# PRESSURE MEASUREMENTS IN RAILROAD TRACKBEDS AT THE RAIL/TIE INTERFACE USING TEKSCAN SENSORS

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ABSTRACT:

It has been desirable for years to develop non-intrusive/non-invasive procedures to directly measure pressures and stresses at various levels and interfaces in the railroad track structure in order to optimize track designs and improve subsequent track performance. Recent research has developed satisfactory procedures for measuring pressures in the track structure at the ballast/subballast/subgrade levels using earth pressure cells. However, these type cells are not applicable for measuring pressures within the rail base/tie plate/tie interfaces due to the inherent thickness and configuration of the cells. This paper documents the recent development of a technique for measuring the pressures in the track – at the rail/tie plate/tie interface – using a very thin pressure sensitive Tekscan sensor. The Tekscan Measurement System uses a sensor composed of a matrix-based array of force sensitive cells, similar to mini strain gauges, to obtain accurate pressure distributions between two surfaces in the track. Included herein are discussions and descriptions of 1) the proper procedure to calibrate the sensors in a laboratory testing machine, 2) optimum procedure to install the sensors into the track, 3) recommended practices to effectively collect data with the software, and 4) accepted techniques for analyzing the results, 5) test results from numerous in-track tests under a variety of axle loadings, trackbed conditions and supports, tie plate configurations and compositions, and train speeds. The findings attest to the usefulness and practicality of the Tekscan system for accurately measuring uniaxial vertical pressures in railroad tracks. The procedure appears applicable for a wide variety of specific track related measurements to include: 1) analyzing pressure distribution patterns at the rail base/tie plate/tie interfaces to minimize wear and extreme pressure points, 2) validating and optimizing horizontal curve geometric design criteria relative to superelevation, 3) assessing crossing diamond, other special trackwork, and bridge approach impact pressures, and 4) evaluating the advantages/disadvantages of various types of tie plates, fastenings, and tie compositions with the objective of equalizing pressure distributions over the interface areas.

## INTRODUCTION

Many innovative practices have been utilized by the railroad industry in recent years. These provide increased efficiency so the railroad industry can achieve greater profitability and compete with other modes of transportation. Designs and materials selection for the track structure have advanced in recent years to accommodate the increased tonnages and car weights. Continuously welded rail, larger size rail, cleaner steel and premium steel for specific applications represent advances in rail technology. Various new designs and material compositions for ties and fasteners are in use and undergoing evaluations. The advantages of selecting high quality ballast materials are well documented.

Hot mix asphalt (HMA) has been used as a subballast layer to replace granular subballast. A substantial amount of this developmental research has been conducted in the United States at the University of Kentucky during the past twenty years. Papers describing this development have been presented at previous Railway Engineering AREMA Conferences and Exhibitions (Rose, 2000; Rose & Tucker, 2002; Rose, Li & Walker, 2002; Rose & Tucker, 2003; Rose, Su & Long, 2003).

Asphalt underlayments have shown to be particularly applicable to special track features such as railroad crossing diamonds, rail/highway crossings, tunnel floors, and bridge approaches. The underlayment is also applicable to areas of open track with weak subgrades, soft soils or poor drainage. According to the Asphalt Institute there are multiple benefits of a hot mixed asphalt (HMA) layer in a track structure including (Asphalt Institute, 1998):

- A strengthened track support layer below the ballast to uniformly distribute reduced loading stresses to the roadbed (subgrade);
- A waterproofing layer and confinement to the underlying roadbed that provides consistent load, carrying capability for track structures, even on roadbeds of marginal quality;
- An impermeable layer to divert water to side ditches, essentially eliminating subgrade moisture fluctuations;
- A consistently high level of confinement for the ballast so it can develop high shear strength and provide uniform pressure distribution;
- A resilient layer between the ballast and roadbed to reduce the likelihood of subgrade pumping without substantially increasing track stiffness; and,
- An all-weather, uniformly stable surface for placing the ballast and track superstructure.

It has been desirable for years to develop non-intrusive/non-invasive procedures to determine the pressures and stresses at various levels and interfaces in the railroad track structure in order to optimize track designs and improve subsequent track performance. Geokon Pressure Cells are applicable for measuring pressures at the subballast/ballast and subballast/subgrade interfaces (Rose, Li, & Walker, 2002). However, pressure cells are not suitable for use in the upper regions of the track structure. In order to understand the pressure distribution in the entire track structure another method had to be devised.

The research reported in this paper documents the development of a technique for measuring the pressures in the track -- at the rail/tie plate interface -- using a very thin pressure sensitive Tekscan sensor. The system uses a sensor composed of a matrix-based array of force sensitive cells, similar to mini strain gauges, to obtain accurate pressure distributions between two surfaces in the track. This paper specifically describes:

- The optimum procedure to install the sensors into the track,
- The recommended practices to effectively collect data with the software, and
- The accepted techniques for analyzing the results.

Both laboratory calibration and in-track testing have been conducted and the results are presented. The findings attest to the usefulness and practicality of the procedure for accurately measuring pressures in railroad tracks.

## TEKSCAN PRESSURE DISTRIBUTION SYSTEM

Tekscan Inc., the company that produces the force distribution measurement system, provides sensors, software, and technical support for the product. The measurements are made with a thin (≈ 0.1 mm thick) matrix-based sensor consisting of two flexible polyester sheets with silver conductive electrodes printed on them. One sheet has a semi-conductive "ink" printed in rows while the other sheet has the "ink" printed in perpendicular columns. These two sheets of polyester are glued together at the edges. The illustration in Figure 1 shows a basic sensor and its components.

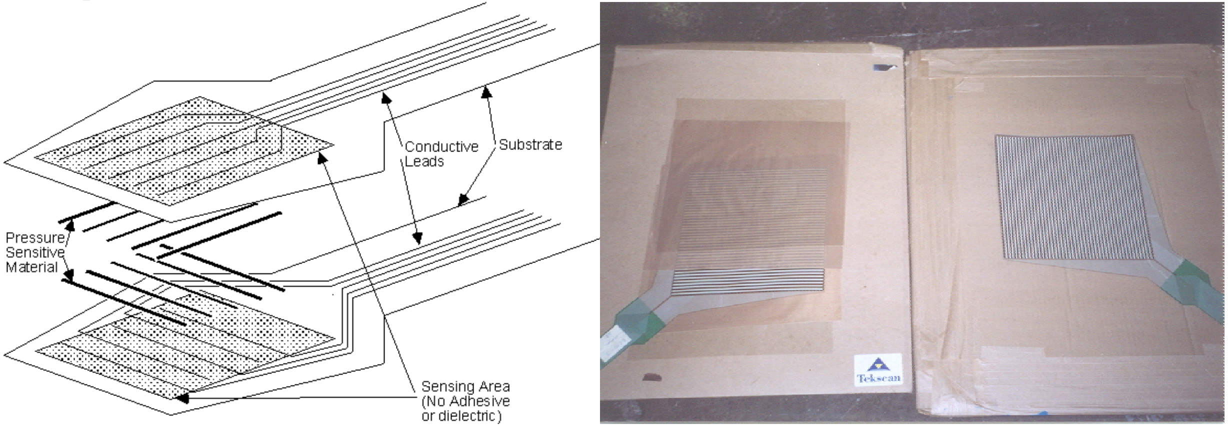

Figure 1. Basic Tekscan Sensor Schematic (www.tekscan.com/technology 2003)

The "ink" is pressure sensitive and its conductivity varies with the force applied to it, similar to a strain gauge. By exciting one row and one column at a time the system isolates the location where the row and column meet which completes the circuit. The force applied is determined by measuring the change in resistivity through the circuit. The process is repeated for all the rows and columns and the distribution of force over the active area is thus determined. This is recorded as a movie with each scanning of the sensor consisting of the frames of the movie.

Tekscan produces sensors of various sizes and shapes. The sensor primarily used in this study was the Tekscan 5250. The 5250 is a square sensor with an active area of 9.68 inches by 9.68 inches (246 mm by 246 mm) and the column and row cell spacing of 0.22 inches (5.59 mm) for a total of 44 cells per row or 1936 total cells per sensor. The factory saturation pressure used was approximately 1200 psi (8.3 MPa). The active area of a sensor is the area covered by the "ink". Within this portion of the sensor, readings can be recorded and it is imperative that all forces considered during a measurement be applied to this part of the sensor.

