RAILROAD TRACK PRESSURE MEASUREMENTS AT THE RAIL/TIE INTERFACE USING TEKSCAN SENSORS

Jason C. Stith
University of Kentucky
ABSTRACT OF MSCE THESIS

RAILROAD TRACK PRESSURE MEASUREMENTS AT THE RAIL/TIE INTERFACE USING TEKSCAN SENSORS

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. Recent research has developed satisfactory procedures for measuring pressures in the track structure at the ballast/subballast/subgrade levels using earth pressure cells. The research reported in this thesis documents the development of a technique for measuring the pressures in the track, at the rail/tie plate/tie interfaces, 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. This thesis specifically describes: 1) the optimum procedure to install the sensors into the track, 2) the recommended practices to effectively collect data with the software, and 3) 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. The procedure may also be applicable for a wide variety of specific track related measurements such as validating curve geometric criteria, assessing crossing diamond impact pressures, and evaluating the advantages/disadvantages of various types of tie plates, fastenings and tie compositions.

KEYWORDS: Railroad Track, Pressure Distribution, Experimental Measurement Technique, Tekscan Sensor, Rail/Tie Plate Interface Pressure

Jason C. Stith
April 29, 2005
RAILROAD TRACK PRESSURE MEASUREMENTS AT THE RAIL/TIE INTERFACE USING TEKSCAN SENSORS

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RAILROAD TRACK PRESSURE MEASUREMENTS AT THE RAIL/TIE INTERFACE USING TEKSCAN SENSORS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the College of Engineering at the University of Kentucky

By

Jason Clarence Stith
Lexington, Kentucky

Director: Dr. Jerry G. Rose, Professor of Civil Engineering
Lexington, Kentucky
2005
I dedicate this thesis to the memory and legacy of my grandfather Muriel “Lefty” Stith. He was a farmer who valued education and instilled those values into his children who all received their Masters Degrees and subsequently helped in the formation of my education to date and continues to be a source of inspiration and wisdom.
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In addition to the assistance above, I also received equally important assistance from my family. My wife, Samantha Stith, provided support and assistance throughout the thesis process. My father and mother, Richard and Veronica Stith, also provided support and encouragement. The assistance of these individuals has been invaluable.
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Chapter One

Introduction and Scope of Research

Background

On May 10, 1869 at Promontory, just outside Ogden, Utah, crews from the Union Pacific Railroad working from the east and crews from the Central Pacific Railroad working from the west met for the famed ‘Golden Spike Ceremony’ to celebrate the completion of the first transcontinental railroad. This was the precursor for western expansion and the growth of a great nation. Since that time of inefficient coal powered locomotives traveling on light-duty tracks built by armies of men, the railroad industry has strived to be a more efficient and productive operation while providing reliable service to its customers. This has been achieved by innovations in all areas of the industry. Today 6,000 hp locomotives pull ever increasing loads. Railcar axle loads of 36 tons are common and experiments continue with 39 ton axle load cars. This increased efficiency is making the modern railroads more profitable and a greater competitor to the highway trucks that have taken large shares of the transportation freight market. However, these ever increasing loads carried by the rail cars demand a superior track structure to withstand the loadings.

Innovation in this area has been slow with very few changes from the original track structure design and materials selections of 100 or more years ago. Continuously welded rail was a major step which eliminated the pressure peaks at the joints that would cause rapid deterioration of the rail. In addition, the size
at the joints that would cause rapid deterioration of the rail. In addition, the size of rail has continuously increased with 132, 136, and 140 lb/yard rail used regularly today. Research with steel, concrete, and composite ties has progressed, but wide implementation has yet to be adopted. Hot mix asphalt underlayment as a subballast layer (replacement for granular subballast) in the track structure, has shown promise. Extensive research in the latter has been conducted at the University of Kentucky over the past 20 years with continuing success (Rose, 2000; Walker, 2002; Rose, Walker & Durrett, 2002; Rose, Li & Walker, 2002; Rose & Tucker, 2003; Rose, Su & Long, 2003).

The 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.

Trackbed Settlement Studies

These advantages have been documented with both observations and experiments. Settlement studies have been conducted at rail/highway crossings to demonstrate the prolonging effects of a superior subgrade. Tracks with an asphalt underlayment settle about 1/3 to 1/2 as much the adjacent sections of open ballast track (Adwell, 2004). Normally the highway approach elevations change very little while railroad track will settle into the ballast and then maintenance crews will raise the track and renew the crossing periodically as needed. This causes problems at the rail/highway crossing and a stiffer track structure is desirable to minimize settlement and ensure a smooth level crossing surface.

The settlement study was accomplished by monitoring several rail/highway crossings. Elevations were taken on top of the rail for 100 feet on either side of the crossings. The rail elevations were recorded shortly after installation of the HMA underlayment and then periodically for over a year. Figure 1.1 shows a representative example of the top of rail elevation at a typical
crossing without an underlayment. Note that the settlement is almost constant along the track (The bold line indicates the crossing area). Figure 1.2 shows a representative example of a top of rail elevation at a typical crossing with an underlayment. Note that the elevation difference initially was uniform. However, after the initial compaction of the ballast the elevation difference in the middle portion, where the underlayment was present, was much less than the settlement on either ends which is a normal open track all-granular structure.

Figure 1.1: Typical Rail/Highway Crossing Elevations after Reconstruction without a HMA Underlayment
Figure 1.2: Typical Rail/Highway Crossing Elevations after Reconstruction with a HMA Underlayment

**Trackbed Pressure Studies**

In addition to settlement studies, tests have been conducted at the University of Kentucky to understand how HMA underlayment provides better pressure distribution in the track structure by measuring the pressure on the asphalt layer. This prior research was accomplished by using Geokon Model 3500 Earth Pressure Cells consisting of two stainless steel nine inch diameter cylindrical disks (Walker, 2002). The disks are sealed at their periphery and filled with de-aired hydraulic fluid (Figure 1.3). As pressure is applied to the cell the fluid is forced out the connected tube. This tube contains a pressure transducer, which converts the pressure of the hydraulic fluid into an electrical signal that can
be read by the computer. A schematic diagram of the test process is shown in Figure 1.4.
After initial tests with the cells located in several areas of the track it was determined that the highest pressures were located directly under the rail-cross tie intersection with very low pressure under the rail in the crib of the track or in the center of the track. Table 1.1 is a summary of the typical train loading.

Table 1.1: Typical Train Loadings

<table>
<thead>
<tr>
<th>Loading Type</th>
<th>Total Weight (lbs)</th>
<th>Wheel Load (lbs/wheel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-Axle Locomotives</td>
<td>395,000 – 432,000</td>
<td>33,000 - 36,000</td>
</tr>
<tr>
<td>4-Axle Locomotives</td>
<td>262,000 – 288,000</td>
<td>33,000 - 36,000</td>
</tr>
<tr>
<td>Loaded Coal Hoppers</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>263,000</td>
<td>33,000</td>
</tr>
<tr>
<td></td>
<td>286,000</td>
<td>36,000</td>
</tr>
<tr>
<td>Empty Coal Hoppers</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50,000</td>
<td>6,250</td>
</tr>
<tr>
<td></td>
<td>63,000</td>
<td>7,900</td>
</tr>
<tr>
<td>Loaded Auto Carriers</td>
<td>72,000 – 80,000</td>
<td>9,000 – 10,000</td>
</tr>
<tr>
<td>Empty Auto Carriers</td>
<td>27,000 – 35,000</td>
<td>3,375 – 4,375</td>
</tr>
</tbody>
</table>

The average peak pressures recorded were approximately 14-17 psi at the ballast/subballast interface under 36,000-lbf wheel loads. Figures 1.5 and 1.6 are typical pressure readings at the ballast/HMA layer using Geokon pressure cells at two different locations (Walker, 2002).
Figure 1.5: Loaded Auto Train at Richmond

Figure 1.6: Empty Coal Train at Conway
The pressures under the locomotives on the HMA underlayment are only two to three times greater than the pressure of a normal size person standing directly on the asphalt or one-tenth the pressure under most semi-truck tires on a highway pavement surface (see Figure 1.7).

![Pressure Comparison Image]

<table>
<thead>
<tr>
<th>Load</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>286,000 lb</td>
<td>13 - 17 psi</td>
</tr>
<tr>
<td>62,000 lb</td>
<td>2 - 4 psi</td>
</tr>
<tr>
<td>180 lb</td>
<td>6 psi</td>
</tr>
<tr>
<td></td>
<td>100 - 200+ psi</td>
</tr>
</tbody>
</table>

Figure 1.7: Vertical Pressure on Asphalt Surfaces for Various Loadings

The additional cost of the asphalt underlayment has been found to be minimal adding only 3% to the rehabilitation cost. It has been determined that the best way to obtain all of these advantages at a minimal cost is by cooperative arrangements of the railroad companies and the local highway agencies (Walker, 2002).
Objectives and Scope

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. As mentioned previously the Geokon Pressure Cells are applicable for measuring pressures at the subballast/ballast interface. 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 thesis documents the development of a technique for measuring the pressures in the track -- at the rail/tie plate and tie plate/tie interfaces -- 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 thesis specifically describes:

1) The optimum procedure to install the sensors into the track,

2) The recommended practices to effectively collect data with the software, and

3) 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. The procedure may also be applicable for a wide variety of specific track related
measurements such as validating curve geometric criteria, assessing crossing
diamond impact pressures, and evaluating the advantages/disadvantages of
various types of tie plates, fastenings and tie compositions.
Chapter Two
Tekscan Pressure Distribution System

After expending considerable effort exploring multiple options for determining pressure distribution in the upper regions of the track structure, it was decided that conventionally available equipment was insufficient. A system manufactured by Tekscan Inc. was subsequently discovered while searching for information on pressure measurement systems. A laboratory demonstration was organized with a representative of Tekscan, Chuck McWilliams. The sensor was first placed at the ballast/tie interface, but the sharp edges of the ballast were deemed unsuitable for the thin polyester pressure sensor. Then a test was conducted with the sensor at the rail/tie plate interface and this location was found to be more suitable for the system.

