Field Validation of Tie Reaction Measurement using Rail Strain Gauge Circuits

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ABSTRACT

This paper presents results from successful field validation of an alternative method to measure tie reactions. This method uses a pair of strain gauge circuits mounted on the web of the rail placed in a crib between ties and above a tie. Tie reactions have been traditionally measured using instrumented tie plates or load cells placed at the rail-tie interface. These methods require modifications to ties and tie plates which makes them expensive and difficult to use in revenue service. The field test, conducted in October 2020 at the Letterkenny Yard in Chambersburg Pennsylvania, compared tie reactions obtained by the three methods. The test also confirmed independence of rail circuit calibration from the calibration device configuration. Measurements of tie reactions provide an indication of load distribution and vertical support along the track structure. Locations with weak support condition tend to develop geometry conditions that are prone to further deterioration and component failure. The newly validated method allows the collection of tie reaction measurements without disturbing the ties or the rail-tie interface, making it cost-effective and easier to implement in revenue service.
INTRODUCTION

A railroad track can experience axial, lateral and, vertical forces under train loading as well as due to environmental factors. These loads generate forces and torques in the rail fastening system, anchors, as well as tie plates, and are transmitted to different track components such as ties, ballast, and the subgrade layer (1). The load transmission process follows a complex stress path in the indeterminate structural configuration of a railway track. Adequate performance of different track components depends to a large extent on uniform and smooth transmission of these forces. The nature of this force transmission chain is greatly affected by the structural integrity and condition of individual track components; for example, wheel defects or defects on the railhead can lead to amplification of the load levels imparted by trains. Similarly, damage to a particular tie or lack of adequate support underneath the tie affects the distribution of stresses to the underlying layers. The magnitude of force being transmitted through a particular rail-tie interface is largely governed by the support condition underneath the tie.

Track health monitoring plays a critical role in facilitating safe and reliable passage of trains over a railroad track. Depending on the specific components being targeted, railroad agencies employ different short- or long-term monitoring strategies for track health monitoring. Technological advancements in sensor development and deployment are evident from the state of practice in railroad instrumentation over the past several decades (2). Researchers and practitioners have successfully deployed acoustic sensors, accelerometers, fiber optics sensors, high-resolution cameras, Piezoelectric sensors, and strain gauges in track performance monitoring systems. Track monitoring sensors are now more reliable and can withstand extreme weather and loading conditions. Although sensors are now relatively small, thin, and easy to install, some sensors still require significant track outage during installation, thus limiting their applicability.

One of the critical factors affecting the force transmission from a train wheel through the rail to the substructure concerns the support condition underneath crossties. An accurate measure of the force being transmitted through the rail-tie interface can be obtained by using load cells or by instrumented tie plates. However, both these approaches require modification of existing track components. For example, to install a load cell (or multiple load cells) at the rail-tie interface, the tie in question needs to be removed, and modified (often by cutting grooves) to accommodate the sensor arrangement. The same is true for instrumented tie plates. This requires substantial track time which may be difficult in many revenue service scenarios. This is particularly critical along high-traffic rail corridors where long work windows can lead to significant operational challenges. On the other hand, regular monitoring of track conditions along these corridors is important due to the volume of traffic. Lack of adequate support underneath ties can lead to recurrent geometric defects, and ultimately to component failure or derailment. Therefore, a non-intrusive method of measuring the tie support conditions is highly desired.

Ahlbeck et al. (1) showed a strain gauge-based monitoring system that can be used to measure the wheel load as well as the tie reaction force. The proposed technique used a pair of strain gauge circuits to measure the shear strain in the crib between two ties and across a tie. The measured shear strains are used to calculate the wheel loads as well as tie reaction forces. The proposed method does not require modification to any track component, and is based on the following fundamentally sound principle: for a beam subjected to bending under a point load, as one moves from one side to the other of the point load, the difference in shear force equals the magnitude of the point load. Although the application of this strain gauge-based system to measure wheel loads is relatively common (such as in the case of Wheel Impact Load Detector Systems or WILD Systems), its application to monitor tie reaction forces is limited (3-12). The most significant advantage of a strain gauge-based measurement approach lies in its cost effectiveness, durability, and accuracy. Strain magnitudes induced in the rail under bending can be analytically predicted using beam theory. However, field calibration is required because the field-measured
The strain values are highly sensitive to the rail geometry, accuracy of strain-gauge placement within the rail section, as well as inclination of loading. Although the cross-section properties are constant for a given rail size, the values may change under repetitive loading and the associated rail head wear requiring re-calibration for long-term installations.