Saturation of the cell occurs when the pressure reaches the capacity of that particular sensor. Sensors are made for a variety of saturation pressures. The Tekscan sensors are an 8-bit system which means that the cells record a raw value from 0-255. The cell is considered saturated when it reads 255. This capacity is only a few psi for low capacity sensors. This allows for very good resolution over that range. However, for our application a much higher capacity sensor was desirable and used. The 5250 sensor with a capacity of approximately 1200 psi (8.3 MPa) was conveniently available. This made for about 6 psi (41.4 kPa) resolution on our readings. The factory saturation pressure is a recommended usage pressure at which the sensors will read 200 raw units. The actual saturation pressure should be slightly higher.

Several other components, in addition to the Sensor, are essential in order to conduct an experiment and record a measurement. The first is the Data Acquisition Handle which attaches to the sensor (Figure 2). The handle has pogo pins that tightly clamp to the sensor. Those pogo pins make individual contacts with each of the silver leads ends that connect to the columns and rows of "ink".

The handle's wire is then attached to a Magma Box that houses a cardbus-to-PCI expansion system. This box, manufactured by Magma, Inc., is necessary to transform the output from the handle to a form that the computer can input. The Magma box is powered by 110V. The Power

Source can be from a wall jack in the laboratory or from an inverter attached to a 12 V battery at the track site. It is essential for the electricity to the Magma box to be consistent and uninterrupted because if it loses power the data will not transmit to the computer causing it to freeze up and to lose all data from the current test.

The final piece of equipment is a Computer with the I-Scan Software downloaded on it. I-scan is the computer program developed by Tekscan that enables the user to record and analyze data. For our application a laptop was preferred so that in-track tests could be conducted with minimum power usage. Figure 2 is a schematic of the Tekscan system components.

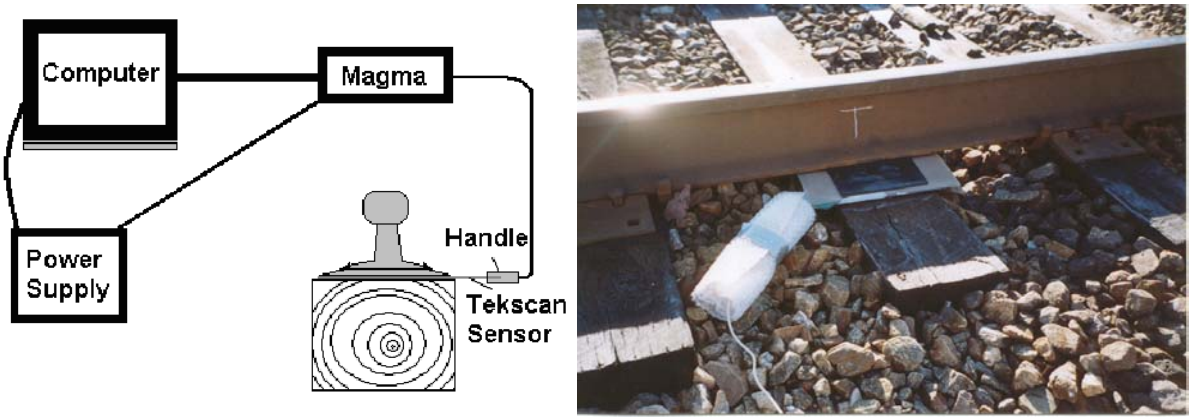

Figure 2. Schematic Diagram of Tekscan Measurement System in the Track

## CALIBRATION

As mentioned previously the Tekscan sensor has an 8-bit output. This means each individual cell reads within a range from 0 to 255. The readings correlate to the resistivity of the circuit. This raw data corresponds to the force applied to the cell and must be calibrated with a laboratory testing machine. When the cell reads 255, it has reached its individual capacity and it is considered saturated. Any additional force applied to the cell will not increase the reading. It is important to make sure the sensor chosen has adequate capacity for the application. This made the initial investigative testing very important because it determined if the saturation pressure would be adequate for our application. Determining the correct procedure to calibrate the sensors has been one of the major research activities.

Calibration tests were originally conducted to increase our familiarity with the sensors and the I-scan software prior to in-track tests. The tests were conducted in the laboratory with a Satec Universal Testing Machine which was assumed to be accurate since the machine had been recently upgraded and calibrated. The Satec Machine is a hydraulic compression and tensile machine with a compression test capacity of 200,000 pounds force. A short piece of wood tie was first placed in the machine and a machined plate, similar to the ones that would be used during in-track testing was placed on the tie. Two metal plates were used to simulate the bottom of the rail base during tests. The arrangement is shown in Figure 3. The results gave good preliminary indications of the kind of results that in-track testing would yield. This allowed us to understand the laboratory test results so that the data from the in-track tests could be interpreted correctly. The calibration tests repetitively showed the sensors to be very accurate under similar loading pressures, times, and materials.

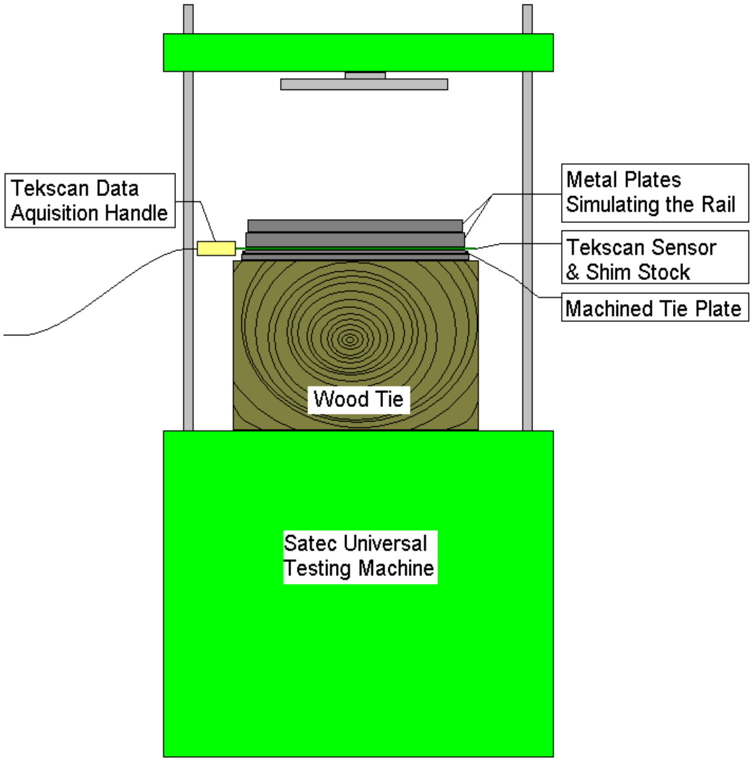

Figure 3. Calibration Test Configuration Using the Satec Universal Testing Machine.

As mentioned previously, developing an appropriate calibration process was a major activity that was necessary to master in order to verify the validity of the new system and to validate tests taken in the track. The most important part of calibration of the Tekscan sensor is to model the in-track test as closely as possible. Due to the nature of the Tekscan System and the unproven railroad track application, it was important that laboratory tests and conclusions be validated with in-track tests. The result was a continuous return to the laboratory after in-track tests to modify and optimize the control set-up to best model new understandings realized from the in-track tests.

In most common Tekscan system applications the loads are normally static of low intensity and vary over a relatively small range. This leads to few calibration problems. However, the sensor does not have a constant output as a constant load is applied. The output drifts higher as the load is applied slowly or statically. In our early laboratory tests this fact was not apparent and loads were applied arbitrarily and the output was recorded.