The initial in-track tests were conducted shortly afterwards on CSX Transportation tracks in the Boston area by Chuck McWilliams and Dr. Jerry Rose. It was concluded that the Tekscan pressure measurement system was applicable for the railroad track structure and could be used to measure pressures under a moving train. It was obvious, however, that considerable effort would be required to develop and apply this technology to obtaining pressure measurements in railroad trackbeds. It is this developmental investigation that comprises the bulk of this thesis research.

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 2.1 shows a basic sensor and its components and Figure 2.2 is a picture of the 5250 Tekscan sensor.

Figure 2.1: 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 two sensors primarily used in this study were the Tekscan 5250 and the Tekscan 5260. The 5250 is a square sensor with an active area of 9.68 inches by 9.68 inches and
the column and row cell spacing of 0.22 inches for a total of 44 cells per row or 1936 total cells per sensor. Appendix A contains the manufacture’s description of the 5250 sensor. The factory saturation pressure used was approximately 1200 psi. The 5260 is a rectangular sensor with an active area of 8.1 inches by 18.9 inches. The 5260 has cell column spacing of 0.36 inches and row spacing of 0.18 inches for a total of 2288 cells per sensor. Appendix A also contains the manufacture’s description of the 5260 sensor. The factory saturation pressure used was approximately 500 psi. 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 (i.e. $2^8 = 256$). The cell is considered saturated when it reads 255. This capacity is only few psi for low capacity sensors. This allows for very good resolution over that range. However, for this research project’s application a much higher capacity sensor was desirable and used. The 5250 sensor with a capacity of approximately 1200 psi was conveniently available. This made for about 6 psi resolution on the 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 2.3). The handle has pogo pins that tightly clamp to the sensor. Those pogo pins make individual contacts with each of the silver lead 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 then 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 this research project a laptop was preferred so that in-track tests could be conducted with minimum power usage. Tekscan, Inc. has set minimum computer recommendations for a laptop to run the I-scan software effectively. Suggested minimum requirements are:

- Pentium 300 MHz
  (Pentium 600 MHz for Multi-Handle Systems)
- 64 MB RAM
• 1 GB hard drive
• CD ROM drive
• Windows operating system 98SE/ME/2000/XP

In addition to these minimal requirements, it can be beneficial to have additional RAM (at least 128 MB) and hard drive (at least 10 GB) to allow for longer movies to be recorded. The maximum length of recording is directly related to the amount of RAM that the computer has available. There are known incompatibilities with I-scan software and the Magma PCI expansion box. The known incompatibilities are:

• Windows 95 and NT – Tekscan software versions 5.20 and higher are not compatible with Windows 95 or NT 4.0
• Laptops using Ricoh Cardbus Controllers
• Laptops with single PCMCIA slot (Windows 2000 & XP only)
• While compatible with Windows 2000 & XP, Magma is typically easier to install with Windows 98SE or ME.

Figure 2.3 is a schematic of the Tekscan system components and Figure 2.4 is a picture from an in-track test showing the placement of the sensor in the track.
Figure 2.3: Schematic Diagram of Tekscan Measurement System in the Track

Figure 2.4: Picture of the Tekscan Sensor During In-track Testing
Chapter Three
Initial Investigations and Richmond Tests

Initial Tests

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 the research project. Determining the correct procedure to calibrate the sensors has been one of the major activities during this study.

Calibration tests were originally conducted to increase 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 tie 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 3.1. The results gave good preliminary indications of the kind of results that in-track testing would yield. This allowed for the understanding of 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. This verified the repeatability of the system.

Figure 3.1: 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 railway 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. After the initial laboratory test the first in-track tests were conducted in Richmond, Kentucky on June 2, 2003.

**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 occurring is minimal; thus a non-intrusive/ non-invasive technique to determine pressures in the track structure is obtainable.

When testing in the track many things are similar to laboratory tests. The procedure to set up the hardware and start the computer is the same and should be followed closely to ensure that the system will operate correctly. The sequence is as follows:

- Connect Magma box to laptop computer.
  - It is important to start by initially attaching the Magma box to the computer so that any voltage difference between the two systems will be eliminated before the power cord is connected.
- Plug power cord into Magma box, then into the power source.
  - During field testing the power is inverted from a 12 V battery to 110 V power.
- Check to see that the green light is illuminated on the Magma.
  - This is a check to make sure that the inverter is working correctly and all connections are made.
  - If the light blinks or flashes it probably means that the power is interrupted and all cords need to be checked to ensure proper connection.
- Plug power cord into laptop, then into the power source.
It has been found that using two separate power sources is preferable during testing, one for the Magma box and the other for the computer. This means having at least two batteries and two inverters, or direct connections to 110 V.

- Power up the computer.
  - It is very important that the Magma box has power and is attached to the computer before starting it, because I-scan is a Microsoft Windows based program. Windows recognizes new hardware while booting up and may freeze or not recognize the Magma box if it is plugged in after the computer has finished booting up.

- Plug handle cord into the Magma box.
  - This can be done before or after starting the computer, it does not matter, but it must be done prior to starting Tekscan.

- Open Tekscan’ software, I-scan, on the computer.
  - If the handle is not attached correctly or the Magma box is not recognized as Windows starts a message box will pop up when I-scan is opening. The message will say, “No handles have been found. The allowed handle types are: Accurate.”
  - I-scan will open at this point, but many of the functions will not be accessible, without the handle being recognized. The next step is to close I-scan and check all cords to ensure proper connection before restarting I-scan.

- Once in I-scan:
• Click File

• Click New Session

• Choose the correct pattern that will be used in the experiment

• Click Handle A (Our unit only takes measurements at a single location)

• Click OK

• Plug handle into Tekscan sensor.
  
  o This must be done with care to ensure that the handle’s pogo pins make contact with all the lead wires and thus the computer recognizes all the rows and columns of the sensor.

• The Handle Misaligned error box should disappear from the screen if the handle is properly aligned.
  
  o This box should be appear when I-scan is opened and disappear when the handle is aligned properly.

• Test sensor for continuity by applying test pressure using your finger or end of a pen to the outside rows and columns.
  
  o This is important, even though the computer thinks the sensor is aligned properly, the sensor may not be recognizing one or two rows.

• Begin testing!!!!!

  o A final tip when testing in the track, following these steps prior to installing the sensor in the track structure saves time and hassle and helps ensure the test will be recorded properly.
There are a few protocols that have to be followed prior to any in-track testing. The railroad industry has stressed on-track safety in recent years, with safety classes required for all employees. Personal safety equipment – steel-toe boots, protective eyewear, and hardhats – are specified. It is important for the safety of all persons involved that proper authorization and notification is given before accessing the site, namely the roadmaster in charge of the track where the test will be conducted. 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 procedure to install and remove the sensor from the track is:

- Use the spike puller to remove the spikes from the cross tie where the test will be conducted.
- The hydraulic jack is then placed under the rail in the crib area to raise the rail off the tie plate slightly.
- The existing tie plate is removed by sliding it out.
- The area under the rail is then blown clean of all foreign objects to make sure there are no rocks, sand, or metal scraps remaining that could puncher or damage the sensor. A brush or air from an air tank can aid in this process and if completed thoroughly it will extend the useful life of the each sensor.
- Place the replacement tie plate, either machined steel or polyurethane, under the rail making sure that it is in the same location as the original
one. The new tie plate should have the shoulders removed (grounded off) to allow the sensor to lie flat.

- Place the sensor and shim stock (Mylar, Teflon, and bladder) on the new tie plate in the correct location so that all the contact area of the rail base and tie plate will go through the sensor. (Discussion of the bladder will following later in this chapter).

- Determine the orientation of the sensor with respect to the track and the display on the computer screen for analysis purposes.

- Conduct a preliminary test to verify the connection is correct by moving a finger or pen over the exterior cells of the sensor. Record and save the test to ensure the data collection is functioning properly and the test is being saved.

- Remove the hydraulic jack from the under the rail.

- Conduct the tests.

- After all the tests have been performed, raise the rail using the hydraulic jack and remove the Teflon, Mylar, sensor, and bladder.

- Then remove the test tie plate and reinsert the regular tie plate.

- Remove the hydraulic jack and use the sledge hammer to re-spike the rail.

When it is desirable to perform the tests, the I-scan software is used as the data acquisition software. The steps necessary to conduct a test are as followed:

- Open I-scan by clicking the appropriate icon.
• Click the ‘File’ tab in the upper left corner of the screen. A drop down menu will appear. Select ‘New Session’ from this menu. Another box will open in the middle of the screen. Select the correct sensor type, and click ‘OK’.

• Click ‘Option’ and a drop down menu will appear. Select ‘Acquisition Parameters . . .’ and another box will open in the middle of the screen.

• Set the scan rate to the appropriate level, which can be given in frames per second or seconds per frame depending on the test. For a static test this should be set to 1 frame per second and for a dynamic test the maximum scan rate should be selected. The two sensors used were the 5250 and 5260 with maximum scan rates of 147 frames per second and 125 frames per second respectively.

• In the lower left corner of the same window click the box beside pre-triggering so that a check mark appears. Then set the pre-triggering frame count at approximately 10 frames for static loads and about 2 seconds of frames for dynamic loads or at 300 frames.

• Then in that same window click ‘Pre-trigger’ and another window will open. This box tells the computer when to start the test. Set the force and contact area to a level approximately 10% higher than the dead load to account for fluctuations and prevent a premature start of the test. If either of these limits are reached then the test will start. Click ‘OK’ and the pre-triggering window will disappear and then click ‘OK’ to close the acquisition parameters.
• At this point the test is ready to be conducted when a train approaches. In the upper middle portion of the window there are buttons similar to those on a VCR. Click the red diamond and the test will begin when a pre-triggering level has been reached.

• Stop the test by clicking the blue square when adequate data have been collected or the desired event has occurred.