The calibration process involves application of a known load to the rail and measuring the strain gauge circuit electrical response. A calibration curve can be developed by repeating this process for different load magnitudes. The calibration curve is subsequently used to estimate wheel loads based on voltage responses from the strain gauge circuits. The calibration process is often performed using a triangular frame, also referred to as the A-Frame, that pulls against the rail at the ends of the frame and leverages the pull mechanism to apply a vertical load to the rail in the middle of the frame. A schematic of the A-frame is illustrated in Figure 3a. Instead of using an A-Frame, a load of known magnitude can also be applied by pushing against a rail car or any heavy reaction frame. If the applied load magnitude is known, the calibration curve for the strain gauge circuit can be easily established. The applied calibration load is commonly measured using an external load cell. Mishra et al. (4, 5), recently used an A-frame to calibrate the strain gauges in the field. Although strain gauge circuit calibration using an A-frame is conceptually simple, the effect of A-frame configuration on the calibration results has never been studied in detail and published. Moreover, there are no published results of field validations of the differential shear measurement approach for tie reaction measurements.

RESEARCH OBJECTIVE AND SCOPE

The primary objective of this research effort was to validate a differential shear-strain based approach to measure the loads transmitted through the rail-tie interface. This can be a direct indication of the support conditions underneath the cross-tie. In addition, this research effort also investigated whether the dimensions of the calibration frame or configuration of the loading system has any effect on the accuracy of the calibration process.

The research tasks undertaken to accomplish the overall objective can be broadly divided into two categories: (1) Numerical Modeling; and (2) Field Experimentation. In Part-1, the theory of a strain gauge-based track monitoring system was evaluated using a simplified three-dimensional numerical model. In Part-2, a field instrumentation effort was designed to first establish the independence of strain gauge circuit calibration from calibration fixture configuration. Three different loading configurations were employed during the test. Subsequently, the suitability of the differential shear measurement approach for tie reaction measurement was established. For this purpose, measurements from the differential shear strain circuit were compared against two traditional methods of force measurement at the rail-tie interface.

THEORY AND CONCEPT OF DIFFERENTIAL SHEAR STRAIN MEASUREMENT ON THE RAIL

The strain gauge-based track monitoring system uses differential shear strains measured on rail web to estimate the wheel load magnitudes well as tie support reactions. Ahlbeck et al. (1) proposed this system, where the differential shear strain measured at the crib and tie locations are used to monitor the wheel load and tie reaction force, respectively. In this system, two individual circuits, referred to as the crib circuit and the tie circuit, measure the differential shear strain at the rail neutral axis in the crib and tie locations, respectively. Each circuit consists of four (4) strain gauges, two on each face of the rail web at a sufficient distance from the tie face (to avoid boundary effects). As already mentioned, the measurement approach is based on the fundamental principle that as one moves from one side to the other side of a point load applied to a beam, the difference in the change in shear force equals the magnitude of the point load.

Figure 1 shows schematics of the crib and tie circuits. Points A and B lie on one face of the rail, whereas points C and D lie on the other face. A 45-degree orientation of strain gauge with respect to the
beam’s neutral axis ensures measurement of the maximum shear strain values. The shear strain at any point can be used along with the rail geometrical properties to calculate the shear force value. The difference in shear force between points A and B (or C and D) equals the magnitude of the point load applied in between these two points. Equations 1, 2, and 3 are used to calculate the shear strain, shear force, and resultant force respectively, for both the crib as well as tie circuits. In case of the crib circuit, the reaction force R in Equation-3 equals ZERO. Thus, using Equation-3, the crib circuit measures the wheel load (P). Similarly, Equation-3 for the tie circuit uses the wheel load (P) to calculate the tie reaction force (R).