After our initial in-track tests it was noted that the output was lower than expected. It was determined that the calibration of the sensor was not accurate. One possible problem, mentioned briefly in the Tekscan Users Manual (Tekscan, 2003), is drift. Drift is the change in sensor (and system) output when a constant force is applied over a period of time. Among other things, the drift may be influenced by the sensor design, the sensor sensitivity, the interface material, the applied load, and environmental conditions. It is important to take drift into account when calibrating the sensor, so that its effects can be minimized. The simplest way to accomplish this is to perform sensor calibrations in a time frame similar to that which will be used for in-track test applications. The solution was to apply the loads as rapidly as possible and repeat each test in a similar manner so that accurate comparisons could be made. Because moving trains produce rapid dynamic loadings, the laboratory calibration tests must be conducted as rapidly as possible. According to the manufacturer's Users Manual, the sensors under sustained loading have a drift associated to them. This drift is a logarithmic function of time, about 3% of applied load per log time. Table 1 shows the percentage increase of the output as a constant load is applied to the sensor.

Table 1. Percentage Increase in Applied Load Due to Drift as a Function of Time

| Drift (as a % of applied load) | Time (duration of time load is applied to sensor) |
|---|---|
| 3% | 1 second |
| 6% | 10 seconds |
| 9% | 100 seconds (1 minute 40 seconds) |
| 10% | 215 seconds (3 minutes 35 seconds) |
| 12% | 1000 seconds (16 minutes 40 seconds) |

This drift would not be a factor or problem during in-track testing, because the time duration by each wheel is only a fraction of a second. Calibration was another matter all together. Because the calibration process must be as similar as possible to the field to minimize the effects of drift, the solution to the problem was to load the sensor as quickly as possible for all calibration tests using the Satec Machine. Because the initial tests were first analyzed without understanding drift, the calibrations did not reflect the in-track conditions; thus all the reported forces and pressures were below the expected values.

The origin of the many complications is due to the nonlinear output of the sensor's cells. As mentioned previously, the "ink" resistivity changes as force is applied. The sensor outputs this change as raw units from 0 to 255. However, the correlation between the force and raw output is not one-to-one. Therefore, a rapid calibration test was conducted. The Satec Load Machine recorded specific loads applied while the total raw units and the contact areas were simultaneously acquired by the I-scan software. The results of the test are shown in Table 2.

Table 2. Results from Calibration Test

Calibration of 5250-3 Sensor

| Machine Load Lbf | Total Raw Units Tekscan | Contact Area in^2 |
|---:|---:|---:|
| 0 | 0 | 0 |
| 100 | 905 | 8.18 |
| 200 | 1760 | 12.29 |
| 1000 | 7890 | 28.12 |
| 5000 | 28200 | 39.98 |
| 10000 | 49500 | 42.59 |
| 15000 | 66300 | 43.32 |
| 20000 | 82700 | 43.66 |
| 25000 | 96700 | 44.04 |
| 30000 | 106600 | 44.43 |

| | | |
|---|---|---|
| 35000 | 119900 | 44.87 |
| 40000 | 130400 | 45.06 |
| 45000 | 140350 | 45.54 |
| 50000 | 151700 | 45.88 |

The table shows the calibration of the third 5250 sensor. The left column is the total force in pounds applied by the Satec Machine. The middle column is the total raw units recorded at the instant when the respective loads were applied. The right column is the area that was in contact as the test was conducted. The amount of area that each sensor covers is known because each sensor is made up of the intersection of the rows and columns of “ink.” Therefore, when a sensor records pressure the I-scan software sums the total number of sensors with applied pressure and multiplies that by the area of each sensor to obtain an area of contact. These are the values recorded in the right column.

The next step was to graph the data and determine a curve of best fit. The best fit curve would serve two purposes. First, it would interpolate between all the data points. Secondly, with the equation of the curve, field tests could be conducted with unknown loads and the force applied to the sensor would be accurately determined.

When the Machine Load versus the Total Raw Sum is graphed the data does not produce a straight line. Figure 4 shows the individual data graphed in Microsoft Excel with a linear regression line superimposed and the calculated $R^2$ value shown.

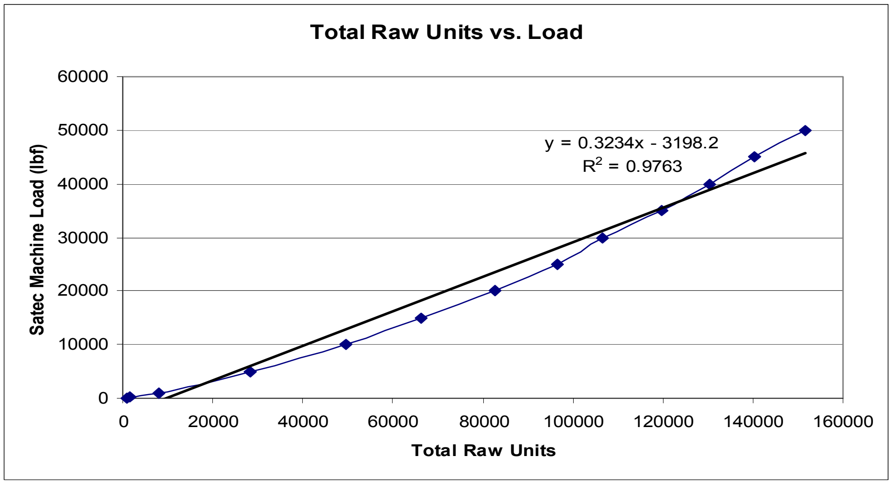

Figure 4. Graph of Total Raw Units vs. Satec Machine Load from Initial Calibration Test with Linear Regression

The linear regression produces an equation of:

$$y = 0.3234x - 3198.2$$

and a $R^2$ value of 0.9763. The closer the $R^2$ value is to 1.0000 the closer the curve fits the data. Note that the line meets the data at two points, approximately 20,000 raw units and 120,000 raw units, at which it would be precisely accurate. Additionally, at loads near where the line meets the data the recorded raw sum would accurately represent the actual load. However, as the load varies, the accuracy would be compromised. While the $R^2$ value is relatively close to 1.0000 it is not satisfactory for our purposes and a better fit was required. The actual nature of the material when graphed gives a power log equation in the form of:

$$Y = Ax^B$$

With the curve varying it was concluded that with multiple power curves the data could more accurately be described.

The data was broken down into several groups and then Microsoft Excel was used to produce multiple curves to fit the data. The curves were examined and the $R^2$ values were compared. As a result of this it was determined that the best representation of the data was using three curves. One curve was used for the <u>low end</u> values or values up to 8,000 raw units. This is used for the unloaded track tests. A second curve was used for the <u>middle</u> values of force between 8,000 raw units and 105,000 raw units. This is used for the empty (unloaded) car tests, 50,000 to 60,000 pounds. A final curve was used for <u>high end</u> values or values over 105,000 raw units. This is used for loaded cars and locomotives test, 263,000 to 286,000 pounds.

Figures 5, 6, and 7 shows the same data with three separate power curves applied to different ranges. With the collection of all three curves the data is represented very well.

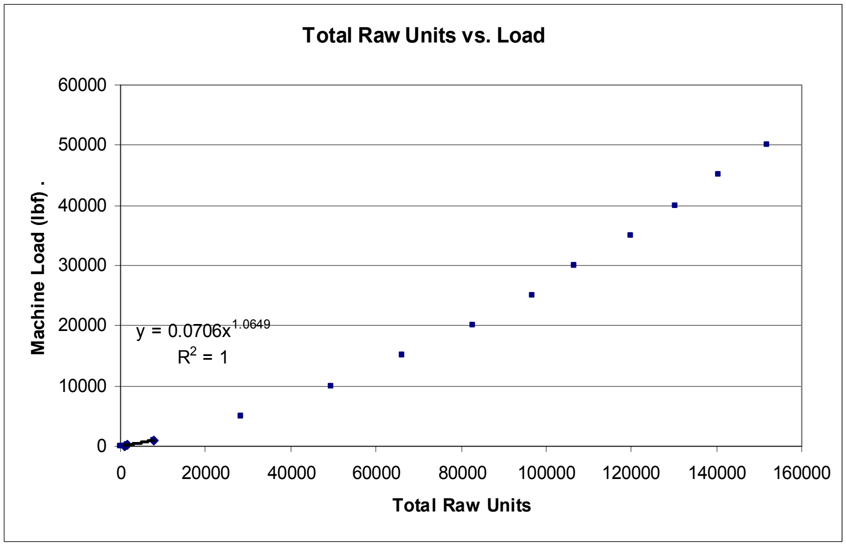

Figure 5. Graph of Total Raw Units vs. Satec Machine Load from Calibration Test with Power Curve Regression applied to Low End Forces