• Save the file in a folder specific for the tests. To save a file click the icon that looks like a 3.5" floppy and another box will appear in the middle of the screen. Type in the file name and click ‘SAVE’.

The movie that was recorded can be played back immediately if desired by clicking the blue right arrow. However, most of the analysis will be conducted in the office and not during in-track testing. It is good though to record specifics of the test in comments. By right clicking on the movie and clicking ‘Comments . . . ’ a box will appear. Typing in location, date, time, test name, sensor location, sensor orientation, setup, and other information can be recorded for future reference during the analysis portion of the sequences.

Richmond, Kentucky Tests

The tests were performed adjacent to the Main Street Railroad crossing by the CSXT office. A modified tie plate with a ground surface at the rail/tie plate interface was used to replace the existing plate. CSXT personnel raised the rail up high enough for removal of the existing tie plate and placement of the
Tekscan sensor, shim stock, and plate in the track structure. The first train tested did not record for an unknown reason at the time. In an effort to correct the problem the 12 V battery and inverter that were used as the power supply for both the computer and the Magma box were replaced with several electric extension cords from the CSXT office. The remainder of the tests were recorded without any computer problems.

It was learned, through this initial in-track test and by conferring with technical support at Tekscan, that a constant electrical supply must be sent to the Magma box or it will momentarily stop outputing data to the computer. This lost of input to the computer confuses it and will subsequently cause the computer to freeze. The test will be lost and the data will not be recorded. This had not been a problem for tests conducted in the laboratory where the power supply was a 110 V wall jack and the electric power was constant. The solution for track tests is to have the computer and Magma box attached to independent power supplies. The subsequent tests were recorded by having two batteries and two inverters powering the computer and Magma box separately. The result was a consistent power supply able to meet the demands of track testing. Obviously the 12-volt batteries should be completely charged.

Another challenge arose from the types of materials being used in the tests. The steel rail base and steel tie 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 tie 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 3.2. It is obvious that rigid objects such as commercially produced tie 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 tie plate’s three highest points would be the “high plane” of the tie plate. Assuming the tie 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 was found from the initial tests. Figure 3.2 is from an initial test run under the middle wheel of a 6-axle locomotive near the Main Street Crossing in Richmond.

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 tie plate. The dimensions of the picture physically are approximately 6 in. by 8 in. corresponding to the 6 in. base of rail and the 8 in. wide tie plate. The color scale has 13 gradients spanning the visible spectrum with dark blue representing the lights pressures and the red representing the highest pressures.
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) substitute the existing tie plate with a commercially machined smooth steel tie plate or a tie plate made of a smooth, softer material (polyurethane plastic or rubber) and 2)
add a rubber (fluid filled) bladder shim stock that could furthermore evenly distribute pressures over a steel plate.

The steel tie plate was found unsuitable for the initial test being conducted at Richmond. Other types of tie plates were subsequently evaluated for possible application as a substitute. For the subsequent laboratory tests, polyurethane tie plates and rubber tie 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 tie plate needed to be removed so that the life of the sensor would be extended. The new tie plates were ordered with shoulders removed and surfaces machined. Figure 3.3 shows the three tie plates. The left tie plate is the machined tie plate with the shoulders removed. The middle tie plate is the ground tie plate done by the University of Kentucky machine shop. The right tie plate is a used tie plate removed from the railroad track.
Figure 3.3: Machined, Ground, and Existing Tie Plates.
Chapter Four

Detailed Calibration Procedure

Drift

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 statically. In the early laboratory tests this fact was not apparent and loads were applied arbitrarily and the output was recorded.

After the initial test at Richmond 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 that is mentioned briefly in the Tekscan Users Manual is drift (Tekscan, 2003). 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 the effects can be minimized. The simplest way to accomplish this is to perform the sensor calibration in a time frame similar to that which will be used in the 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 4.1 shows the percentage increase of the output as a constant load is applied to the sensor.

Table 4.1: Percentage Increase in Applied Load Due to Drift as a Function of Time

<table>
<thead>
<tr>
<th>Drift (as a % of applied load)</th>
<th>Time (duration of time load is applied to sensor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>1 second</td>
</tr>
<tr>
<td>6%</td>
<td>10 seconds</td>
</tr>
<tr>
<td>9%</td>
<td>100 seconds (1 minute 40 seconds)</td>
</tr>
<tr>
<td>10%</td>
<td>215 seconds (3 minutes 35 seconds)</td>
</tr>
<tr>
<td>12%</td>
<td>1000 seconds (16 minutes 40 seconds)</td>
</tr>
</tbody>
</table>

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 at Richmond 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.
Non-linearity

The origin of the many calibration 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. On December 16, 2003 a calibration test was conducted. This was accomplished by setting up the Tekscan System in the laboratory. First, a short piece of a tie was placed in the Satec Machine and a machined steel tie plate was placed on the tie. Next, a sheet of Mylar and Teflon was placed on the tie plate. After that the Tekscan sensor was placed on the Teflon and then another sheet of Teflon and Mylar was placed. Finally, a fluid filled rubber bladder was placed on top and two pieces of steel simulating the rail were then placed above the bladder. 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.

Table 4.2 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.

Table 4.2: Results from Calibration Test Conducted on 12/16/03

<table>
<thead>
<tr>
<th>Machine Load Lbf</th>
<th>Total Raw Units Tekscan</th>
<th>Contact Area in^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>905</td>
<td>8.18</td>
</tr>
<tr>
<td>200</td>
<td>1760</td>
<td>12.29</td>
</tr>
<tr>
<td>1000</td>
<td>7890</td>
<td>28.12</td>
</tr>
<tr>
<td>5000</td>
<td>28200</td>
<td>39.98</td>
</tr>
<tr>
<td>10000</td>
<td>49500</td>
<td>42.59</td>
</tr>
<tr>
<td>15000</td>
<td>66300</td>
<td>43.32</td>
</tr>
<tr>
<td>20000</td>
<td>82700</td>
<td>43.66</td>
</tr>
<tr>
<td>25000</td>
<td>96700</td>
<td>44.04</td>
</tr>
<tr>
<td>30000</td>
<td>106600</td>
<td>44.43</td>
</tr>
<tr>
<td>35000</td>
<td>119900</td>
<td>44.87</td>
</tr>
<tr>
<td>40000</td>
<td>130400</td>
<td>45.06</td>
</tr>
<tr>
<td>45000</td>
<td>140350</td>
<td>45.54</td>
</tr>
<tr>
<td>50000</td>
<td>151700</td>
<td>45.88</td>
</tr>
</tbody>
</table>

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 could be accurately determined.

When the Machine Load versus the Total Raw Sum is graphed the data does not produce a straight line. Figure 4.1 shows the individual data graphed in Microsoft Excel with a linear regression line superimposed and the calculated $R^2$ value shown.
Figure 4.1: Graph of Total Raw Units vs. Satec Machine Load from Calibration Test Conducted 12/16/03 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 this research project’s purposes and a better fit was
required. The actual nature of the material when graphed gives a power log equation in the form of:

$$Y = Ax^B$$

Figure 4.2 shows the same data graphed with a power curve regression applied. Note the $R^2$ value is much closer to 1.0000.

![Figure 4.2: Graph of Total Raw Units vs. Satec Machine Load from Calibration Test Conducted 12/16/03 with Power Curve Regression](image)

The power curve regression produces an equation of:

$$y = 0.0211x^{1.2204}$$

and a $R^2$ value of 0.9974. This is much closer to 1.0000. Note the curve follows the data closely and gives an accurate representation of the data until it is in the very high end force range.
Chapter Five
In-Track Tests

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

TTI Rail Yard Paris, Kentucky Tests

The next in-track tests were conducted on August 1, 2003 at the TTI rail yard in Paris, Kentucky. TTI is a short line railroad that agreed to let us use one of their 4-axle locomotives for repeated tests in their rail yard. This had many advantages, most notably, the lack of variation in the train’s weight and load distribution. The same locomotive would repetitively load the sensor and give a comparable sampling for analysis purposes. One other variation that was considered negligible was the jointed rail used in the rail yard, which is different from the continuously weld rail used in the majority of main line tracks.

The two main activities examined were:

1) Evaluate different types of tie plates – machined steel, polyurethane, and rubber, and

2) Measure the distributing effects of the track, by noting when the pressure increases with respect to the location of the locomotives wheel as it slowly approaches the test site.
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 tie 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 tie plates with the shoulders removed.
4) Polyurethane plastic tie plates with a rubber fluid filled bladder.
5) Thin Polyurethane plastic tie plate with a rubber fluid filled bladder to see if the full thickness tie plate produced any bridging effect.

Figures 5.1, 5.2, 5.3, 5.4, and 5.5 are representative samples of the five configurations evaluated at TTI rail yard. Notice that the first test (Figure 5.1) reconfirms that even with machined tie plates the rail/tie plate interface is too uneven and provides small contact area and saturation of the sensor’s cells. This can be compared to the next test run (Figure 5.2) with the fluid filled bladder. Note that the pressure is distributed with no saturation and an accurate measurement was obtained. The other three tests all gave similar values and were useful for understanding the interaction between the rail/tie plate interface with different tie plate materials. With the success of the machined steel and rubber bladder, most subsequent tests were performed without using polyurethane tie plates. Steel is likely to be the predominate tie plate for wood ties for many years.
Figure 5.1: This represents a typical pressure distribution between a steel tie 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 force applied at these areas could and probably are much higher than the 1200 psi recorded and that would lower the overall force recorded.
Figure 5.2: This represents a typical pressure distribution between a machined steel tie 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 shown. The difference was due to the initial lack of understanding of the Tekscan sensor calibration process.
Figure 5.3: This represents a typical pressure distribution between a polyurethane plastic tie plate and the rail. 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 20,200 shown. The difference was due to the initial lack of understanding of the Tekscan sensor calibration process.
Figure 5.4: This represents a typical pressure distribution between a polyurethane plastic tie 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 21,000 shown. The difference was due to the initial lack of understanding of the Tekscan sensor calibration process.
Figure 5.5: This represents a typical pressure distribution between a polyurethane plastic tie plate that was machined 0.150 inches with a rubber bladder and the rail. 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 22,000 lbs rather than the 16,800 shown. The difference was due to the initial lack of understanding of the Tekscan sensor calibration process.
The same one point calibration curve was applied to all of the previous results. Note that the recorded force is slightly different with about 25% higher recorded value using the polyurethane tie plate and a rubber bladder or ground steel tie plate and rubber bladder as opposed to using the rubber tie 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 that 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 tie plate and the polyurethane tie plate were approximately the same thickness as a typical tie plate. Then by adding a bladder it can cause a bridging effect which would increase the load applied to that cross tie. This was corrected for in later tests by having machined tie plates from the manufacturer that where machined thinner to compensate for the added thickness of the bladder. In addition the machined tie plates were smoother than the plates ground by the University of Kentucky machine shop.