![Diagram of Crib Circuit and Sleeper/Tie Circuit](image.png)

**FIGURE 1 Theory of Differential Shear Strain Measurement Approach**

**NUMERICAL VERIFICATION OF THE DIFFERENTIAL SHEAR BASED LOAD MEASUREMENT APPROACH**

A 39.37 in. long AREMA RE-132 rail section was modeled using the commercial finite element software package ABAQUS. Actual rail geometry and standard materials properties were used in the modeling. Figure 2 shows some of the rail material properties used in the model. Points A and B are the strain collection locations situated at the rail’s neutral axis. The section was simply supported, and two types of concentrated loads (1) Vertical Load ($V_L$) and (2) Reaction Force ($R_F$) were applied through the centroid of the rail section in opposite directions. The vertical load represents a static wheel load on top of the rail, whereas the reaction force applied to the base of the rail represents the tie reaction force. The concept of using the differential shear strain approach for tie reaction measurement was tested by applying different magnitudes of $V_L$ and $R_F$ to the rail section. For every combination, the shear strain values at points A and B were retrieved from the ABAQUS model, and Equation 3 (refer to Figure 1) was used to estimate the resultant force. Figure 2 shows details of the loading configuration, and Table-1 lists the different loading combinations applied to the rail section, along with the estimated resultant load magnitudes. As seen from Table 1, for each of the load combinations, the estimated resultant force values (calculated from the measured strains) were very close to the actual applied loads. Therefore, results presented in Table-1, numerically prove that the proposed strain gauge circuits can measure wheel loads and tie reaction forces. The next step in the research involved validating this approach in the field. The field instrumentation effort also focused on verifying the independence of the calibration results from calibration fixture configuration.
FIGURE 2 Numerical Verification of the Differential Shear Strain Concept for Measuring Tie support Condition

**Table 1: Load Estimation using the Differential Shear Strain Approach: Results from a 3-Dimensional Numerical Model**

<table>
<thead>
<tr>
<th>Applied Load VL kips (kN)</th>
<th>Reaction Force RF, kips (kN)</th>
<th>Resultant (R=VL-RF) R, kips (kN)</th>
<th>Strain Location 𝝁 (μm/m) A (C)</th>
<th>B (D)</th>
<th>Estimated Load P kips (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.48 (100)</td>
<td>00.00 (0.0)</td>
<td>22.48 (100)</td>
<td>254.4</td>
<td>-254.4</td>
<td>22.42 (99.75)</td>
</tr>
<tr>
<td>22.48 (100)</td>
<td>11.24 (50)</td>
<td>11.24 (50)</td>
<td>127.6</td>
<td>-127.6</td>
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<td>00.00 (0)</td>
<td>0.713</td>
<td>-0.713</td>
<td>00.06 (0.279)</td>
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<tr>
<td>44.96 (200)</td>
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<td>-255.0</td>
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<td>44.96 (200)</td>
<td>508.0</td>
<td>-508.0</td>
<td>44.84 (199.5)</td>
</tr>
</tbody>
</table>

**Table 1** shows the load estimation using the differential shear strain approach, with results from a 3-dimensional numerical model. The table includes the applied load, reaction force, resultant force, strain location, and estimated load for different scenarios.
FIELD CALIBRATION OF STRAIN GAUGE CIRCUITS

Site Selection

A tangent track section within the Letterkenny yard operated by the Pennsylvania Southern Railroad in Chambersburg, Pennsylvania was selected for the field validation effort. The field instrumentation effort focused on vertical loading of the track only. Load cells and an instrumented tie plate were installed at the rail-tie interface on two adjacent ties. The yard track comprised of 115 lb. rail and wooden ties with variable spacings. The center-to-center spacing between the two instrumented ties was 25 in. Surrounding ties had 21 in. or 22 in. spacing. The tie cross-section was 9 in. x 7 in.

Strain Gauge Calibration Configurations

Three calibration configurations were investigated. Two of them used A-Frames with different dimensions and one used a car-body as a reaction frame. Figure 3.a and Figure 3.b show schematics of the A-Frame and car-body calibration setups. In all arrangements, a hydraulic jack was used to apply vertical loading to the railhead. A pin joint was placed at the point of contact between the rail head and the loading arm to ensure no moment transfer.
Two different A-frame geometries were used; short base A-frame with a base length of 34 in., and a long base A-frame with a base length of 66 in. The primary difference between calibration using the A-frames vs. the car body as reaction frame is that the rail does not experience any upward force when pushing against the car body. The A-frame, on the other hand, pulls the rail upwards where diagonals are attached to the rail.