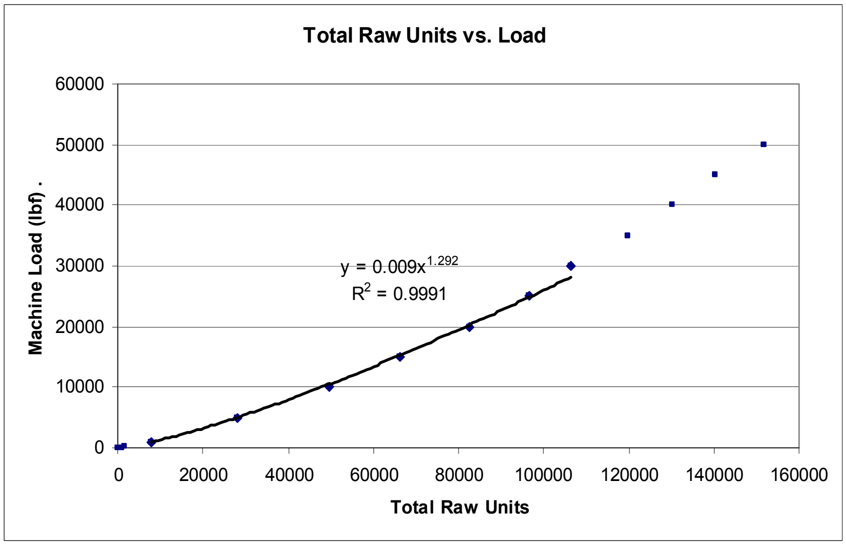

Figure 6. Graph of Total Raw Units vs. Satec Machine Load from Calibration Test with Power Curve Regression applied to Middle Forces

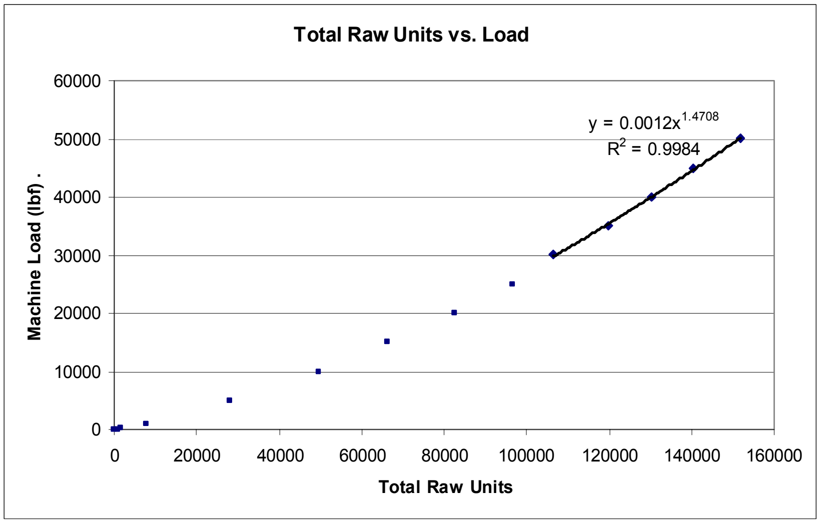

Figure 7. Graph of Total Raw Units vs. Satec Machine Load from Calibration Test with Power Curve Regression applied to High End Forces

Note that these $R^2$ values range from of 0.9984 to 1.0000. These three curves follow the data very closely and give the best representation of the data. Of course the primary purpose of calibration is to subsequently record accurate measurements in the track. These curves will allow for that with the number three 5250 sensor. Additionally, calibration allows familiarization of the system in a laboratory controlled environment prior to in-track testing.

## IN-TRACK TESTING PROCEDURE

Many aspects of track environment testing are not present during laboratory testing. A factor that had to be considered and resolved was the unusually harsh nature of the railroad track. Previous Tekscan applications had primarily been done in controlled interior environments and had not been subject to all the elements that are present in a railroad track. The sensors are applicable for force applied orthogonal to the sensor. But because of their thin design, puncture by sharp edges or corners is a real concern. In addition, the sensor is composed of two flexible polyester sheets making it susceptible to delamination caused by shear force. To prevent this, two thin Teflon sheets, 0.15 mm thick, were used on either side of the sensor to reduce friction and prevent shear forces that might build up during tests. To prevent puncturing of the sensor, two Mylar sheets, 0.18 mm thick, were used on each side of the Teflon. The added shim stock plus the thickness of the sensor itself added only 0.89 mm of thickness. With this thin insertion into the track the chance that any altercation is minimal; thus a non-intrusive/non-invasive technique to determine pressures in the track structure is obtainable.

There are a few protocols that have to be followed prior to any in-track testing. The roadmaster can obtain the track time needed to install and later remove the sensor, each activity takes approximately 10 to 15 minutes. The required equipment that must be assembled to install a sensor in the track is a spike puller, hydraulic jack, and sledge hammer. The in-track plate must be removed and a different plate is placed in the track along with the sensor.

### CSXT Richmond, Kentucky Test

These initial in-track tests were performed adjacent to the CSXT Main Street Railroad crossing. A modified plate with a ground surface at the rail/ plate interface was used to replace the existing plate. CSXT personnel raised the rail high enough for removal of the existing plate and placement of the Tekscan sensor and plate in the track structure.

Another challenge arose from the types of materials being used in our tests. The steel rail base and steel plate are two very rigid and uneven surfaces. It is difficult to obtain uniform pressure distribution between the two surfaces. It was known from previous laboratory work that a potential problem could arise from the uneven distribution of pressures. Before conducting the initial test at Richmond a plate was ground by the Machine Shop at the University of Kentucky and used for the Richmond test. The output from the sensors showed that the force was concentrated over a few small areas of the sensor. This produced a few very high pressure peaks as shown in Figure 8. It is obvious that rigid objects such as commercially produced plates and rail bases will inevitably have a few high contact points on their supposedly "flat" surfaces. From geometry, it is known that three points define a plane. So a plate's three highest points would be the "high plane" of the plate. Assuming the plate does not deform, these three or possibly four high points would take the entire load applied to the plate resulting in very poor pressure distribution. This was precisely what we found from our initial tests. Figure 8 is from an initial test run under the middle wheel of a 6-axle locomotive near the Main Street Crossing in Richmond.

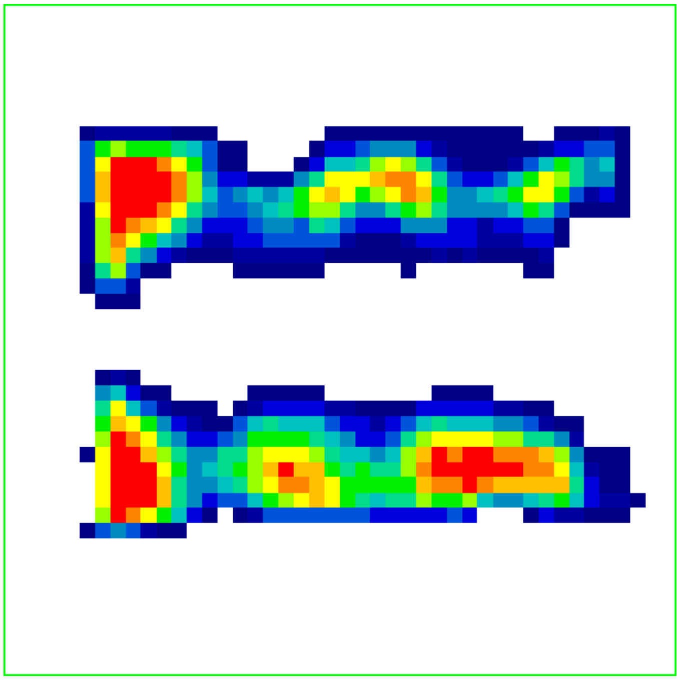

Figure 8: Initial Test; Pressure Distribution under 6-Axle Locomotive between Base of Rail and Top of Plate.