Secondly, it was desirable to measure the distributing effects of the rail, by noting when the pressure increases with respect to the location of the locomotives wheel. The test was conducted by having the locomotive stop its lead wheel five cross ties from the location of the sensor. The snapshot ability of I-scan software was utilized and the results are shown in Appendix D1. The results show that a very low pressure of 50 psi is applied at five cross-ties, or 100
inches, away. The pressure increases proportionally, but is still relatively low
with approximately 90 psi by the time the lead wheel is four ties from the sensor
and then increases to approximately 150 psi when the lead wheel is three ties
from the sensor. It is not until the lead wheel is two ties from the sensor that
significant force was applied to the tie. Table 5.1 shows the entire summary of
force and pressure. Figure 5.6 is a graphical depiction of the pressures and
Figure 5.7 is a representative view of a measurement setup in the track. The
green arrow indicates the location of the Tekscan sensor.

Table 5.1: Wheel Load Distribution at Rail Base / Tie Plate Interface

<table>
<thead>
<tr>
<th>Location of Lead Wheel with Respect to the Sensor</th>
<th>Force (lbf)</th>
<th>Average Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Ties Before Sensor</td>
<td>2,316</td>
<td>48</td>
</tr>
<tr>
<td>4 Ties Before Sensor</td>
<td>4,149</td>
<td>86</td>
</tr>
<tr>
<td>3 Ties Before Sensor</td>
<td>7,501</td>
<td>156</td>
</tr>
<tr>
<td>2 Ties Before Sensor</td>
<td>12,915</td>
<td>269</td>
</tr>
<tr>
<td>1 Tie Before Sensor</td>
<td>17,626</td>
<td>367</td>
</tr>
<tr>
<td>Directly Above Sensor</td>
<td>20,985</td>
<td>437</td>
</tr>
<tr>
<td>1 Ties Past Sensor</td>
<td>19,623</td>
<td>410</td>
</tr>
<tr>
<td>2 Ties Past Sensor</td>
<td>18,007</td>
<td>375</td>
</tr>
<tr>
<td>3 Ties Past Sensor</td>
<td>17,782</td>
<td>370</td>
</tr>
<tr>
<td>4 Ties Past Sensor</td>
<td>18,131</td>
<td>378</td>
</tr>
<tr>
<td>5 Ties Past Sensor</td>
<td>13,139</td>
<td>275</td>
</tr>
</tbody>
</table>
Figure 5.6 Positioning of Lead Wheel with Respect to Sensor

Figure 5.7: Snapshot of the Lead Wheel Directly above the Sensor
Note that the highest pressure is when the lead wheel is directly over the sensor. The pressure does not drop off after the lead wheel, but the distributing effects of the lead wheel and the trailing wheel combine, so that the pressure drops off only slightly and then peaks again as the trailing wheel moves over the sensor. The trailing wheel is 80 inches behind the lead wheel or 4 ties. That is the reason that the final reading is somewhat lower, because the entire truck has started to move past the sensor and the pressure will decrease rapidly. This test was conducted using polyurethane tie plates.

Conway, Kentucky Tests

These in-track tests were conducted at Conway, Kentucky on August 7, 2003. 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 tie plates – machined steel, polyurethane, and rubber,

3) To measure the distributing effects of the rail, by noting when the pressure increases with respect to the location of the locomotives wheel as it slowly approaches the test site, and
4) To evaluate the ability of Tekscan to measure pressures in the tie plate / tie interface.

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 5.8. The frame vs. force plot shows how fast the five locomotives moved past the sensor recording the event in less than 2000 frames.

In addition, to the test conducted at TTI rail yard on several tie plate materials, an additional test was conducted at Conway on a rubber tie plate. The distribution of pressures 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 tie plates was beyond the scope of this project and its applications could be better explored at a later time. Figure 5.9 shows the results of the rubber tie 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 tie plate.
Figure 5.8: This represents a typical pressure distribution between a polyurethane plastic tie 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 5.9: This represents a typical pressure distribution between a rubber tie 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.
After testing the wheel load distribution at the rail base / tie plate interface at TTI it was desired to understand the same process for the 6-axle locomotives as well. The wheels of the 6-axle locomotive are each 80 inches apart. This meant that the test would have to run longer than the time before. So the experiment was expanded to include ten ties before the lead wheel and continue for ten ties after the lead wheel. The last two tests would include frames after the trailing wheel had cleared the sensor. The snapshot ability of I-scan software was utilized and the results are shown in Appendix D2. The results are summarized in Table 5.2. Figure 5.10 is a graphical depiction of the pressures and Figure 5.11 is a representative view of a measurement setup in the track. The green arrow indicates the location of the Tekscan sensor.

![Figure 5.10 Positioning of Lead Wheel with Respect to Sensor](image)
<table>
<thead>
<tr>
<th>Location of Lead Wheel with Respect to the Sensor</th>
<th>Force (lbf)</th>
<th>Average Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Ties Before Sensor</td>
<td>2199</td>
<td>46</td>
</tr>
<tr>
<td>9 Ties Before Sensor</td>
<td>2503</td>
<td>52</td>
</tr>
<tr>
<td>8 Ties Before Sensor</td>
<td>2756</td>
<td>57</td>
</tr>
<tr>
<td>7 Ties Before Sensor</td>
<td>3393</td>
<td>71</td>
</tr>
<tr>
<td>6 Tie Before Sensor</td>
<td>4039</td>
<td>84</td>
</tr>
<tr>
<td>5 Ties Before Sensor</td>
<td>4828</td>
<td>100</td>
</tr>
<tr>
<td>4 Ties Before Sensor</td>
<td>5870</td>
<td>122</td>
</tr>
<tr>
<td>3 Ties Before Sensor</td>
<td>9440</td>
<td>197</td>
</tr>
<tr>
<td>2 Ties Before Sensor</td>
<td>14136</td>
<td>295</td>
</tr>
<tr>
<td>1 Tie Before Sensor</td>
<td>19171</td>
<td>400</td>
</tr>
<tr>
<td>Directly Above Sensor</td>
<td>25372</td>
<td>529</td>
</tr>
<tr>
<td>1 Ties Past Sensor</td>
<td>25446</td>
<td>530</td>
</tr>
<tr>
<td>2 Ties Past Sensor</td>
<td>25986</td>
<td>541</td>
</tr>
<tr>
<td>3 Ties Past Sensor</td>
<td>27002</td>
<td>563</td>
</tr>
<tr>
<td>4 Ties Past Sensor</td>
<td>27730</td>
<td>578</td>
</tr>
<tr>
<td>5 Ties Past Sensor</td>
<td>27159</td>
<td>566</td>
</tr>
<tr>
<td>6 Ties Past Sensor</td>
<td>26179</td>
<td>545</td>
</tr>
<tr>
<td>7 Ties Past Sensor</td>
<td>26725</td>
<td>557</td>
</tr>
<tr>
<td>8 Ties Past Sensor</td>
<td>25313</td>
<td>527</td>
</tr>
<tr>
<td>9 Ties Past Sensor</td>
<td>19259</td>
<td>401</td>
</tr>
<tr>
<td>10 Ties Past Sensor</td>
<td>12234</td>
<td>255</td>
</tr>
</tbody>
</table>
Several conclusions can be made from these test results. First, the distributing effects of the wheel, as recorded previously at TTI rail yard is only significant 2 or 3 cross ties from the wheel location. The hypothesis is that the track modulus would greatly affect this result. The distributing affects were being measured in a section of track with an asphalt underlayment. This track would have a higher modulus than that of a typical all-granular track and thus not deflect as much as the train passed over. However, if the modulus was lower, then the track would require additional ties to support the same load.

Another interesting conclusion of this data is the location of the maximum pressure. It is four ties after the lead wheel. This is located under the middle wheel of the 6-axle locomotive. Therefore the sensor is under the load of the
middle wheel plus the distributing effect of the other two wheels. This has been the situation for all the tests with a 6-axle locomotive. The middle wheel will produce a slightly higher force than when either of the other two are centered over the sensor.

**Tie Plate/Cross Tie Interface Tests**

The final tests that were conducted at Conway were tests using the 5260 sensor to measure pressure at the tie plate/tie interface. The 5260 sensor is a larger rectangular sensor, which is inserted into the track in the same procedure as the 5250 sensor. These two tests used the 5 locomotives to measure the pressure at the tie plate/tie interface. The 5260 sensor has 500 psi saturation pressure. Two different types of tie plates were used for this test, polyurethane and steel. Figure 5.12 is a typical distribution of the polyurethane tie plate. Figure 5.13 is a typical distribution of the steel tie plate.

