potvin et al. (*8*) and is 20% greater than the timber sleeper panels (i.e., 6.3 kN/

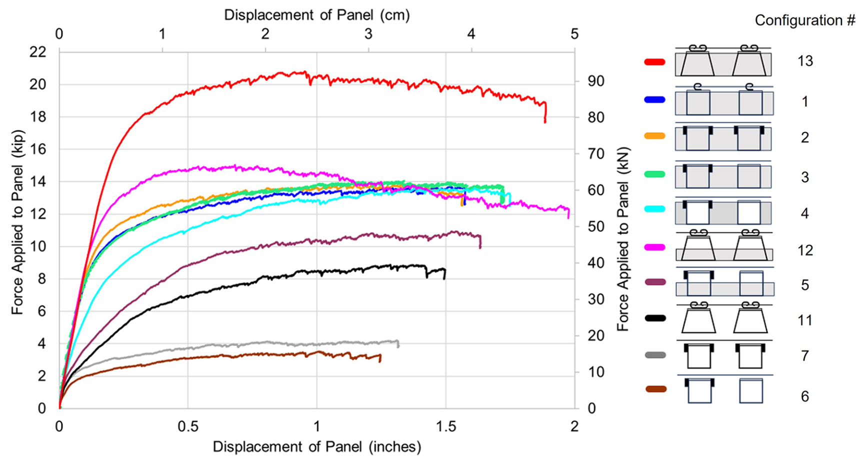


Figure 4. Selected load versus displacement data of undisturbed ballast for 10 panel configurations.

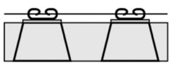
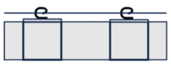
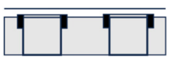
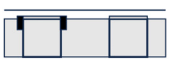
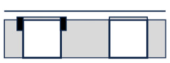
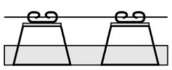
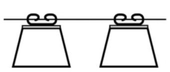
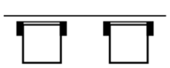
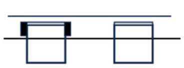
m [36.2 lb/in.]). This 6.3 kN/m (36.2 lb/in.) resistance aligns with the ETA strong recommendation provided by Kish (*22*). However, the TPPT longitudinal resistance values of the timber sleeper panels with full ballasted cribs exhibited longitudinal resistance values within 5% of one another, regardless of the fastening system or presence of shoulder ballast (i.e., timber with elastic fasteners, ETA, and EOTA were all within 5%). This indicates that the fasteners were well engaged with the sleepers and were stronger than the ballast, as the slip occurred at the sleeper–ballast interface and not the rail–fastener interface. Further, this is not a surprising result given the maximum force applied to each rail seat was below the longitudinal slip strength of the fasteners. For example, the approximate maximum force applied to a 10-sleeper timber panel was 14 kips, which means there was approximately 1.4 kips placed on each fastener, which is below their approximate 2.5 kip capacity (Table 1). This contrasts with data found in the literature that states EOTA fastener track should exhibit resistance values 33%–50% lower than ETA track (*10*, *22*). It is hypothesized that this difference is primarily caused by the differences in mechanics between SRBs and TPPTs and because all fasteners were engaged with the sleepers in the laboratory TPPT but were not necessarily engaged during field SRBs.

The ballast condition consistently had a significant impact on longitudinal resistance. When comparing the compacted and disturbed TPPT results, there was a 13.0% reduction in longitudinal resistance, on average, when excluding the cases without crib ballast. The reduction ranged from 9.1% with timber sleepers and ETA to 18.9% when no shoulder was present. It is hypothesized that when there was no shoulder ballast, the crib ballast would not only be disturbed but leak into the shoulders, further weakening the panel. Reducing the ballast in the cribs by 50%, the longitudinal resistance was reduced by 25% and 18% for concrete and timber panels, respectively. Further, for compacted ballast, the resistance was not significantly affected when the shoulder was not present and was reduced by approximately 8% when the ballast was disturbed.

Leveraging these data, the respective contributions from the bottom, cribs, and shoulders can also be quantified for timber panels as discussed by De Iorio et al. (*14*) and Zakeri and Yousefian (*18*) for concrete sleepers and compared to the lateral resistance values provided by Kish (*23*) (Figure 6). The amount of longitudinal resistance generated by the shoulders was quantified by comparing full cribs and shoulders to the cases where there was no shoulder but full cribs (e.g., Tests 3 and 4). The portion of resistance generated by the cribs was quantified by comparing full cribs and no shoulders (e.g., Tests 4 and 6) or comparing the results of full cribs and shoulders to no cribs or shoulders, while subtracting the influence of the shoulders (e.g., Tests 2 and 7).