The colored areas indicate the points of contact with the red showing the highest pressure. Note that there are three red areas representing the three highest points on the plate.

In the laboratory the problem was explored, but the severity was not understood until the in-track tests were conducted. Because the pressure distribution was poor and the peak pressures too high, a modified procedure had to be developed that would distribute the pressure more evenly and reduce the exceedingly high pressure peaks. The solution was two fold 1) substituting the existing plate with a commercially machined smooth steel plate or a plate made of a smooth, softer material (polyurethane plastic or rubber) and 2) by adding a rubber (fluid filled) bladder shim stock that could furthermore evenly distribute pressures over a steel plate.

The steel plate alone was found unsuitable for the initial test being conducted at Richmond. Other types of plates were subsequently evaluated for possible application as a substitute. For the subsequent laboratory tests, polyurethane plates and rubber plates were obtained. Obtaining a basic understanding of the nature of these materials and their effect on the Tekscan sensor was a concern and the subject of later laboratory and in-track tests.

The Richmond test also provided information relative to the optimum arrangement of the shim stock. It was determined from tests that the Mylar should be on the exterior to protect the sensor from being punctured by rocks or sand. The Teflon was placed above and below the Tekscan sensor so that no shear forces would develop to adversely affect the reading or damage the sensor. Another observation made at Richmond was that the shoulders of the plate needed to be removed so that the life of the sensor would be extended. The new plates were ordered with shoulders removed and surfaces machined. Figure 9 shows the three plates. The left plate is the machined plate with the shoulders removed. The middle plate is the ground plate done by the University of Kentucky machine shop. The right plate is a used plate removed from the railroad track.

Figure 9: Machined, Ground, and Existing Plates.

<u>TTI Test Paris, Kentucky</u>

After learning from the experiences at Richmond, corrections were made to address the problems that were discovered as a result of the early test. The next step was to return to the trackbed to conduct tests to verify that our model was correct and our calibration procedure was justified.

Our next in-track tests were conducted at the TTI rail yard in Paris, Kentucky. TTI is a short line railroad that allowed us to use one of their 4-axle locomotives for repeated tests in their rail yard. This had many advantages, most notably, that we would not have variations in the train consist. The same locomotive would repetitively load our sensor and give us a good comparable sampling for analysis purposes. One other variation that was considered negligible was the jointed rail in the rail yard, which is different from the continuously welded rail in the majority of main line tracks. The main activity to be examined was to evaluate different types of plates – machined steel, polyurethane, and rubber.

The test involved the locomotive passing over the sensor at 4 mph in one direction. Then the locomotive reversed directions and passed over the sensor at 2 mph in the other direction. Several different configurations of plates and sensors were used. Two tests were recorded for each configuration. The configurations were:

1) Machined steel to re-examine the results from Richmond.
2) Machined steel with a rubber fluid filled bladder to assist in distributing the load.
3) Polyurethane plastic plates with the shoulders removed.
4) Polyurethane plastic plates with a rubber fluid filled bladder.
5) Thin Polyurethane plastic plate with a rubber fluid filled bladder to see if the full thickness plate produced any bridging effect.

Figures 10 and 11 are representative samples of two configurations evaluated at TTI rail yard. Notice that the first test (Figure 10) reconfirms that even with machined plates the rail/plate interface is too uneven to prevent a small contact area and saturation of the sensor's cells. This can be compared to the next test run (Figure 11) with the fluid filled bladder. Note that the pressure is distributed with no saturation and an accurate measurement was obtained. With the success of the machined steel and rubber bladder, most subsequent tests were preformed without using polyurethane plates. Steel is likely to be the predominate plate for wood ties for many years.

The same one point calibration curve was applied to all of the previous results. Note that the recorded force is slightly different with about a 25% higher recorded value using the polyurethane plate and a rubber bladder or ground steel plate and rubber bladder as opposed to using the rubber plate. This difference can be accounted for in two ways. Later laboratory tests showed that the sensor's output was affected by the material used in the test. That accounts for much of the difference. It is also the reason the note at the bottom of each result has a corrected force value from calibration curves determined at a later date. However, the rubber still shows a 10% lower value of the force applied by the same train. This can be accounted for by realizing that the ground plate and the polyurethane plate were approximately the same thickness as a typical plate. Then by adding a bladder it can cause a bridging effect which would increase the load applied to that tie. This was corrected in later tests by having machined plates from the manufacturer that were machined thinner to compensate for the added thickness of the bladder.

### CSXT Conway, Kentucky Test

These in-track tests were conducted at Conway, Kentucky later in our testing program. This is a section of open track on CSXT main line between Cincinnati and Atlanta. A variety of trains were measured. A loaded coal train, mixed freight train, and five locomotives were utilized for several tests. The main activities examined were:

1) To evaluate the ability of Tekscan to record higher speed trains in a section of open track,
2) To evaluate the effects of different types of plates – machined steel, polyurethane, and rubber, and

The scan speed of the Tekscan 5250 is 147 frames per second. For a train traveling 30 miles per hour or 44 feet per second the 9-inch 5250 sensor will record a little more than two frames in the time it takes for the wheel to move over the sensor. The result is a less accurate measurement. However, the capability is available and was utilized to record five locomotives in figures 12. The frame vs. force plot shows how fast the five locomotives moved past the sensor recording the event in less than 2000 frames.