Both figures have large amounts of saturation causing inaccuracy in the force and pressure measurement. However, the area over which the force is applied shows very interesting and ultimately useful information. Figure 5.12 indicates the area of contact is 63.88 in$^2$. This is a 33% increase in the area of contact over the 48 in$^2$ that is in contact at the rail/tie plate interface. The area in figure 5.13 is 108.11 in$^2$. That is over twice the area at the rail/tie plate interface. The difference is due to the nature of the materials. Steel is stiff and will distribute the force better than the polyurethane, which only spreads out the pressure to the tie slightly. In conclusion, steel tie plates lower the average pressure applied to a tie and provide a larger wearing surface for the ties.
Figure 5.12: This represents a typical pressure distribution between a machined polyurethane tie plate 0.150 inches thinner with a fluid filled rubber bladder and the cross tie. Note that there is not good contact area and the sensor is saturated over most of the applied area. The sensor had a 500 psi capacity. The plastic did not have enough stiffness to distribute the load over an area much larger than the bottom of the rail.
Figure 5.13: This represents a typical pressure distribution between a steel tie plate with a fluid filled rubber bladder and the cross tie. Note that there is good contact area, but the sensor saturated over most of the applied area. The sensor had a 500 psi capacity. The steel, due to stiffness, distributed the load over an area much larger than the bottom of the rail.
Chapter Six
Analyzing and Editing 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 tie 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 have about the same axle loadings. The result of this assumption was that most all the 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 axle loadings 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. I-scan allows for this type of editing and can be completed by the following steps:
• Click the ‘File’ tab in the upper left corner of the screen and a drop menu will appear. Click ‘Save Movie As . . .’ and a box will appear in the middle of the screen. Save the move as ‘name-edit.fsx’ and click ‘SAVE’. This will preserve the raw data and allow for other parts of the test to be analyzed.

• View the movie by clicking the blue right arrow. Determine which events are relevant to the test; during this research project the location of the locomotives were of most interest. Then determine which frames contain the desired events.

• Click ‘Edit’ and a drop menu will appear and then click ‘Cut Frames . . .’ I-scan will cut out unnecessary frames. This can reduce data and allow for better analysis. After typing the frame numbers that are to be cut, click ‘OK’.

Once the desired event becomes the full movie it may be important to edit out errors. One possible problem that can occur is a saturated cell. It has happened that a single cell malfunctions and records itself saturated. This may be caused by a rock or sand particle. Figure 6.1 is an example of a frame that has an erroneous cell that will need to be edited. Figure 6.2 is the same frame with the erroneous cell assuming the value of the average of the four cells surrounding it. The correction is equivalent to 133 lbf which is only 1.6% error. While the actual error amount may not be relevant to the interpretation of the data it does provide more accurate data that is also better for presentation.
purposes. In addition, if several cells were to malfunction the problem would be magnified by the number of malfunctioning cells. This editing is accomplished by the following steps:

- Click ‘Edit’ and a drop menu will appear. Then click ‘Edit Mode . . .’ and another box will appear.
- Click ‘Average Cells’ and then click ‘Add Edit Cell’.
- Add the edit cells by clicking on the erroneous cells on the move.
- Then click ‘Apply’ and another box will appear. It will ask for the first and last frame to edit. This allow for frame by frame editing or editing of the entire movie if desired. When that is completed click ‘OK’.

Figure 6.1: Unedited Frame of an Unloaded Flat Car Recorded at Milford Junction, Indiana on 8-19-03.
Another helpful part of the averaging method of editing is that it can be used to extrapolate data from tests that may otherwise be unusable or extend the life of a damaged sensor. Figures 6.3, 6.4, and 6.5 are a series of frames recorded during the test conducted at Milford Junction, Indiana under a 6-axle locomotive using a machined steel tie plate and a fluid filled bladder with the Teflon and Mylar. Notice that Figure 6.4 has a column of data that is missing for some reason. The correction that was made was to add an edit box which is done by the same method and from the same menu box as adding an edit cell. The edit box will average all the values surrounding the box and interpolate the data to give the best possible result. Figure 6.6 is the edited version of Figure
6.4 with the edit box over the dead column. Note that the interpolation makes the edited frame as good as Figure 6.3 and 6.5.

Figure 6.3: One Frame before Erroneous Frame Recorded at Milford Junction, Indiana 8-7-03
Figure 6.4: Erroneous Frame Recorded at Milford Junction, Indiana 8-7-03

Figure 6.5: One Frame after Erroneous Frame Recorded at Milford Junction, Indiana 8-7-03.
As mentioned previously, this type of editing can extend the life of a sensor. Often during extensive testing a sensor may have a row or column that becomes damaged because of usual wear and tear. The sensor can continue to be used with this type of editing after the test is conducted.

One final editing tool that I-scan provides is deleting parts of the cells. In the Figures 6.3 – 6.6 the rail/tie plate interface is the contact area on the right side of the picture. The contact made by the left side is the guard rail attached to a crossing diamond. The test of these frames was conducted at Milford Junction, Indiana which is were an east-west CSX Transportation double track line crosses a north-south Norfork-Southern Railroad single track line. The force from the guard rail affects the total force measurement very little, but does affect the total
contact area and thus the pressure at the rail/tie plate interface. This erroneous static can cause exterior sensor cells to record a value when no pressure is present. In these cases the data can be erased. This is performed by using the same edit menu as before. An edit box can be used to either delete all cells inside the box or delete all cells outside the edit box. Both methods work and for cases where the contact area is roughly rectangular, such as the rail/tie plate interface, it is useful to delete all cells outside of this known area. Figure 6.7 is essentially figure 6.6 with the guard rail deleted from the frame. Notice that the contact area displayed at the upper right hand corner of each is different by 12.05%. However, the force difference caused by deleting these cells is only 2.03% and thus the change in recorded pressure is 8.93%. It is therefore very important that the editing be conducted with care and an understanding of what is being changed. The results of the test and all information reported can be dictated by accurate editing. Once all editing is complete, save all the changes in the name-edit.fsx file.
Figure 6.7: Two Identical Frames with Cells Edited Deleted. Contact Area Reported. Recorded in Milford Junction, Indiana 8-7-03.
Frame Interpretation

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 that 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 one 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 performed. 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 unknown loads, 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 considered.
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, if tests are conducted with varying loads, such as within the track structure, then 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 are presented in a picture form which corresponds to the sensor’s output. One point calibration assumes a linear output and shows the variations 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 underestimates the lower pressure areas and overestimates the higher pressure areas. The total load is recorded accurately, but the distributions are distorted.

Figures 7.1 and 7.2 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 7.1 is the frame shown with a one point calibration applied at a 10,000 lb load. The distribution is good, but the total load shown in the upper right corner of the figure is lower than expected. Figure 7.2 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 what was expected, but the distribution is distorted.

Figures 7.1 and 7.2 were recorded using machined tie plates and a fluid filled rubber bladder inserted in the track to replace the existing tie plate. The distribution of force over the entire tie plate is very good in both figures, but in figure 7.2 the higher pressures are exaggerated and show up as red areas, while the light blue areas, low pressure areas, of Figure 7.1 show up as dark blue areas, lowest pressure, in figure 7.2. Figure 7.3 is a typical pressure scale used by I-scan software. The pressure scale has 13 gradients and provides values for the pressure in pounds per square inch (psi).
Figure 7.1: One Point Calibration of Frame Showing Front Wheel of 4-Axle Locomotive at TTI Rail Yard Paris, Kentucky 8-1-03
Figure 7.2: Two Point Calibration of Frame Showing Front Wheel of 4-Axle Locomotive at TTI Rail Yard Paris, Kentucky 8-1-03

Figure 7.3: Typical Scale used by I-scan Software
Movie Interpretation

Aside from the individual frames, the entire recording of an event can be analyzed as a movie. These force vs. time or pressure vs. time graphs can provide information about the relative force distribution of a train, as well as provide a comparison of locomotive to cars. This also allows for further frame evaluation after preliminary evaluations have been accomplished. Figure 7.4 and 7.5 are examples of force vs. frame and pressure vs. frame graphs produced using the I-scan software.

Figure 7.4: Force vs. Frame Graph from I-scan of Three 6-axle Locomotives and Initial Cars
Figure 7.5: Pressure vs. Frame Graph from I-scan of Three 6-axle Locomotives and Initial Cars

The limitation of this is that only the calibration available in I-scan can be applied to the graph. From the experiments it was determined that for an accurate force vs. time relationship, three calibration curves are required to account for the nonlinear nature of the sensors. In order to accomplish this Microsoft Excel was utilized. The steps necessary to convert an I-scan movie to Excel are as follows:

- Save the desired movie as ASCII by clicking the Save ASCII... under the File menu.
- Set the Movie Range: Custom range. Save up to 1400 frames at a time because this is the capacity of Excel.
• Open Excel and then selecting Open... under the File menu and then set Files of type: All Files. Then select the desired ASCII.

• Set the Original data type: Delimited. Then set File Origin: US-ASCII. Then Click Next >.

• In the Delimiters box uncheck Tab and Check Comma. Then set Text qualifier: {none}. Then click Finish.

When the file opens it will contain a lot of data and the first rows will contain information about the test’s name, sensor type, comments, etc. Then it will display every sensor cell recording in a separate Excel cell, frame by frame. With 44 rows and 44 columns on a 5250 sensor, columns A – AR are used and 44 rows per frame are used. An ASCII file containing 1400 frames uses almost 65,000 rows. This information is unusable in this form. To better utilize it and develop force vs. frame graphs, the cells of each frame must be summed to give the total. To do this a Microsoft Visual Basic program was developed in Macro. Macro is an Add-in that can be selected in the Tools menu. The following is the Macro Visual Basic program used:

    Sub Sum()
    Dim x As Double
    Dim t As Double
    Dim l As Double
    x = 0
    For i = 1 To 1400
        t = i * 46 - 46
        For k = 0 To 43
            l = t + k
            For j = 0 To 43
                ...
It is important that the correct cell is selected in the [Range("A32")]
command. This cell should correspond to the first cell of the first frame. This will
differ depending on the amount of comments made in the original I-scan file.
Once the program runs, the output comes in the form of a list in columns AU and
AV. AU has the frames counted from 1-1400 and AV has the sum of the
sensors. This can be graphed with an x-y scatter plot to develop the graphs. For
movies with more than 1400 frames, several ASCII files need to be made with
the results copied to a common file so the x-y scatter plot can be graphed.
Figure 7.6 and Figure 7.7 are examples of the Excel plots made from the same
file as Figures 7.4 and 7.5. This example had 4000 frames which means that
three separate ASCII files where complied to make this graph.
Figure 7.6: Excel Graph of Force vs. Frame

Figure 7.7: Excel Graph of Pressure vs. Frame
Chapter Eight
Redefined Calibration Process

Three Curve Calibration

Since the calibration curve was non-linear, it was concluded that with multiple power curves the data could more be accurately described.