In order of greatest to least influence, the cribs, bottom, and shoulders will provide approximately 65%, 30%, and 5% of the longitudinal resistance, respectively. In comparison to the lateral resistance, the crib plays a much more significant role in providing longitudinal resistance (i.e., 65% versus 33%, respectively). The shoulders provide little to no longitudinal resistance (e.g., ˜5%) compared to approximately 25% lateral resistance. These findings generally agree with De Iorio et al. (*14*) and Zakeri and Yousefian (*18*), although the influence of the crib appears to be even greater in the current study, contributing more than 70% of the resistance in some instances. Further, while the longitudinal resistance values are dependent on sleeper type, unlike

Table 3. Summary of Longitudinal Resistance and Stiffness Data From 10 Configurations for Disturbed and Consolidated Ballast Conditions

			Longitudinal resistance				Longitudinal stiffness			
Test configuration		Ballast condition	Trial 1	Trial 2	Trial 3	Avg.	Trial 1	Trial 2	Trial 3	Avg.
	(lb/in.)	Consolidated	48	45	44	46	91	87	83	87
	(kN/m)		8.4	7.9	7.6	8.0	16.0	15.3	14.5	15.3
	(lb/in.)	Disturbed	38	38	37	38	22	25	23	23
	(kN/m)		6.6	6.6	6.5	6.6	3.8	4.4	4.1	4.1
	(lb/in.)	Consolidated	35	36	38	36	98	97	108	101
	(kN/m)		6.2	6.2	6.7	6.3	17.1	16.9	18.8	17.6
	(lb/in.)	Disturbed	34	33	31	33	18	16	16	17
	(kN/m)		5.9	5.8	5.4	5.7	3.2	2.9	2.8	3.0
	(lb/in.)	Consolidated	36	36	36	36	97	94	79	90
	(kN/m)		6.2	6.2	6.4	6.3	17.0	16.4	13.9	15.8
	(lb/in.)	Disturbed	34	31	32	33	18	21	19	20
	(kN/m)		6.0	5.5	5.6	5.7	3.2	3.7	3.4	3.4
	(lb/in.)	Consolidated	36	35	35	35	96	77	84	85
	(kN/m)		6.3	6.1	6.1	6.1	16.7	13.4	14.7	14.9
	(lb/in.)	Disturbed	28	32	33	31	14	18	18	17
	(kN/m)		4.9	5.7	5.7	5.4	2.5	3.2	3.1	2.9
	(lb/in.)	Consolidated	35	35	35	35	86	100	85	90
	(kN/m)		6.1	6.2	6.1	6.1	15.0	17.5	14.9	15.8
	(lb/in.)	Disturbed	28	28	29	28	9	11	11	10
	(kN/m)		4.9	4.9	5.1	5.0	1.7	1.9	1.9	1.8
	(lb/in.)	Consolidated	35	35	33	34	91	87	83	87
	(kN/m)		6.1	6.1	5.9	6.0	16.0	15.3	14.5	15.3
	(lb/in.)	Disturbed	No data recorded							
	(kN/m)									
	(lb/in.)	Consolidated	28	29	29	29	61	62	59	61
	(kN/m)		4.9	5.0	5.2	5.0	10.7	10.8	10.3	10.6
	(lb/in.)	Disturbed	25	25	26	25	12	11	8	10
	(kN/m)		4.4	4.4	4.6	4.5	2.1	1.9	1.4	1.8
	(lb/in.)	Consolidated	21	15	15	17	48	41	25	38
	(kN/m)		3.6	2.6	2.7	3.0	8.3	7.2	4.5	6.7
	(lb/in.)	Disturbed	6	12	12	10	6	16	16	12
	(kN/m)		1.0	2.1	2.2	1.7	1.0	2.8	2.7	2.2
	(lb/in.)	Consolidated	11	11	11	11	49	44	44	45
	(kN/m)		1.9	2.0	1.9	1.9	8.5	7.7	7.6	8.0
	(lb/in.)	Disturbed	11	10	12	11	6	13	6	9
	(kN/m)		2.0	1.8	2.1	2.0	1.1	2.3	1.1	1.5
	(lb/in.)	Consolidated	9	10	10	10	37	38	42	39
	(kN/m)		1.6	1.8	1.8	1.7	6.4	6.7	7.4	6.8
	(lb/in.)	Disturbed	8	9	No data	8	8	6	No data	7
	(kN/m)		1.3	1.6	recorded	1.5	1.4	1.1	recorded	1.2

Note: Avg. = average.

lateral resistance, longitudinal resistance percentages appear to be independent of sleeper type.