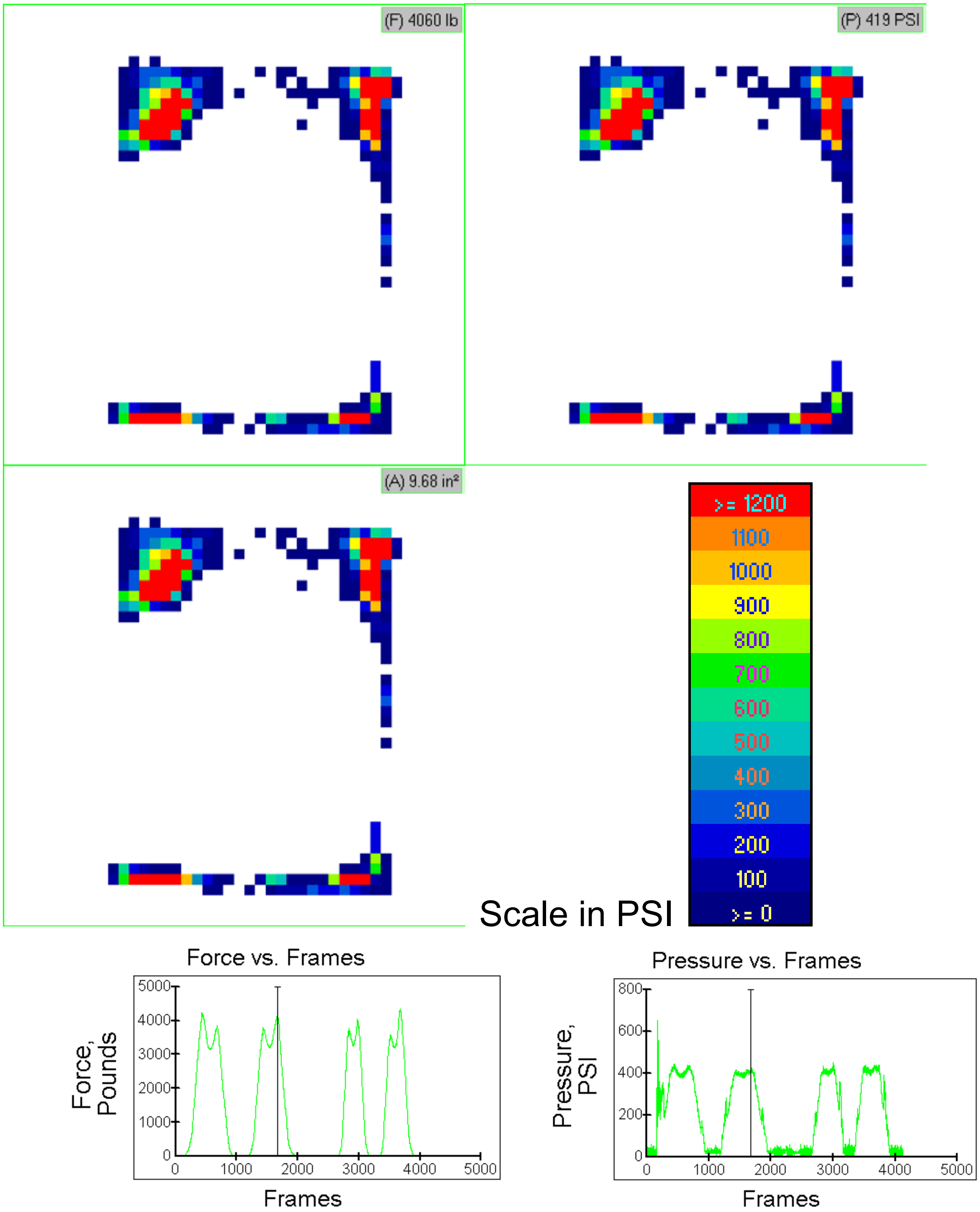

Figure 10. This represents a typical pressure distribution between a steel plate and the rail. There is very little contact area. The sensor has a 1200 psi capacity and the red areas indicate saturation zones. The forces applied at these areas are probably much higher than the 1200 psi recorded and that would lower the overall force recorded.

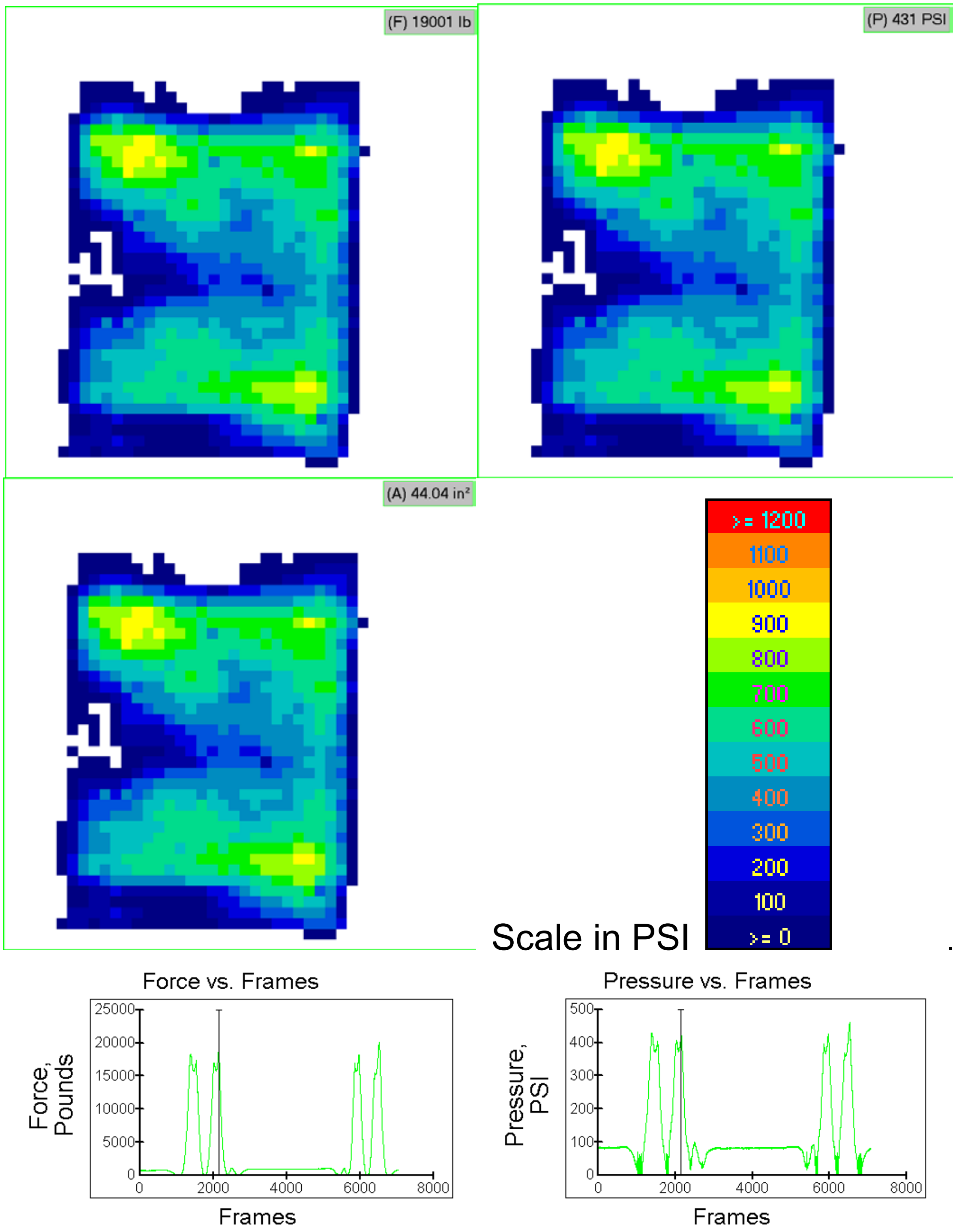

Figure 11. This represents a typical pressure distribution between a machined steel plate and the rail with an included rubber bladder. There is good contact area with good representation of the pressures. The sensor had a 1200 psi capacity and there was no saturation of the sensor in this test. Using the calibration curves from revised laboratory tests the actual force applied would be approximately 24,000 lbs rather than the 19,000 lbs shown. The difference was due to the initial lack of understanding of the Tekscan sensor calibration process.

In addition, to the test conducted at TTI rail yard on several plate materials, an additional test was conducted at Conway on a rubber plate. The distribution of pressure was good, but the overall pressure read low and the calibration of rubber was not as consistent as other materials. It was therefore concluded that evaluating rubber plates was beyond the scope of this project and its applications could be better explored later. Figure 13 shows the results of the rubber plate test. Note that the pressure shown is considerably lower. This is due to two factors:

1) Tekscan sensors have a varied output that depends on the materials that apply the force to the sensor, and
2) The rubber actually distributes pressure better. Note the larger contact area of 53.34 in$^2$, or more than 10% larger than the usual 48 in$^2$.

These two factors contribute to the extremely low pressure recorded by the sensor on the rubber plate.

## INTERPRETING DATA

Once a recording is made, especially after a dynamic test, the amount of information collected is enormous and understanding it becomes a challenge. The first step is to edit the file and delete all unimportant or erroneous data. For example when conducting an in-track test it may be important to record the entire train which may take 15,000 to 20,000 frames depending on the length and speed. It is impossible to analyze or plot this data in a meaningful way other than to distinguish differently loaded sections of intermodal or mixed freight trains. During the tests conducted for this research it was important to compare and contrast similar loads using different plates, located in different track features, and with different trains. It was therefore important to assume some constants when analyzing the data. The major assumption was that all similar locomotives weigh about the same. The result of this assumption was that most all of our test analyses were comparing and contrasting the differences under the locomotive in each test. The error introduced by this assumption would be minimal with few variables affecting the weight between locomotives, none of which are significant when compared to the locomotives massive weight, such as amount of fuel and sand on board. It was thus important only to have the data collected while the locomotive was over the sensor. The I-scan software allows for many kinds of editing (Stith, 2004).

Teksan's I-Scan software provides two ways for calibrating the sensors, a one point calibration or a two point calibration. These two calibration methods are applicable depending on the application, the sensor used, and the purpose of the test. A one point calibration assumes a linear output of the sensor noting that zero force applied results in zero total raw sum of output. After a known load is applied the total raw sum at that point is associated with the load and a linear extrapolation is calculated by I-scan using the two points to determine a slope and then the point slope form to calculate the line. One point calibrations can be performed one of two ways. The first on is during a real time recording when a known load is applied. The software performs the calibration as a dynamic calibration. Second, if a recording of a movie is made and a known load is applied at a particular time or frame, then a frame calibration can be preformed. The real time calibration is appropriate for laboratory settings when a known load is being applied and a movie recording is not necessary for the test being conducted. However, if an in-track test is recorded with some known loads and others unknown then a frame calibration is necessary. The known load can be used to calibrate the entire movie. This also allows for random non-applicable forces to be edited out and only the known applicable forces are considered.