The data were separated into several groups and Microsoft Excel was used to produce multiple curves to fit the data. The curves were examined and the $R^2$ values were compared. The best representation of the data was determined by using three curves. One curve was used for the low end values or values up to 8,000 raw units. This is used for the unloaded track tests. A second curve was used for the middle 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 high end values or values over 105,000 raw units. This is used for loaded cars and locomotives tests, 263,000 to 394,000 pounds.

Figures 8.1, 8.2, and 8.3 shows the same data presented in chapter 4 (Figures 4.1 and 4.2) with three separate power curves applied to different ranges. With the collection of all three curves the data are represented very well.
Figure 8.1: Graph of Total Raw Units vs. Satec Machine Load from Calibration Test Conducted 12/16/03 with Power Curve Regression applied to Low End Forces

Figure 8.2: Graph of Total Raw Units vs. Satec Machine Load from Calibration Test Conducted 12/16/03 with Power Curve Regression applied to Middle Forces
Figure 8.3: Graph of Total Raw Units vs. Satec Machine Load from Calibration Test Conducted 12/16/03 with Power Curve Regression applied to High End Forces

Note that these $R^2$ values range from 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.

Through all of the experimentation, especially with the calibration studies, best practices emerged from the knowledge. It was determined that the sensors “age” as they are used. This means that as the sensors are used repeatedly over several experiments the amount of force required to produce a given output
reduces. For example the most used sensor is the 5250-2 which has been used on numerous tests over the past year. Originally at 10,000 lbs the raw electronic output was 43,000 units. Today if 10,000 lbs is applied to the sensor the output is in the range of 80,000 units. This sensor continues to be repeatable, with an consistent output on repeated tests, but the calibration curves developed six months or a year ago do not apply today. The solution is to conduct a test in the field and then on a following day repeat the test as close as possible in the laboratory. The goal of the test is to repeat the output from the field test and record the force applied by the Satec machine. This approach can relate field test results most closely to the actual recordings. A calibration curve could be determined at that time and be used to analyze the data farther if desired. Note that many times just the maximum is desired and a calibration at that output is necessary and the calibration can be saved for a specific set of tests.

Applying Multiple Calibration Curves

Once the calibration for a particular sensor and test is complete then it may be desirable for the calibration curves to be applied to the data. I-scan does not allow for multiple calibration curves to be displayed simultaneously. However I-scan data can be imported into Excel as mentioned earlier and the most accurate force vs. time graphs can be made. This is usually done for presentation purposes, because there is too much information to effectively draw conclusions, but the need for accurate representation of the data is important.
This is accomplished using IF statements in Excel. Once the ASCII file has been imported into Excel, the Visual Basic program can be run. The data are shown as a total raw sum similar to that in I-scan. In the column adjacent to the total raw sum an IF statement can be written to vary the curve selected, depending on the raw sum.

IF functions in Excel contain a logic test, a function to perform if the logic test is true, and a function to perform if the logic test is false. Using the calibration curves from the above calibration performed on December 16, 2003 the following IF function would be inputted into Excel to apply the calibration curves to the correct portions of data.

```
= if(AV2 < 8000, 0.0706 * AV2^1.0649, if(AV2 < 105000, 0.009 * AV2^1.292, 0.012 * AV2 ^ 1.4708))
```

The first logic test determines if the physical case was the unloaded track with total raw sum less than 8000 units. If this is true then the first calibration curve is applied. If the sum is greater than 8000, meaning the logic test was false, then there are two other options. In this case a second logic test is performed testing if the physical case is an unloaded car or a loaded car. If the raw sum is less than 105000 then the actual raw sum is between 8000 and 105000 and the second equation is used. The reason for this is because the value has failed the first logic test which determines that it is greater than 8000. However it passes the second logic test which determines that the load is less than 105000. If the datum fails the second logic test then it is greater than 105000 units and the third calibration equation used. Once this IF function is inputted into Excel then it
can be applied to all the data by filling down the column. The results can be graphed in an x-y scatter to give the most accurate force vs. time graphs.

Using this technique the recording at Paris, Kentucky, utilized in Chapter 7, was analyzed. The 5250-3 sensor used in the experiment was calibrated and Figure 8.4 is the three calibration curves applied to the data.

![Figure 8.4: Graph of Total Raw Units vs. Satec Machine Load from Calibration Test Conducted 10/13/04 with Power Curve Regression at Three Different Ranges](image)

From this information the most accurate force vs. time graphs could be obtained. Figures 8.5 and 8.6 are the force vs. time and the pressure vs. time graphs using this three calibration curve technique.
Figure 8.5: Excel Graph of Force vs. Frame with 3-Calibration Curves Applied

Figure 8.6: Excel Graph of Pressure vs. Frame with 3-Calibration Curves Applied
Chapter Nine

Findings and Conclusions

The purpose of this study has been to experimentally evaluate the pressures at the rail/tie plate interface and the tie plate/cross tie interface using an existing technology in a new application. The initial test indicated that the Tekscan Measurement System was applicable. The optimum procedure to install the sensor into the track, the recommended practices to effectively collect data with the software, and the accepted techniques for analyzing the results were determined during the study. Experimental data have been collected and a process for verifying previous theoretical predictions of force and pressure were obtained.

The findings during the duration of this study are as follows:

Tie Plate

- The shoulders should be removed from tie plates.
- Tie plate surface should be smooth or machined.
- Steel tie plate tests must include a rubber bladder to distribute the loadings.
- Tie plates must be reduced in thickness to accommodate the bladder, mylar, Teflon, and Tekscan sensor.
- Rubber and polyurethane plastic tie plates can distribute the loadings without the need for a bladder.
- Tie plate, rail, and cross tie all need to be cleaned of foreign materials (sand gravel, dirt) to prevent damage to Tekscan sensor.
• Rubber bladder should be placed directly under the rail or directly on the cross tie to distribute loads on the least smooth surface. Tie plate surface smoothness can be controlled.

• When measuring pressures at the tie plate/cross tie interface, steel is stiff enough to distribute the load over the bottom area of the tie plate.

• Polyurethane and rubber tie plates apply approximately all the load directly under the rail to the cross tie and do not distribute the load over the entire area of the tie plate.

• Sensors should be calibrated for each different tie plate material and configuration.

**Calibration**

• Calibration should be performed using the same configuration as will be used in the track. Use the same materials and relative placement of sensor, bladder, shim stock, etc.

• Calibration loadings should be similar to expected loadings under trains.

• Calibration loadings should be applied as fast as possible to minimize drift.

• Sensor output is not linear. A power curve in the form \( y = ax^b \) is desirable to determine accurate results.

• Calibration is repeatable for similar rates of loading and for similar materials.

• Repeatability is very good for in-track testing under similar trains and similar situations.

• The Satec machine is assumed accurate for sensor calibrations due to recent calibration.
• The calibration delay should be set to zero on the computer to aid the Satec operator.

• Calibration must be determined for three situations: unloaded track, empty car, and locomotive & loaded car.

• Calibration should be done shortly after in-track test before other tests are run so that sensor does not ‘age’.

• Before calibration of a new sensor it should be ‘conditioned’ with 3 to 5 loads 20% greater than that expected during testing. This will prevent the sensor from drifting radically during early test.

• Calibration in the laboratory should be to the total raw sum as determined from review of the in-track test.

• When calibrating in the laboratory the total raw sum can be determined by taking a snapshot of the sensor when the Satec machine has reached the desired load. This will increase accuracy of the test by reducing operator judgment of raw sum value.

**In-Track Tests**

• Total thickness of the tie plate that is removed should be equal to total thickness of replacement plate, sensor, mylar, Teflon, and bladders(if used). This prevents bridging which would lower overall forces or mounting which would raise overall forces.

• Sand, gravel, dirt, etc. should be removed from surface to prevent damage to sensor.
• Use new tie plate on a good quality cross tie, one that is both level and relatively smooth.

• Protect sensor from shear stress with Teflon paper.

• Protect sensor from punctures or cutting with mylar sheets.

• Place Teflon above and below sensor.

• Place mylar above and below the Teflon.

• Protect handle from moisture, oil, sand, and dirt. Protect handle from vibrations. Recommend covering or wrapping in cloth or foam and a plastic bag.

• Have Magma and computer on separate power inverters and power sources unless connected to 110 volt outlet.

• Carefully connect all wires and computer cardbus to ensure perfect contact. Failure to have continuous contact will result in computer failure or freeze.

• Test sensor with simple field test. Run finger over surface of sensor before placing it in the track to ensure that it is operating correctly.

• Choose sensor size that completely covers or exceeds the area of contact to ensure all force is applied through the sensor.

• Choose sensor that has a capacity of at least 1,200 to 1,500 psi. Even higher capacity sensors would be preferred, but some resolution will be sacrificed.

• Handle and sensor are most vulnerable to damage due to placement within the track area.

• Adjust the tie plate in the track to obtain consistent dead loads.
• The Tekscan pressure measurement system is applicable for measuring pressures above and below tie plates under railroad loadings.

Analysis and Interpretation

• All tests should be saved in the raw form before editing begins.

• During the tests it is important to compare and contrast similar loads when different locations, different track features, and different trains are used. It was assumed that all similar locomotives (either 4 axle 263,000 pounds or 6 axle 394,000 pounds) will remain constant.