Longitudinal stiffness values were quantified (Table 3 and Figure 5). The effect of sleeper type on stiffness is less apparent than what was documented for resistance. That is, when considering panels with full shoulder and crib ballast levels, the stiffness ranges from 14.9 to 17.6 kN/m (85–101 lb/in.) with no apparent trend between timber and concrete. In contrast to what was reported by De Iorio et al. (*14*), the lack of shoulder ballast did not immediately affect the stiffness of the panel. However, when looking at the full load versus displacement curve (Figure 4), one can see a reduction in stiffness by approximately 40% once the panel starts to displace. When no crib or shoulder ballast was present, the stiffness dropped to between 6.7 and 8.0 kN/m (38–45 lb/in.), or by approximately 45%. Finally, when the ballast was disturbed, the stiffness was reduced by 81%, on average, when compared to the consolidated cases with crib ballast.

Up until now, the data analysis has excluded "frozen" ballast. This is because to execute these experiments, the timber sleepers were restrained from moving, thus forcing the slip to occur between the rail and fastener. In the 10-sleeper panel, four different tests were run in which one,

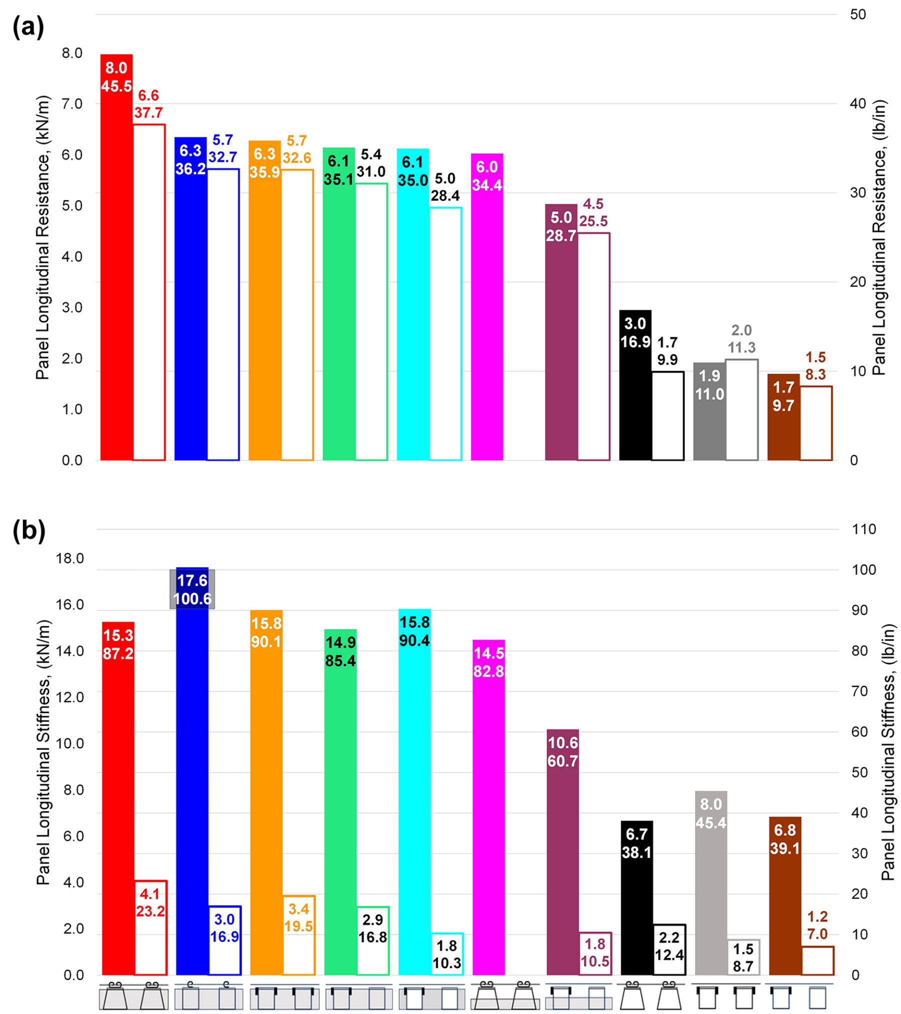


Figure 5. Average longitudinal resistance (*a*) and stiffness (*b*) values by configuration for compacted (solid colored) and disturbed (empty) ballast.