Direct Measurement of Force at the Rail-Tie Interface

Load Cells Mounted on Tie Plate

A tie plate with load cells is one of the most direct approaches for force measurement at the rail-tie interface. In this technique, a single or multiple load cell are placed at the rail-tie interface. In this research effort, force measurement at the rail-tie interface was accomplished by installing four (4) individual load cells into a customized tie plate. Figure 4 (a) shows the four individual load cells attached to a base plate. The load cells were arranged in a square pattern. A cover plate was used to sandwich the four load cells and to ensure adequate contact with the load cells. A tie plate was placed on top of the cover plate. Figure 4 (a and b) show the load cells placed at the rail-tie interface. The sum of loads measured by the four individual load cells indicates the total load transmitted at the rail-tie interface.

Instrumented Tie Plate

Another approach to measure the force transmission at the rail-tie interface is by an Instrumented Tie Plate (ITP). An ITP contains strain gauges that estimate the force applied to the tie plate by measuring the plate bending. Figure 4 (c and d) show the ITP installed at the rail-tie interface.

Restoration of Tie Support Condition

Installation of the load cells and ITP required removal of ties from the track. Therefore, tie support conditions were restored by hand tamping once the instrumented ties were placed back in the track. New ballast was poured underneath the ties during the tamping process. For identification, the tie with load cells is referred to as Tie-1, whereas the tie with ITP is referred to as Tie-2. The tie adjacent to Tie-1 was named Tie-A and the tie adjacent to the Tie-2 was named Tie-B (See Figure-3).
Strain Gauge Installation

Twelve (12) dual-element shear strain gauges were installed on the web of the rail. A total of three full-bridge strain gauge circuits were installed, one at a crib location (between Tie A and Tie 1), and two across Tie-1 and Tie-2, respectively. Each full-bridge circuit consists of four (4) shear strain gauges, connected to the four arms of a Wheatstone bridge to complete a full bridge connection. Figure-5 shows a photograph of the instrumented rail section.
FIELD CALIBRATION OF STRAIN GAUGE CIRCUITS

Crib Circuit Calibration
The maximum load applied by both the A-frames was 31 kips, whereas the maximum load that could be safely applied when pushing against the car body was 27 kips. The applied load was measured using an external pre-calibrated load cell. Voltage output from the strain gauge circuit was plotted against the applied load. Figure 6 a, c, and e illustrate the calibration process using the long-base A-frame, short-base A-frame, and car-body, respectively. Similarly, Figures 6 b, d, and f show the corresponding calibration curves obtained for these set-ups. The calibration curve slopes for the three configurations were almost identical to each other. This establishes independence of the calibration process from the loading configuration.
Once the crib circuit was calibrated, the next step involved static loading of the tie circuits to quantify how the load applied on top of the tie gets registered by different measurement arrangements on the rail and at the rail tie interface. The long-base A-frame was used to apply load directly above Tie-1. The applied load was measured by an external load cell. Outputs from the tie circuit (full-bridge strain gauge circuit mounted to the web of the rail across the tie) and the load cells at the rail-tie interface were recorded simultaneously. The results are plotted in Figure 7(a). Continuously recorded data from the external load cell, load cells mounted to the tie plate, and the loads calculated using the Tie-1 strain gauge circuit are plotted on the left. Computed percentage of loads measured by different sensors as a percentage of the total applied load is shown on the right. The full-bridge tie circuit over Tie-1 recorded 89% of the applied load. This means, a major portion of the applied load was utilized in bending of the rail, whereas 11% of the load was transferred through the rail-tie interface. This can be attributed to the nature of the A-frame loading process. The A-Frame reactions at the ends of its diagonals pull the rail upwards resulting in significant bending of the rail without significant downwards deflection above the tie. Figure 7(b) shows similar data for the Tie-2 static
loading using the A-frame. In this case, approximately 96% of the load contributed towards bending of the rail, and only 4% was transmitted to the underlying tie.