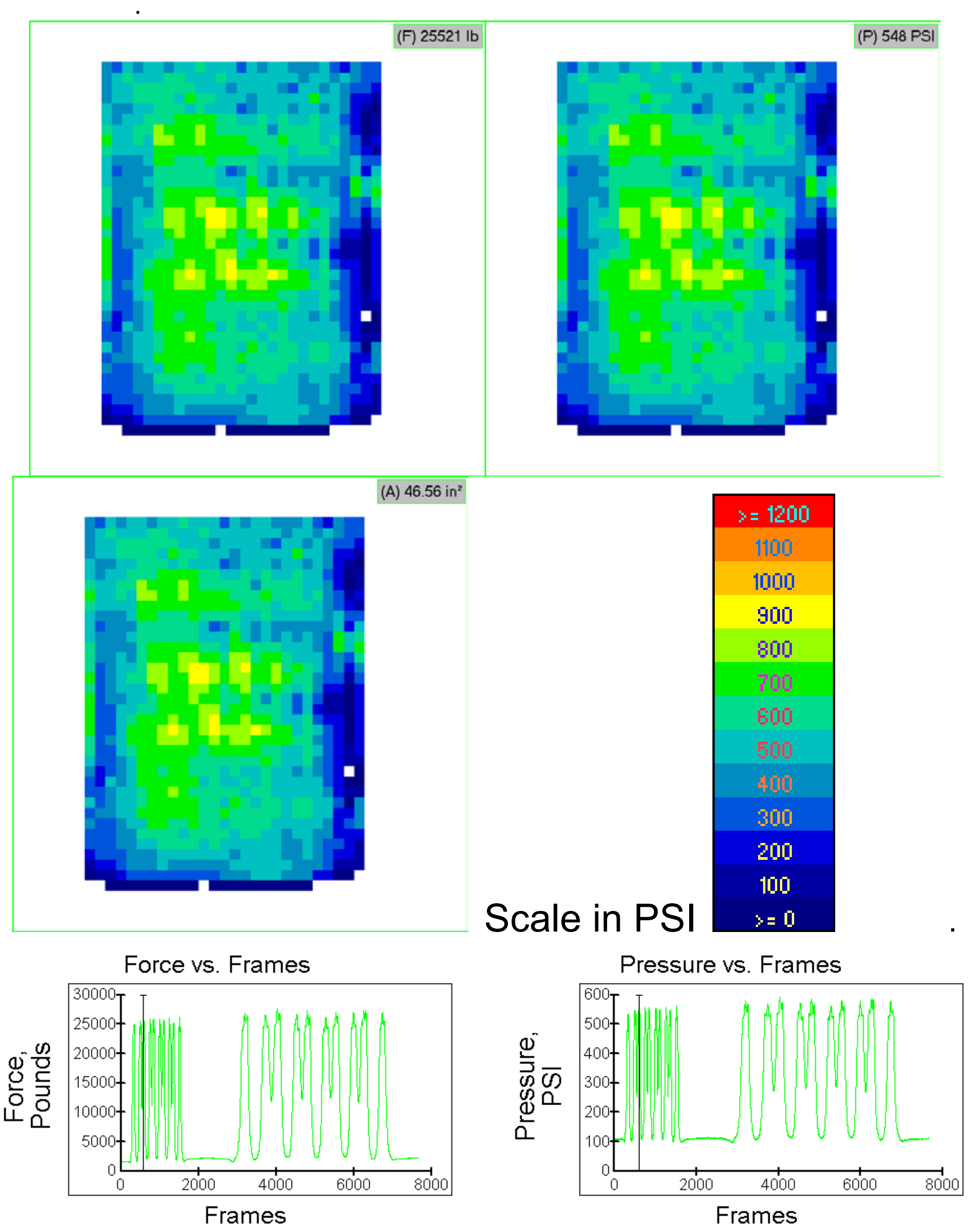

Figure 12. This represents a typical pressure distribution between a polyurethane plastic plate and the rail. Note that there is good contact area with good representation of the pressures. The sensor had a 1200 psi capacity and there was no saturation of the sensor in this test. The speed of the train was approximately 30 mph.

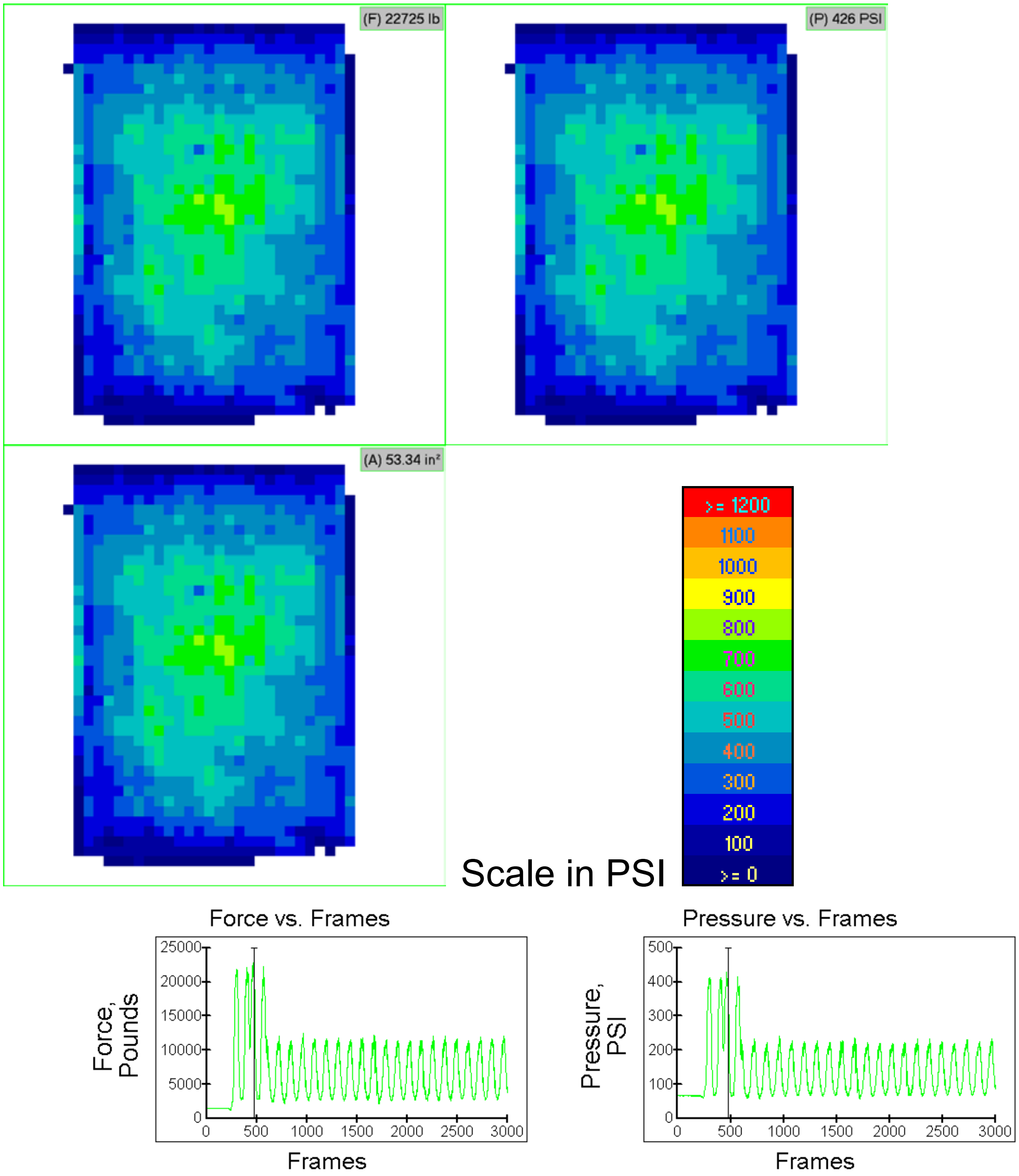

Figure 13. This represents a typical pressure distribution between a rubber plate and the rail. The lead truck of the second 6-axle locomotive is represented. Note that there is good contact area with good representation of the pressures. The sensor had a 1200 psi capacity and there was no saturation of the sensor in this test.