two, three, and five sleepers were anchored (i.e., with five sleepers anchored representing the EOTA condition). When the number of anchors was reduced, the number of sleepers in the panel in the load path also reduced (Figure 7). During the experiments with two, three, and five sleepers anchored, the actuator was not able to cause slip to occur, and thus the longitudinal resistance could not be calculated; however, it was known to at least exceed 13.2 kN/m (75 lb/in.). When a single sleeper was anchored in the 10-sleeper panel, the rail slipped through the fastener at a force of 22.5 kips, which results in a resistance of approximately 40.4 kN/m (230 lb/in.).

Summary and Conclusions

There are, on average, 12.5 FRA reportable derailments per year on U.S. mainlines and sidings caused by "defective or missing spikes or rail fasteners." Analytical models have been developed and employed by various researchers to quantify fastening system loading demands and reduce the probability of failure. Therefore, to support the further refinement and validation of analytical models that leverage longitudinal track resistance and stiffness, two of the critical inputs required for load propagation analysis, TPPTs were executed in the laboratory. These TPPTs quantified the effect of the fastening system and sleeper type, crib ballast height, shoulder width, and ballast condition on the panel's longitudinal resistance and stiffness.

From these experiments and the resulting analysis of the data, the following conclusions were made and a summary of salient results are provided in a summary table with relevant values from the literature (Table 4):

Table 4. Summary of Track Panel Pull Test (TPPT) Longitudinal Resistance Values With Present Study Values Shaded

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							
Concrete	Yes	Good	EF	Dieterman et al. (3)	Unspecified	17.60	100.5
						27.60	157.6
				Nobakht et al. (19)	5	26.10	149.0
						18.78	107.3
						25.03	142.9
				Zand and Moraal (11)	5	27.12	154.9
						21.67	123.7
		Disturbed	EF	Kerokoski (13)	10	13.50	77.1
						15.50	88.5
Concrete	No	Good	EF	Dieterman et al. (3)	Unspecified	6.00	34.3
						10.00	57.1
				De Iorio et al. (14)	6	7.82	44.7
				ERRI (24)	Unspecified	7.58	43.3
				Esveld (25)	Unspecified	9.17	52.3
				Kerokoski (13)	10	7.80	44.5
						8.20	46.8
				Markine and Esveld (26)	Unspecified	7.50	42.8
				Mohammadzadeh et al. (16)	108	8.03	45.9
				Nobakht et al. (19)	5	9.13	52.1
				Present study	10	8.00	45.7
				Queiroz (12)	7	8.22	46.9
				UIC (4)	Unspecified	10.00	57.1
				Xiao et al. (15)	4	6.67	38.1
				Zakeri and Yousefian (18)	5	5.92	33.8
				Zand and Moraal (11)	5	9.17	52.4
		50% crib	EF	Present study	10	6.00	34.3
		Various conditions	Not applicable	Liu[c] et al. (17)	1	8.8–19.6	30–67
		Disturbed	EF	Kerokoski (13)	10	6.72	38.4
				Present study	10	6.60	37.7
				Xiao et al. (15)	4	4.38	25.0
				UIC (4)	Unspecified	6.00	34.3
		Frozen	EF	UIC (4)	Unspecified	30.00	171.3
			EF	Queiroz (12)	7	6.31	36.0
				Present study	10	6.30	36.0
Timber	No	Good	EOTA	Potvin et al. (8)	10	6.15	35.1
				Present study	10	6.10	34.8
				Samavedam (10)	4	8.41	48.0
			ETA	Potvin et al. (8)	10	6.29	35.9
				Present study	10	6.30	36.0
				Samavedam (10)	4	10.16	58.0
		50% crib	EOTA	Present study	10	5.00	28.6
		Disturbed	EF	Present study	10	5.70	32.5
			ETA	Present study	10	5.40	30.8
				Samavedam (10)	4	7.44	42.5
			EOTA	Present study	10	5.40	30.8
			E3TA	Samavedam (10)	4	6.48	37.0
		Disturbed, 50% crib	EOTA	Present study	10	4.50	25.7
				Samavedam (10)	4	3.24	18.5
Bi-block	No	Unspecified	EF	Queiroz (12)	7	7.70	44.0
Steel	No	Unspecified	EF	Queiroz (12)	7	5.70	32.5
Single rail break							
Timber	No	Good	EOTA	Samavedam (21)[d]	Not applicable	2.98	17
	No	Good	ETA	Samavedam (21)[d]		5.25	30