**FIGURE 7: Tie Circuit Calibration Results using the A-Frame: (a) Tie-1; (b) Tie-2**

Static loading of Tie-1 and Tie-2 showed that the strain gauge circuits adequately accounted for the portion of the load that contributed to bending of the rail. The validity of the strain gauge measurement was confirmed because the load contributing towards rail bending measured by the strain-gauge circuit and the force measured at the rail-tie interface (using load cells or ITP) added up exactly to the applied load. Therefore, the differential shear strain circuit mounted across a crosstie can adequately measure the load carried by the rail. This combined with an independent wheel load measurement accomplished through the crib circuit can give an accurate estimate of the tie reaction force.
SUMMARY AND CONCLUSIONS

This research effort numerically and experimentally validated several aspects of the differential shear strain measurement approach. The results showed that the strain gauge circuit calibration process is independent of the calibration configuration. Identical calibration constants were obtained from the strain gauge circuit when the calibration was performed using A-Frames with different geometries, or by pushing against a car body. In addition, a differential shear strain circuit installed on the rail web above tie can accurately measure the force carried by the rail right above the tie. When combined with a known applied load, the tie reaction force can be obtained. Therefore, application of differential shear strain measurement was established as a suitable method for tie support condition assessment. In revenue service application, applied loads by passing trains would be measured by a crib strain-gauge circuit. The field test included additional testing under moving locomotives as well as varying support conditions. The objective of this dynamic testing was to demonstrate the applicability of the strain-gauge based tie reaction force measurement under passing train loads and assess its accuracy. Results of the dynamic testing are beyond the scope of this manuscript and will be reported in future publications.

ACKNOWLEDGMENTS

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REFERENCES


Field Validation of Tie Reaction Measurement using Rail Strain Gauge Circuits

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Radim Bruzek, ENSCO Inc.
Ted Sussmann, Volpe National Transportation Systems Center
Hugh Thompson, Federal Railroad Administration
**Premise of the Topic**

\[
P = V_A - V_B = \frac{EIt}{2Q(1 + v)} (\gamma_A - \gamma_B) = \frac{EIt}{2Q(1 + v)} [(\varepsilon_1 - \varepsilon_2)_A + (\varepsilon_1 - \varepsilon_2)_B]
\]

Reference-Rabbi et al. 2019
Premise of the Topic
Support Condition Assessment

With introduction of a new ‘tie’ circuit, % support can be estimated

For fully rigid support

\[ P - R = 0; \text{ so } \frac{P_c - (P_s - R)}{P_c} \times 100\% = 100\% \text{ Supported} \]

For unsupported tie

\[ R = 0; \text{ so } \frac{P_c - (P_s - R)}{P_c} \times 100\% = 0\% \text{ Supported} \]

Is theory valid under field (or 3D geometry) conditions?
Theory of Differential Shear Strain Measurement Approach

Crib Circuit

\[ P = V_{A(C)} - V_{B(D)} \quad [R=0] \]

Sleeper/Tie Circuit

\[ P - R = V_A - V_B \]

\[ \gamma_{x_{\text{max}}} = \varepsilon_{\text{top}} - \varepsilon_{\text{bottom}} \quad (1) \]

\[ V_x = \frac{\gamma_x E I t}{2Q(1+v)} \quad (2) \]

\[ P - R (\text{Crib} = 0) = V_{A(\text{or},C)} - V_{B(\text{or},D)} = \frac{E I t}{2Q(1+v)} \left( \gamma_{A(\text{or},C)} - \gamma_{B(\text{or},D)} \right) \quad (3) \]
Questions to be Answered

Questions regarding the validity of this approach have been raised in the industry

Questions concern:

✓ Effect of calibration frame dimensions?

✓ Effect of soft zones or gaps underneath crossties?

✓ Effectiveness of this approach in quantifying tie support conditions; can the approach provide more than ‘supported/unsupported’ classification?