• The first step in analysis is to determine events in the movie that are to be interpreted.

• The next step is to cut out unnecessary frames.

• Editing can be accomplished by either deleting erroneous cells or averaging malfunctioning cells.

• Tekscan provides for two procedures to calibrate – either one point or two point calibrations. One point calibrations provide a good relative representation of the pressure distribution for a frame. Two point calibrations provide a more accurate total pressure and total force value for a frame.

• Force vs. Frames and Pressure vs. Frames graphs can be useful when comparing trains and for identification of events.

• Accurate Force vs. Frame and Pressure vs. Frame graphs can be obtained by importing the files into Microsoft Excel.

• Multiple calibration curves can be applied by using an IF function in Excel.
Based on the information in this study Tekscan Measurement System is applicable to railroad applications. The sensors have the capacity and repeatability to measure forces and pressures in the upper regions of the track structure.

Best practice methods were determined for calibration, testing, and evaluation of data. Calibration should be done immediately following an in-track test with similar shim stock setup. This calibration should be conducted for three ranges:

- First: for the unloaded rail
- Second: for the empty rail cars
- Third: for the loaded rail cars and locomotives

The in-track test environment is harsh and precautions should be taken to ensure the safety of the persons testing as well as the sensitive equipment. The large amount of data that is collected should be saved in the raw form and editing and evaluation should be done to different files to preserve the original data.
Chapter Ten

Summary and Recommendations for Future Research

Initially it was felt that the technology was not applicable for railroad trackbed measurements. However, modification and further refinement of the calibration and testing procedures defined a best practice that was both precise and accurate. The result was a method of testing that can be utilized satisfactorily in a variety of future railroad research investigations.

The primary objective of this study was to show that Tekscan sensor technology can provide precise measurements for determining pressures in the upper region of the track structure. Great strides have been made toward determining pressures experimentally. This was done by pushing the limits of technology over a broad range of pressures in a dynamic and harsh environment for testing. This will allow for further investigation into track geometry, crossing diamonds, and rail/highway crossing fatigue.

While the present system used in this study does not have the capacity to measure multiple sensors simultaneously, the purchase of additional hardware is available that makes this possible. With this technology track geometry or more specifically curve superelevation could be validated by placing a sensor under the both the low rail and high rail. The compared data would validate the distribution of forces to the two rails and future designs could have actual test data to facilitate design.
Another area where accurate data has been difficult to obtain is at railroad crossing diamonds. These rail/rail intersection are expensive to maintain and there is very little experiment information on the magnitudes of the forces and impacts. Some work was begun during this study at a crossing diamond in Milford Junction, Indiana, but a full study was not completed. The test did prove that the non-intrusive Tekscan technology could be used under the crossing diamond. Extra precautions are needed to protect the sensor and the handle from the high impacts and vibrations that are present when a train crosses the flange way gaps at a diamond. The most significant conclusion from this test was that the handle is sensitive and foam cushion or cloth is needed to protect it during extreme impact and vibration testing conditions. However, with additional testing the results could result in significant savings for the railroad industry.

A final area where future research could utilize the Tekscan technology is at another costly location on the railroad system, the rail/highway intersection. Like the crossing diamond this special feature requires a disproportionately large amount of construction and maintenance expenditures per track foot. Research is currently underway to determine the pressure applied to the crossing and to the rail under both automotive and heavy truck traffic. Due to the non-intrusive nature of Tekscan, the 5260 sensors can be simply laid on the pavement or crossing surface and then the vehicles roll over them measuring the pressure.

Another related possibility is using the smaller 6300 sensor to attach to the side of the rail head so that lateral force applied to the rail head by vehicles at
degrading crossings can be measured to help predict head-web separation of the rail, which is a major derailment problem.

This is a new application of technology to verify what previously was only calculated by computer and theoretical models. It provides a better understanding of the forces and pressure distributions in the railroad tracks; thus a better quality and longer lasting track structure can be designed. The results will lead to less maintenance of the track and a longer life cycle of track components all of which will reduce cost for the railroad industry that is currently challenged in an ever increasingly competitive market.
Appendix A

Manufacturer’s Description of Sensors
MAP AND SENSOR MODEL NUMBER: 5250
SENSOR NAME: CMP

Application Examples: CMP machine and screen printing machine set up.

Special Feature: Trimmable from two sides.
MAP AND SENSOR MODEL NUMBER: 5260
SENSOR NAME: CATALYST

Application Examples: Catalytic converter manufacturing.

Special Features: Can be trimmed from two sides.
- External and Internal vents.

Tekscan, Inc., 307 West First Street, South Boston, MA 02127  Phone:617-464-4500  Fax 617-464-4266  Website: www.tekscan.com
**MAP AND SENSOR MODEL NUMBER:** 6300  
**SENSOR NAME:** STRIP

**Application Examples:** Car door seals, oil pan seals and roller roundness measurements.

**Special Features:** Sensor can be cut from either edge to make it shorter or narrower without affecting the output.

- Internal vent.

<table>
<thead>
<tr>
<th>Model Number</th>
<th>General Dimensions</th>
<th>Sensing Region Dimensions</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>US 6300</td>
<td>Overall Length 8.7 (in)</td>
<td>Matrix Width 10.4 (in)</td>
<td>No. of Sensels 2288</td>
</tr>
<tr>
<td></td>
<td>Overall Width 12.4 (in)</td>
<td>Matrix Height 1.3 (in)</td>
<td>Sensel Density 166.7</td>
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<td></td>
<td>Tab Length 5.7 (in)</td>
<td>Columns 0.125 (in)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Matrix Width 264 (mm)</td>
<td>Rows 0.2 (in)</td>
<td></td>
</tr>
<tr>
<td>Metric 6300</td>
<td>Overall Length 222 (mm)</td>
<td>Matrix Height 3.18 (mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overall Width 315 (mm)</td>
<td>Columns 5.08 (mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tab Length 145 (mm)</td>
<td>Rows 0.25 (mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Matrix Width 264 (mm)</td>
<td>Sensel Density 2288 (sensel per sq-cm)</td>
<td>25.8</td>
</tr>
<tr>
<td></td>
<td>Matrix Height 34 (mm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Application Examples:** Car door seals, oil pan seals and roller roundness measurements.

**Special Features:** Sensor can be cut from either edge to make it shorter or narrower without affecting the output.

- Internal vent.
Appendix B

I-scan Calibration Processes
The process to apply a previously saved calibration file to an existing movie is accomplished by the following steps using I-scan software:

1. Open the desired movie by, clicking the ‘File’ tab in the upper left corner of the screen. A drop down menu will appear. Select ‘Open Movie’ from this menu. Another box will open in the middle of the screen. Select the desired movie and double click it.

2. The movie will open. Then click the ‘Tools’ tab in the upper center of the screen. A drop down menu will appear. Select ‘Calibration . . ’ from this menu.

3. The calibration box will appear in the middle of the screen. Click ‘Load Cal. File’. Another box will appear. Select the calibration file that is applicable for the movie and double click it.

4. The previous box will show details about the calibration file. Click ‘OK’ to apply the calibration file to the movie.

The process for calibrating a file using real time calibration in I-scan software is accomplished by the following steps:

1. Set up the Tekscan Measurement System with the correct configuration of sensors, shim stock, tie plate, and rail in the Instrom test machine.

2. Open a new session by clicking the ‘File’ tab in the upper left corner of the screen and then clicking ‘New Session…” Choose the sensor type to be calibrated and click ‘OK’
3. Then click the ‘Tools’ tab and then click ‘Calibration…’ on the drop down menu. A new menu will appear in the middle of the screen.

4. To calibrate click ‘Add…’ and another menu will appear.

5. Set the ‘Applied Force’ to the target load for the calibration. Reduce the ‘Begin calibrating in’ to 0(zero) seconds so that when the ‘Start’ button is pushed the computer will immediately take the calibration rather than delay by the ‘Begin calibration in’ amount.

6. Apply the load using the Instrom machine as quickly as possible.

   When the desired load is applied click ‘Start’ and the calibration will be taken for the given total raw sum and area of contact at that time.

7. To add a second calibration point repeat steps 4 through 6. This is considered a two point calibration.

To calibrate for multiple calibration curves, the process is slightly different. The following steps should be taken to collect the data necessary for determining multiple calibration curves.

1. Follow steps 1 and 2 of calibrating in real time.

2. Determine the range of the loads expected during testing.

3. Divide the range into a reasonable number of divisions. For this research project calibrations were taken at 100, 200, 1000, 5000, 10000, 15000, 20000, 25000, 30000, 35000, 40000, 45000, and 50000 pounds.

4. Load the sensor in the Instrom machine to the desired load.
5. When the load is applied, click the Snapshot icon which is located in the upper middle of the screen next to the record button on the movie control bar. The icon looks like a camera. This will take a one-frame movie of sensor at the time when the snapshot was taken.

6. Record both the total raw sum and contact area from the frame.

7. Click the ‘File’ tab and then click ‘New Recording’. This will open a new window and steps 5 and 6 should be repeated for each of the loads determined in step 3.