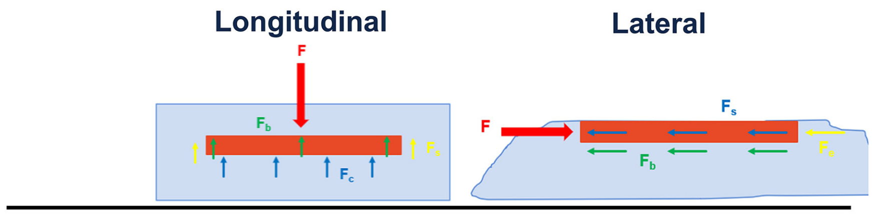
Note: EOTA = every other sleeper anchored; E3TA = every third sleeper anchored; ETA = every sleeper anchored.

[a]Many (9, 11) have hypothesized 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.

[c]Liu pushed a single sleeper within a four-sleeper panel and thus the resistance continued to increase as other unfastened sleepers engaged the fastened sleeper within the panel and, thus, the values are outliers on the high side.

[d]The Samavedam results are the only single rail break tests. All other results come from a TPPT.



	$F = F_c + F_b + F_s$	$F = F_e + F_b + F_s$
Shoulder	F_s ~ 0-10%	F_e ~ 20-25%
Bottom	F_b ~ 25-40%	F_b ~ 35-40%
Crib	F_c ~ 60-75%	F_s ~ 30-35%

Figure 6. Summary and comparison of longitudinal and lateral resistance components as quantified in this study and by Kish (*23*).

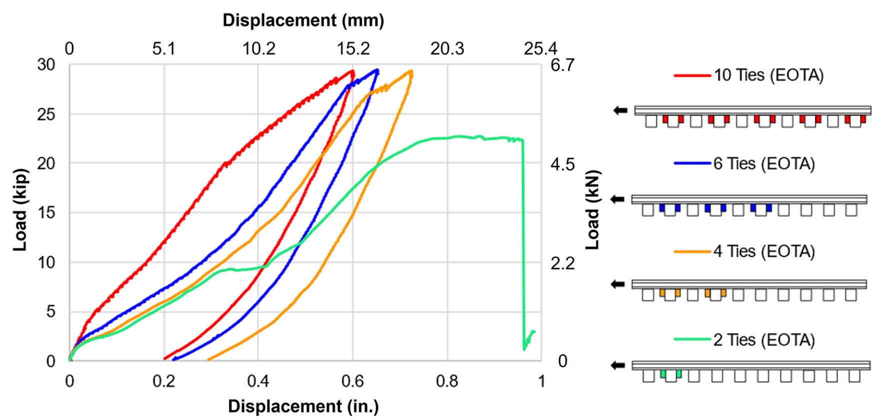


Figure 7. Summary of load versus displacement experiments of 10-sleeper "frozen" panels with one, two, three, and five sleepers anchored.
Note: EOTA = elastic fasteners or anchors on every other sleeper.

- concrete sleeper panels exhibit 20% higher resistance than timber sleeper panels;
- slip regularly occurred at the sleeper–ballast interface, except for the "frozen" panels;
- changing fastening systems (elastic fasteners, ETA, and EOTA) did not affect the panel resistance when the ballast was compacted, and fasteners were engaged with the sleepers;
- panel stiffness was affected by both sleeper and fastener type;
- disturbing ballast reduced the longitudinal resistance by 13% and stiffness by approximately 80%;
- crib ballast provides 60%–70% of the longitudinal resistance, significantly more than it contributes to lateral resistance;
- shoulder ballast provides 0%–10% of the total longitudinal resistance, significantly less than it contributes to lateral resistance;
- the sleeper bottom provides between 25% and 40% of the total longitudinal resistance;
- when sleepers are fixed (e.g., frozen ballast, dry mud-spots, fixed structures) the resistance is driven by the fastening system strength with resistance values exceeding 40.4 kN/m (230 lb/in.).

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: M.S. Dersch, A. Lima, J.R.

Edwards; data collection: M. Potvin, M. Dersch; analysis and interpretation of results: M. Potvin, M. Dersch; draft manuscript preparation: M. Dersch, J.R. Edwards. All authors reviewed the results and approved the final version of the manuscript.

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