✓ Can the impact of ballast degradation on tie support conditions be quantified?
Research Objective and Scope

Recent activities focused on rail stain gauge measurements of wheel loads and tie reactions

1. Effect of calibration configuration

2. Validity of using rail stain gauges to measure tie reactions
Numerical Verification
**Theory: Crib (or Tie) Circuits Evaluation**

<table>
<thead>
<tr>
<th>Applied Load</th>
<th>Reaction Force (RF, kips (kN))</th>
<th>Resultant Force (R=VL-RF, kips (kN))</th>
<th>Strain Location (γ (μm/m))</th>
<th>Estimated Load (P, kips (kN))</th>
</tr>
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<td>44.84 (199.5)</td>
</tr>
</tbody>
</table>

**Applied Force = Strain Gauge Measured Force + Reaction Force**
Theory: Crib (or Tie) Circuits Evaluation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Poisson's Ratio</td>
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</tr>
<tr>
<td>Modulus of Elasticity (Pa)</td>
<td>2.07E+11</td>
</tr>
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</table>

AREMA 3D Model Geometry

- Vertical Load
- Reaction Force
- Gauge Side (GS)
- Field Side (FS)
- Location A (FS)
- Location C (GS)
- Location B (FS)
- Location D (GS)
- 3D Model of Rail Concrete Crossbars

3D Model Geometry

- AREMA 132 Rail
- Concrete Crossbars
- Weak Zone (Variable Modulus)
- Ballast
- Sub-Ballast
- Subgrade

Vertical Load (VL)
Reaction Force (RF)
Parametric Analysis

Impact of weak Zone

Reference-Rabbi et al. 2019
Field Validation
Calibration Systems

A-Frame Calibration Configuration

<table>
<thead>
<tr>
<th>Color Code</th>
<th>Notation</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Crib Circuits</td>
</tr>
<tr>
<td></td>
<td>Tie-2 Full Bridge Circuits</td>
</tr>
<tr>
<td></td>
<td>Tie-1 Full Bridge Circuits</td>
</tr>
<tr>
<td></td>
<td>Load Cell (On Tie-1)</td>
</tr>
<tr>
<td></td>
<td>Instrumented Tie Plate (On Tie-2)</td>
</tr>
</tbody>
</table>

Empty Gondola

Car-body Calibration Configuration
Instrumentation Plan for Ties and Rail

Removed Selected Ties for Instrumentation

Installation of New Ties
Instrumentation Set-Up

Instrumentation List

1. Strain Gauges
2. Instrumented Tie Plate
3. Load Cell
Crib Circuit Calibration
Three Different Calibration Approaches

Obtained calibration constants were independent of the loading configuration

Long-Base A-Frame

Short-base A-Frame

Push Against Rail Car

\[ y = 7.8196x \]

\[ y = 7.8357x \]

\[ y = 7.8388x \]
Load Applied on *Tie-1*

**Load Applied on Top of Tie-1**

1. FB Circuit Shows High Accuracy
2. A part of the load (~3.48 kips) was carried by the tie plate

---

**Graphs and Tables**

- **Graph 1:** Applied Load/Measured Reaction vs. Time (Sce)
  - Applied Load, kips
  - Tie-1, LC, kips
  - Tie-1, FB, kips
  - Tie-1, LC+FB, kips

- **Graph 2:** Applied Load vs. Measured Load/Reaction (%)
  - Tie-1, FB
  - Tie-1, LC
  - Applied Load

---

**Equation:**

\[ F_{\text{Total}} = F_{\text{rail bending}} + F_{\text{Tie-Rail Interface}} \]
Load Applied on **Tie-2**

**Load Applied on Top of Tie-2**

1. FB Circuit Shows High Accuracy
2. A part of the load (~1.36 kips) was carried by the ITP

---

![Graph showing load and strain gauge readings](image-url)

- **FTotal** = **F_rail bending** + **F_Tie-Rail Interface**
Summary and Conclusions

✓ A-frame configuration has no effect on the strain gauge calibration

✓ The wheel load measurements are not influenced by the tie spacing, support condition, etc.

✓ Strain gauge measurements are as reliable as load cell and instrumented tie plate.
Other Configurations Considered

- Moving Load (Locomotives moving at 1, 5, and 10 mph)
- Varying support conditions created by removing certain ties

Dynamic Support Condition Assessment

Track Configurations Considered:
1. Original Condition
2. Remove Tie-A
3. Remove Ties-A & B

Locomotive Speed: 1, 5 and 10 mph

Findings from these additional analyses will be included in future publications and presentations
Acknowledgements

- Harold Harrison
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- Pennsylvania & Southern Railway Staff
Thank You For Your Time

All questions can be directed to:

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