The second type of calibration is a two point calibration which takes into account the nonlinearity of the sensor's cells. A two point calibration uses the same zero force equals zero output assumption, and then calculates a power logarithmic curve using two other calibration points. The two point calibrations can only be done in real time. The method is similar to a one point real time calibration, but another point is added at a different load. It is usually beneficial to use the two point calibration method when measuring widely varying loads. It has also been determined that calibration points should be below and above the working loads expected during a test. This prevents extrapolation of the curve which can vary widely as loads exceed calibration loads. It is important to note that applying the power logarithmic curve works with the assumption that as a load is applied to the cells the output per unit load will continually decrease and the calibration curve will compensate for the difference. Both one point and two point calibrations can be saved as a calibration file and applied later to any movie.

These two methods allow for a range of applications. A one point calibration is desirable for applications where similar loads are recorded repeatedly. In contrast, tests conducted with varying loads, such as within the track structure, a two point calibration would be advantageous.

The different calibration methods are significant when presenting the data. The information from the test is compiled by I-scan. The data is presented in a picture form which corresponds to the sensors output. One point calibration assumes a linear output and shows the variation of the cells output accurately. This presents an accurate pressure distribution with higher and lower pressure areas shown to scale, but total loads that vary from the calibration load may be undervalued or overvalued. In contrast, the two point calibration under estimates the lower pressure areas and over estimates the higher pressure areas. The total load is recorded accurately, but the distributions are distorted.

Figures 14 and 15 are the same frame of a movie recorded in Paris, Kentucky at a TTI rail yard on August 1, 2003. The frame shown is the load under the first wheel of a 4-axle locomotive. Figure 14 is the frame shown with a one point calibration applied at a 10,000 lb. The distribution is good, but the total load shown in the upper right corner of the figure is lower than expected. Figure 15 however, shows the same frame with a two point calibration applied. The two point calibration was calculated using 10,000 and 30,000 lbs. This figure shows a total force very close to the expected value, but the distribution is distorted.

Figures 14 and 15 were recorded with machined plates and a fluid filled rubber bladder inserted in the track and replacing the used plate. The distribution of force over the entire plate is very good in both figures, but in figure 15 the higher pressures are exaggerated and show up as red areas, while the light blue areas, low pressure areas, of figure 14 show up as dark blue areas, lowest pressure, in figure 15. The pressure scale has 13 color gradients representing different levels of pressure.

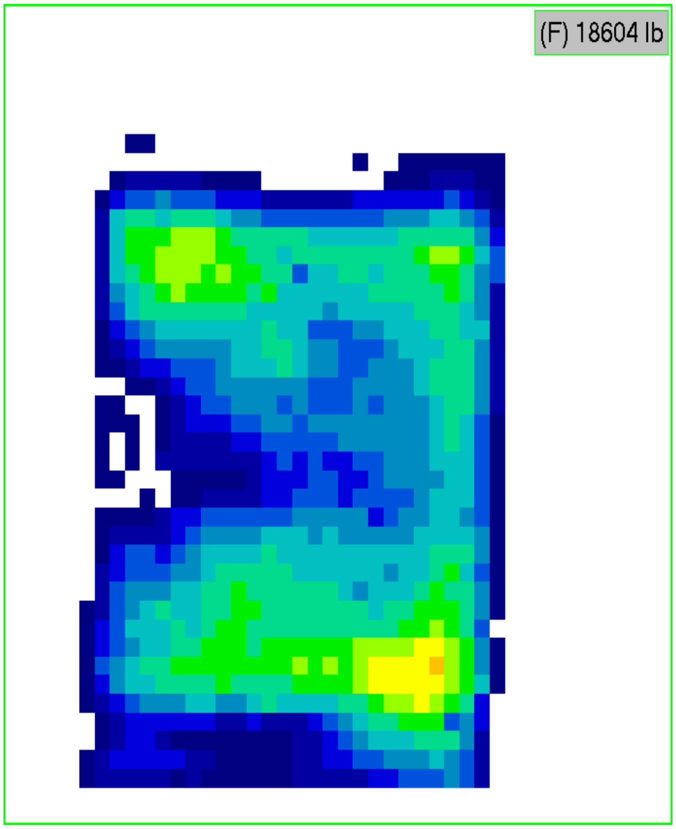

Figure 14. One Point Calibration of Frame Showing Front Wheel of 4-Axle Locomotive at TTI Rail Yard

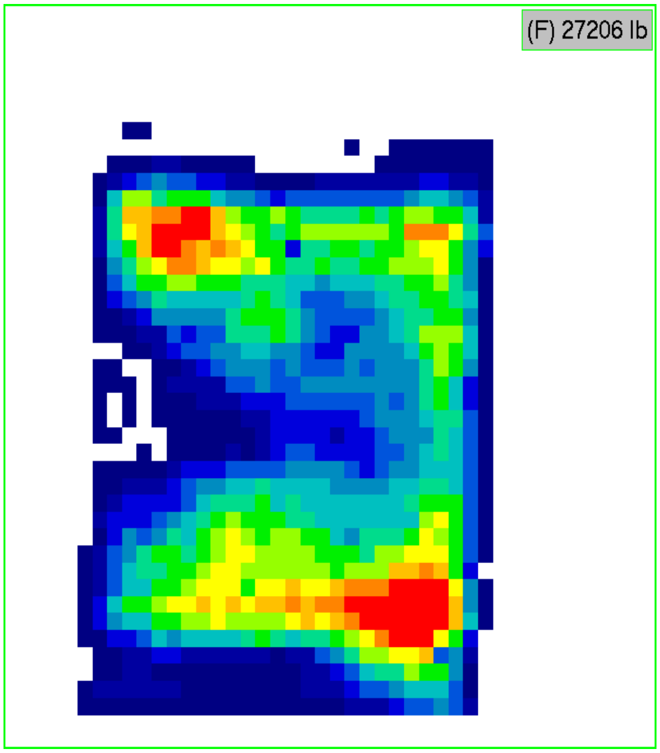

Figure 15. Two Point Calibration of Frame Showing Front Wheel of 4-Axle Locomotive at TTI Rail Yard

## CONCLUSIONS

The Tekscan system is applicable for railroad trackbed evaluation and can be used to measure pressures within the track structure. The non-intrusive nature of the Tekscan sensor makes it ideal for the upper region of the track structure specifically the rail/plate interface. After multiple laboratory and in-track tests the repeatability of the sensor has been shown to be very good. The repeatability is dependent on the loads applied, rate of loadings, and the material surfaces surrounding the sensor.

It was determined that inserting a thin rubber bladder between the rail base and sensor, when using a steel plate, will distribute the pressure over a larger contact area. Shim stock is necessary to protect the sensor. This consists of thin Teflon and Mylar sheets surrounding the sensor during test. Calibration of the sensor must be done in the laboratory under conditions similar to that which will be experienced during in-track test. A three-range calibration technique is required to adequately measure a wide range of loading intensities. Also, the calibration technique must utilize rapid loading on the test machine to minimize the effects of drift. The best way to extend the life of a sensor is to clean the tie area when inserting the sensor in the track and to take pro-active steps to protect handle and sensor from moisture and dirt.

The procedure discussed within this paper exemplifies the use of an existing technology for a new application. The potential applications for future work are vast for specific track related measurements. Validating curves geometric design criteria, assessing crossing diamond and bridge approach impact pressures, and evaluating the advantages/disadvantages of various types of plates, fastenings, and tie compositions may all be within the capacity of this system.

## ACKNOWLEDGEMENTS

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