8. The recorded values can be transferred to Microsoft Excel for data analysis and to determine the calibration curves.
Appendix C

Tekscan Startup Sequence
Tekscan Start-up Instructions

1. Connect Magma box to laptop computer.
2. Plug power cord into Magma box, then into the power source.
3. Check to see that the green light is illuminated on the Magma.
4. Plug power cord into laptop, then into the power source.
5. Power up the computer.
6. Plug handle cord into the Magma box.
7. Open Tekscan software on the computer
8. Once in Tekscan:
   - Click File
   - Click New Session
   - Choose the correct pattern that will be used in the experiment
   - Click Handle A
   - Click OK
9. Plug in handle to Tekscan sensor.
10. The Handle Misaligned error box should disappear from the screen if properly aligned.
11. Test sensor for continuity by applying test pressure to outside columns and rows.
12. Begin testing!!!!!
Appendix D1

Rail Force Distribution

TTI rail yard in Paris, Kentucky
5 Ties Before the Lead Wheel
F = 2316 lbf, P = 50 psi

4 Ties Before the Lead Wheel
F = 4149 lbf, P = 86 psi
3 Ties Before the Lead Wheel
F = 7501 lbf, P = 156 psi

2 Ties Before the Lead Wheel
F = 12915 lbf, P = 269 psi
1 Tie Before the Lead Wheel

\[ F = 17626 \text{ lbf}, P = 367 \text{ psi} \]

Lead Wheel Over Sensor

\[ F = 20985 \text{ lbf}, P = 437 \text{ psi} \]
1 Tie After the Lead Wheel
F = 19623 lbf, P = 410 psi

2 Ties After the Lead Wheel
F = 18007 lbf, P = 375 psi
3 Ties After the Lead Wheel
F = 17782 lbf, P = 370 psi

4 Ties After the Lead Wheel
F = 18131 lbf, P = 378 psi
5 Ties After the Lead Wheel

\[ F = 13139 \text{ lbf}, \quad P = 275 \text{ psi} \]
Appendix D2

Rail Force Distribution

CSXT open track Conway, Kentucky.
5 Ties Before the Lead Wheel
F = 4828 lbf, P = 100 psi

4 Ties Before the Lead Wheel
F = 5870 lbf, P = 122 psi
3 Ties Before the Lead Wheel
F = 9940 lbf, P = 207 psi

2 Ties Before the Lead Wheel
F = 14136 lbf, P = 295 psi
1 Tie Before the Lead Wheel
\[ F = 19171 \text{ lbf}, \ P = 400 \text{ psi} \]

Lead Wheel Over Sensor
\[ F = 25372 \text{ lbf}, \ P = 529 \text{ psi} \]
1 Tie After the Lead Wheel
F = 25446 lbf, P = 530 psi

2 Ties After the Lead Wheel
F = 25986 lbf, P = 541 psi
3 Ties After the Lead Wheel
$F = 27002$ lbf, $P = 562$ psi

4 Ties After the Lead Wheel
$F = 27730$ lbf, $P = 578$ psi
5 Ties After the Lead Wheel
F = 27159 lbf, P = 566 psi

6 Ties After the Lead Wheel
F = 26179 lbf, P = 545 psi
7 Ties After the Lead Wheel
\[ F = 26725 \text{ lbf}, \, P = 557 \text{ psi} \]

8 Ties After the Lead Wheel
\[ F = 25313 \text{ lbf}, \, P = 527 \text{ psi} \]
9 Ties After the Lead Wheel
\[ F = 19259 \text{ lbf}, P = 401 \text{ psi} \]

10 Ties After the Lead Wheel
\[ F = 12234 \text{ lbf}, P = 255 \text{ psi} \]
Appendix E

Study Test Sites and Dates
<table>
<thead>
<tr>
<th>Tekscan Test Sites</th>
<th>Tested</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Kentucky</td>
<td>Car</td>
<td>7-1-03</td>
</tr>
<tr>
<td></td>
<td>First test using Dr. Rose’s Car</td>
<td></td>
</tr>
<tr>
<td>Richmond, Ky</td>
<td>Coal Train &amp; Highrail Truck</td>
<td>7-2-03</td>
</tr>
<tr>
<td></td>
<td>First in-track test.</td>
<td></td>
</tr>
<tr>
<td>George’s Branch, Ky</td>
<td>Loaded Coal Truck &amp; State Truck</td>
<td>7-24-03</td>
</tr>
<tr>
<td></td>
<td>First test using 5260 under coal truck.</td>
<td></td>
</tr>
<tr>
<td>TTI Railyard Paris, Ky</td>
<td>Locomotive</td>
<td>8-1-03</td>
</tr>
<tr>
<td></td>
<td>Study different tie plate material and effect of rail distribution</td>
<td></td>
</tr>
<tr>
<td>Conway, Ky</td>
<td>Locomotives &amp; Coal and Freight Train</td>
<td>8-7-03</td>
</tr>
<tr>
<td></td>
<td>Study different tie plate material, effect of rail distribution, first in-track distribution test at tie/tie plate interface</td>
<td></td>
</tr>
<tr>
<td>Milford Junction, In</td>
<td>Crossing Diamond Impact</td>
<td>8-19-03</td>
</tr>
<tr>
<td></td>
<td>Impact study at rail/tie plate interface at adjacent tie to the diamond.</td>
<td></td>
</tr>
<tr>
<td>Milford Junction, In</td>
<td>Crossing Diamond Impact</td>
<td>10-3-03</td>
</tr>
<tr>
<td></td>
<td>Impact study at adjacent tie and under crossing diamond.</td>
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</tr>
<tr>
<td>CSXT Track Paris, Ky</td>
<td>High speed trains</td>
<td>12-30-03</td>
</tr>
<tr>
<td></td>
<td>Compare high speed train on continuously welded rail to impact from diamond.</td>
<td></td>
</tr>
<tr>
<td>Kentucky Coal Terminal</td>
<td>Loaded Coal Truck &amp; CSXT Suburban</td>
<td>5-25-04</td>
</tr>
<tr>
<td></td>
<td>Study force and pressure of loaded coal truck on asphalt approach to road/railroad crossing and on concrete crossing material.</td>
<td></td>
</tr>
<tr>
<td>TTI Railyard Paris, Ky</td>
<td>Locomotive &amp; Loaded Car</td>
<td>6-1-04</td>
</tr>
<tr>
<td></td>
<td>Test best method of testing</td>
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<tr>
<td>CSXT Track Paris, Ky</td>
<td>Freight &amp; Auto Train</td>
<td>6-4-04</td>
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<tr>
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<td>Test best method of testing</td>
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</table>
Appendix F

Satec Machine Operation

Tutorial of Partner Software
The Satec Testing Machine has data acquisition software – Partner – integrated in the system. Partner is a useful software program for collecting multiple tests and summarizing the results. The capacity of the program was not fully utilized for this study. The software was used to determine force applied by the machine for calibration purposes. Partner has a helpful feature – TestWizard – that aids in setting up test and collecting the required data. TestWizard is a twelve step process that allows the user to format the test to exact specifications. The following screen shots are from TestWizard.

The first step is to select the shape of the object being tested. For this study any object will do, but if a concrete strength test was being performed then a cylinder would be selected and the Next> button is pushed.
The second step allows for labeling of tests. Again this was out of the scope of this research project, but for experimental purposes labels could be assigned for different tests to help organize the results.

The third step tells the computer whether a compression test or tension test will be conducted.
The fourth step determines what measurements will be recorded for each test. For this study only the Load was needed, but the default setting was used.

The fifth step allows for other options of calculating measurements, but the default was used for this study.
The Partner software has the capability to calculate a wide variety related results including compressive strength, Young’s Modulus and others. This was beyond the scope of this study, but could be useful for future studies.

The seventh step allows for any or all of the measurements to be zeroed when the test starts. For this study all measurements were initially zeroed.
The eighth step tells the computer when to start collecting data for a test. This was not necessary for this study, so the default setting was used.

The ninth step is used to protect extra equipment used in a test. This was not necessary for this study. For example, when conducting a steel bar tensile test, transducers are used to measure strain. To prevent the sudden snapping of
a bar and thus damage to the transducer, the software allows for a reminder to be given at a certain level to help prevent damage.

The tenth step determines when the computer will stop recording data and declare the test over. It will either stop at a given level or when the computer detects a break. Again this feature was not necessary for this study and the default was used.
The eleventh step is related to the previous one and because the default is a break detector, this step tells the computer what is classified as a break. This was set at the default setting for this study.
The twelfth step allows for several graphs to be plotted in real time as the test is running. This was not used during this study and the default setting was used.

This final window appears and it is the end of TestWizard.
Once TestWizard is complete any labels selected are displayed and the information for the first test is entered. The Check Procedure button should then be pushed and any errors that occurred during the TestWizard process will be identified and can be corrected.

When the Check Procedure reports No Errors then the Run Test button can be pushed and the measurements will be zeroed and the test can be run.
This screen shot will appear once the test is ready to be run. Note the measurements are zeroed and the graph appears. As the test is conducted, the load, position, and time will change and the graph will develop.
References


Vita

Jason Clarence Stith was born on January 21, 1982 in Elizabethtown, Kentucky. His parents are Richard and Veronica Stith. His elementary education was completed in Vine Grove, Kentucky and his secondary education was competed in Cecilia, Kentucky. Upon graduation from high school in 2000, he attended the University of Kentucky where he received a Bachelor of Science in Civil Engineering in 2004. During the Spring Semester of 2002 he attended the University of New South Wales in Sydney, Australia as a study abroad student. Additionally, he spent the Summer Semester of 2004 on an Institute for Shipboard Education Semester at Sea program which is academically run through the University of Pittsburgh. He began work on his Master’s Degree in Civil Engineering in the Fall Semester of 2004, and since then has been working on obtaining this degree as well as a Master’s Degree in Business Administration. Jason has worked as an Engineer in Training at Palmer Engineering Co. Inc. in Winchester, Kentucky. Jason has been honored with a Charles T. Wethington Fellowship. In addition, he received the College of Engineering Outstanding Senior of the Year Award and the Maurice A. Clay Omicron Delta Kappa College of Engineering Leadership Award. He was a National Science Foundation Computer Science, Engineering, and Mathematics Scholar as an undergraduate and received an American Engineering and Maintenance-of-Way Association National Scholarship. On December 29, 2004 Jason married Samantha Lea Bell of Upton, Kentucky. Portions of this thesis have been co-authored by Jason as Tekscan Sensors – Rail/ Sleeper Interface Pressure Measurements in Railway Trackbeds in the proceedings of the Railway Engineering – 2004 7th International Conference and exhibition and Pressure Measurements in Railroad Trackbeds at the Rail/ Tie Interface using Tekscan Sensors in the proceedings of the American Railway Engineering and Maintenance-of-Way Association 2004 Annual Conference and Exposition.